Storm Surge Measurement with an Airborne Scanning Radar Altimeter

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ABSTRACT

Over the years, hurricane track and intensity forecasts and storm surge models and the digital terrain and bathymetry data they depend on have improved significantly. Strides have also been made in knowledge of the detailed variation of the surface wind field driving the surge. The area of least improvement has been in obtaining data on the details of the temporal/spatial variation of the storm surge dome of water as it evolves and inundates the land to evaluate the performance of the numerical models. Tide gages in the vicinity of the landfall are frequently destroyed by the surge. Survey crews dispatched after the event provide no temporal information and only indirect indications of the maximum surge envelope over land. The landfall of Hurricane Bonnie on 26 August 1998, with a surge less than 2 m, provided an excellent opportunity to demonstrate the potential benefits of direct airborne measurement of the temporal/spatial evolution of storm surge. Despite a 160 m variation in aircraft altitude, an 11.5 m variation in the elevation of the mean sea surface relative to the ellipsoid over the flight track, and the tidal variation over the 5 hour data acquisition interval, a survey-quality Global Positioning System (GPS) aircraft trajectory allowed the NASA Scanning Radar Altimeter carried by a NOAA hurricane research aircraft to produce storm surge measurements that generally fell between the predictions of the NOAA SLOSH model and the North Carolina State University storm surge model.

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POPULAR SUMMARY

The storm surge associated with a landfalling hurricane is a mound of water generated by the high winds and pushed toward the shore. Some of the factors affecting the magnitude of the surge are the maximum wind speed, the radius of maximum wind, and the hurricane's forward speed and track relative to the coastline. The storm surge from Hurricane Katrina exceeded 8 m.

With much of the densely populated Atlantic and Gulf Coast shorelines less than 3 m above mean sea level, storm surge has the potential to destroy lives and property and cut off escape routes. Because the public needs to evacuate before landfall, sophisticated modeling efforts for predicting storm surge have been developed to enable emergency managers to issue timely evacuation orders and effectively position response resources.

Over the years, hurricane track and intensity forecasts as well as the surge models and the digital terrain and bathymetry data they depend on have improved significantly. Strides have also been made in knowledge of the surface wind field driving the surge. The area of least improvement has been in obtaining detailed data on the temporal/spatial variation of the storm surge dome of water as it evolves and inundates the land to evaluate the performance of the numerical models. Tide gages in the vicinity of the landfall are frequently destroyed by the surge and survey crews dispatched after the event provide no temporal information and only indirect indications of the maximum surge envelope over land.

A NOAA hurricane research aircraft carried the NASA Scanning Radar Altimeter (SRA) into Hurricane Bonnie as it made landfall near Wilmington, NC, on 26 August 1998. The SRA surge measurements generally fell between the predictions of two models and much of the difference in the models may have been caused by the different tracks they used. The NOAA SLOSH model used the National Hurricane Center (NHC) 6-hour interval Best Track storm positions while the North Carolina State University (NCSU) model used the eye locations at two hour intervals issued in the NHC advisories during the landfall. The NCSU track sped up Bonnie and diverted it about 25 km to the west as it approached Cape Fear, reaching the Wilmington area about three hours earlier than the Best Track. The SRA aircraft eye fixes indicated that the true track was between the two NHC tracks in both position and timing.

The SRA measurements indicate that airborne measurement of storm surge could provide an absolute standard for evaluating and improving the performance of storm surge models.

SIGNIFICANT FINDINGS

A NOAA hurricane research aircraft carried the NASA Scanning Radar Altimeter (SRA) into Hurricane Bonnie during its landfall near Wilmington, NC, on 26 August 1998. Despite a 160 m variation in aircraft altitude, an 11.5 m variation in the elevation of the mean sea surface relative to the ellipsoid over the flight track, and the tidal variation over the 5 hour data acquisition interval, a survey-quality Global Positioning System (GPS) aircraft trajectory allowed the SRA to produce storm surge measurements that generally fell between the predictions of the NOAA SLOSH model and the North Carolina State University (NCSU) storm surge model.

Averaging the SRA sea surface topography measurements over 450 m by 500 m areas produced storm surge elevations which were generally within 10 cm of their trend lines and demonstrated that the technique could provide an absolute standard for evaluating and improving the performance of storm surge models.

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1. Introduction

The National Aeronautics and Space Administration (NASA) Scanning Radar Altimeter (SRA) has a long heritage in measuring the energetic portion of the sea surface directional wave spectrum (Walsh et al. 1985; 1989; 1996, 2002; Wright et al. 2001, Black et al. 2007). SRA wave spectra have been used to assess the performance of the WaveWatch III numerical wave model (Moon et al. 2003; Fan et al. 2007). This paper demonstrates that an airborne scanning radar altimeter could also routinely provide targeted measurements of storm surge for assessing and improving the performance of numerical storm surge models.

The storm surge associated with a landfalling hurricane is a mound of water generated by the high winds and pushed toward the shore. Some of the factors affecting the magnitude of the surge are the maximum wind speed, the radius of maximum wind, the forward speed of the storm, its angle of track relative to the coastline, and the characteristics of the bathymetry and coastline, including roads, levees and other physical features that modify the storm surge flow pattern. The locally raised sea level gives the storm waves riding on top of the surge access to cause extensive damage to coastal structures and beach erosion.

The storm surge from Hurricane Katrina exceeded 8 m. With much of the densely populated Atlantic and Gulf Coast shorelines less than 3 m above mean sea level, storm surge has the potential to destroy lives and property and cut off escape routes. Because the public needs to evacuate before landfall, sophisticated modeling efforts for predicting storm surge have been developed to enable emergency managers to issue timely evacuation orders and effectively position response resources.

Over the years, hurricane track and intensity forecasts, as well as the surge models and the digital terrain and bathymetry data they depend on have improved significantly. Strides have also been made in knowledge of the surface wind field driving the surge from airborne measurements using GPS dropwindsondes and Stepped Frequency Microwave Radiometers (Powell et al. 1998; 2003; Uhlhorn and Black 2003; Uhlhorn et al. 2007) as well as wind data gathered from temporary towers set up along the coast in the hurricane's projected path (Schroeder and Smith 2003).

The area of least improvement is in obtaining detailed data on the temporal/spatial variation of the storm surge dome of water as it evolves and inundates the land to evaluate the performance of the numerical models. Tide gages in the vicinity of the landfall are useful in determining this variation, but are frequently destroyed by the surge. Survey crews dispatched after the event provide no temporal information and only indirect indications of the maximum surge envelope over land (Fritz et al. 2007; http://www.fema.gov/pdf/hazard/flood/recoverydata/katrina/katrina_ms_hwm_public.pdf).

The landfall of Hurricane Bonnie on 26 August 1998 provided an excellent opportunity to demonstrate the potential benefits of direct airborne measurement of the temporal/spatial evolution of storm surge. Bonnie was a slow moving storm with a large radius of maximum wind, minimizing both the temporal and spatial gradients. The peak of the Hurricane Bonnie storm surge was less than 2 m, providing an opportunity to demonstrate that even a minimal surge can be well documented.

Figures 1 and 2 provide an overview to put the measurements and model results in perspective. Figure 1 indicates the National Hurricane Center (NHC) Best Track eye locations for Hurricane Bonnie at 6-hour intervals from 0000 UTC on 26 August to 0000 UTC on 29 August 1998. Circles of 100 km radius have been placed around the four 0000 UTC eye locations because that was the approximate radius of maximum wind on 26 August when the SRA observations were made.

The thin circles indicate tide gage locations. Unfortunately the Wrightsville Beach tide gage was not in operation during the Bonnie landfall. Figure 2 shows the surge record from all the tide gages except Ft. Pulaski in Georgia, which was south of the near-shore SRA

measurements. The numerical models indicated that the surge peaked on the east side of Cape Fear in the afternoon of 26 August and then slowly diminished as it shifted north along the North Carolina coast.

The most dramatic water level variation seen by the gages during the SRA measurement interval was the depression of the water surface caused by the offshore winds at Springmaid Pier. It is interesting that the largest positive surge observed by the gages occurred at the Oregon Inlet sheltered location. When the wind was onshore, water slowly entered Pamlico Sound through gaps in the Outer Banks and was pushed to the west. When the wind reversed late on 27 August, the water was driven back to the east but couldn't readily escape and piled up against the Outer Banks.

2. The mean sea surface

Figure 3 indicates the track of the NOAA Aircraft Operations Center (AOC) WP-3D hurricane research aircraft (N43RF) carrying the NASA SRA on 26 August 1998 superimposed on elevation contours of the mean sea surface (Wang 2001; GSFC00.1 MSS, hereafter referred to as MSS) relative to the TOPEX/Poseidon (T/P) standard reference ellipsoid (Tapley et al. 1994) used to approximate the overall shape of the earth.

The MSS has been blended with the geoid so that its contours extend over land. The geoid is the gravitational equipotential surface determined by the mass distribution of the earth. The sea surface would conform to the geoid if the earth were not rotating and there were no currents or external forces acting on it such as the wind or the gravitational pulls of the moon and sun. The MSS differs from the geoid in that it incorporates the mean elevation of any currents, such as the Gulf Stream, and any constant tides.

Figure 3 indicates that the sea surface mean elevation varies significantly off the mid-Atlantic coast of the U.S. with a range of 11.5 m over the aircraft track. The high point was 33.5 m below the T/P ellipsoid at position E and the low point was 45 m below the ellipsoid at position H. The continental shelf break is in the vicinity of the -41 m contour.

3. Sea surface topography measurements

Figure 4 shows the measurement geometry of the SRA during the landfall flight. The SRA scanned a 1° (two-way) beam from left to right through the nadir point in the vertical plane containing the aircraft wings and measured the slant range to 64 points over a swath width equal to 0.8 times the aircraft height. The mean altitude of about 2140 m resulted in a 1712 m swath and a 37 m footprint. The 5.5 Hz scan rate and 120 m s^{-1} nominal ground speed produced an along-track separation of 22 m between consecutive 64-point cross-track raster scan lines. The boresight angles of the 64 cross-track antenna beam positions were spaced at 0.7° intervals so adjacent locations were separated by 26 m near the nadir point and 30 m near the edge of the swath.

The NOAA aircraft typically flies in a 2° nose-up pitch attitude and the SRA antenna was mounted looking aft by 2° so it would generally scan through the nadir point during the flights. To obtain the vertical distances from the SRA antenna to the various positions across the swath, the SRA slant range measurements were multiplied by the cosine of the actual off-nadir pitch angle of the beams indicated by the aircraft inertial navigation system (INS) and by the cosine of the off-nadir beam boresight angles in the cross-track plane. When these ranges are subtracted from the height of the antenna, a topographic map of the surface is produced.

The pitch attitude is generally quite stable unless the aircraft is initiating or terminating an altitude transition. But even in level flight the roll attitude continually oscillates by several degrees. Any error in aircraft roll attitude added to the nominal cross-track boresight angles of the beams would make the sea surface appear to be tilted by the same amount. At a 2140 m height, a roll attitude error of only 0.2° would elevate one edge of the swath by 3 m and depress

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the other edge by the same amount. The INS is more accurate than that, but it is located near the front of the aircraft and there is enough torsion in the airframe to cause the roll attitude of the SRA antenna mounted near the back of the aircraft to deviate from the roll attitude measured by the INS.

Figure 5 shows two grayscale-coded sea surface topographic maps produced from different processings of SRA data as the aircraft flew from east to west across Cape Lookout (34.58°N, 76.53°W; point A, Figure 3). The significant wave height was about 4.6 m and the dominant wavelength was about 165 m. The grey-scale spans just 5 m vertically to emphasize the surface tilts. The topography in the top map was generated using the aircraft roll attitude indicated by the INS. There were 16 occasions in the 17 km span of data shown in which torsion in the airframe induced erroneous sea surface tilts whose magnitude exceeded 0.2° (6 m elevation change across the swath). The largest roll excursion (-5°) occurred at 11.7 km but it induced less airframe torsion than the more rapid 3.2° excursion at 15.6 km.

This problem can be greatly mitigated by assuming that a straight line fitted through the elevation points over the 1700 m swath should be horizontal and computing the antenna roll attitude rather than applying the INS roll. The lower sea surface map in Figure 5 was produced in that fashion and does not exhibit the sea surface tilts.

The lower image is similar to Figure 4 of Walsh et al. (2002) except that there is less data retained near the edge of the swath and most of the Cape Lookout terrain (between 6.5 and 9 km) is missing. This is because a higher signal level threshold was used for the storm surge measurements to reduce noise in the range measurements. Land has a significantly lower radar backscatter coefficient than water. The SRA antenna gain varied little over most of the swath but then rolled off rapidly, being 12 dB lower (two-way) at the swath edges.

Since the highest quality range measurements are in the vicinity of the nadir point, each sea surface height used in the storm surge measurement was determined by taking the 20 points of each 64-point cross-track sweep that were nearest nadir on each of 20 consecutive scan lines and averaging those of the 400 total points that exceeded the signal threshold. The starting scan line number for successive storm surge measurements was increased by 10 so there would be a 50% overlap of the data points in adjacent averages. Two examples of the 20-by-20 point areas averaged over are indicated by the black parallelograms near 3 and 13 km in the lower image of Figure 5. The averaging areas are small enough that wave structure will cause the actual water level within the area to deviate from the true mean elevation of the sea surface at that time and position.

An additional editing criterion was that scan lines were not processed if the roll attitude of the aircraft exceeded 6°. This eliminated the most turbulent regions and times when the aircraft was making significant changes in heading.

In addition to the storm surge, the SRA documents the storm waves riding on top of the surge that cause much of the structural damage and beach erosion. In Figure 5 the wave topography shows a dramatic spatial variation in the wave field with the waves propagating toward the northwest on the east side of Cape Lookout, and toward the north on the west side.

4. Airborne measurement of sea surface elevation

The top panel of Figure 6 shows the altitude variation indicated by the aircraft data system during a five hour interval on the 26 August 1998 flight. The height variation spanned 160 m due to changes in atmospheric pressure and updrafts and downdrafts. The precise height variation of the aircraft was determined post-flight with a survey quality differential Global Positioning System (GPS) trajectory.

The original processing in 1998 produced a trajectory with numerous gaps, one larger than 18 minutes, due to the large amount of aircraft maneuvering. After the 1998 hurricane season an actuated antenna mount was developed which would roll the GPS antenna in the

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opposite direction to the aircraft roll to maintain the antenna boresight vertical. The stabilized antenna greatly improved GPS data quality, but the coverage of a landfalling hurricane was never again as extensive as it was for Hurricane Bonnie. Recently improved processing techniques were able to recover a good quality aircraft trajectory for the Bonnie landfall flight.

The reference ellipsoid used for the GPS trajectory was the World Geodetic System of 1984 (WGS84), which is slightly different than the T/P ellipsoid. The ellipsoids are defined by two parameters, the semi-major axis and the flattening. The T/P semi-major axis is 6378136.3 m and the flattening is 1/298.257. The WGS84 ellipsoid semi-major axis is 6378137.0 m and the flattening is 1/298.257223563. Since the ellipsoids are rotationally symmetric, their elevations only differ as a function of latitude. WGS84 is higher than T/P by 0.705 m at 36°N and by 0.704 m at 31.5°N.

The range measurements of the SRA were calibrated on the ground using a 45° reflector placed under the antenna and corner reflectors at 122, 183, and 244 m ranges. Because the SRA antenna looked out the bottom of the aircraft about 4 m below and 4 m aft of the GPS antenna located on top of the aircraft, its precise height was related to the GPS height by -3.94 – 4.21 tan(aircraft pitch attitude).

Subtracting the vertical distance to the sea surface averaged over 20-by-20 point areas from the height of the SRA antenna produced the surface elevations with respect to the WGS84 ellipsoid shown in the middle panel of Figure 6. Because of the GPS trajectory, the 50 and 100 m height excursions in evidence in the top panel did not contaminated the middle panel elevations whose 12-m span was mainly due to the MSS variation shown in Figure 3. When the 0.7045 m difference of the reference ellipsoids was added and the MSS elevation was subtracted from the elevations of the middle panel, the residual elevation variation (bottom panel) was only about 3 m.

The scatter in the elevation data to the right of H in the bottom panel of Figure 6 is significantly greater than the scatter to the right of F. This does not indicate an increased noise in the SRA range measurements but rather increased deviation of the actual sea surface elevation within the measurement areas from mean sea level due to the presence of waves. Figure 3 indicates that the aircraft was traveling north after leaving both points F and H. Walsh et al. (2002, Figures 9 and 10) indicate that the significant wave height was 4.6 m north of point F and 8.2 m north of point H. There was a trimodal wave system with a 139 m dominant wavelength north of point F and a bimodal wave system with 269 m dominant wavelength north of point H. Higher waves and fewer wavelengths within the averaging area produce greater variability in the actual sea surface elevation. The very high scatter present at G and from I to half way between J and K was due to land within the SRA swath.

5. Tide gages and calibration of SRA storm surge

The five hour interval shown in Figure 6 is a significant fraction of a tidal cycle and the predicted variation in the water level must be removed from the elevation data shown in the bottom panel of Figure 6 to arrive at the storm surge. The Beaufort tide gage was not used directly because its location at the Duke Marine Lab was sheltered from the Atlantic. Its tidal cycle showed a significant lag when compared with the Cape Hatteras gage and Hess et al. (2005) indicated that its amplitude was significantly lower than in the adjoining Atlantic.

The tide prediction at Beaufort for 5-7 September 2005 was very similar to the Beaufort prediction for 25-27 August 1998. When the Beaufort prediction for 5-7 September 2005 was multiplied by 1.32 and shifted earlier by 30 minutes, it almost perfectly matched (1.4 cm rms difference) the prediction for the tide gage at Wrightsville Beach. That algorithm was used to convert the Beaufort prediction for the Bonnie landfall into a tide prediction for Wrightsville Beach.

Figure 7 shows the tide predictions used to produce storm surge from the surface elevation measurements shown in the bottom panel of Figure 6. As an expedient for data in the Atlantic Ocean, the tidal elevation for each SRA data point was linearly interpolated using longitude and the predictions for Fort Pulaski, Charleston, Springmaid Pier, Wrightsville Beach and Cape Hatteras. The Cape Hatteras longitude was shifted slightly to the east to encompass the aircraft track.

As would be expected, the Oregon Inlet tide prediction is much reduced in amplitude and significantly lags the Cape Hatteras prediction. It was used for the SRA observations in Pamlico Sound and was nearly constant at a value of -0.08 m during the aircraft transit.

The SRA passed close to the Charleston, Cape Hatteras, and Springmaid Pier tide gages without land contaminating its measurements. This provided an opportunity to tie the SRA storm surge estimates to the observed surge at these three sites. The absolute water level determination of the SRA was also established at the Duck Pier tide gage. In this instance the standard SRA storm surge computation could not be compared directly with the tide gage surge because the aircraft was flying along the shoreline and determining the actual roll attitude of the SRA antenna from the data itself was not possible with land in the swath

A sort segment of fourteen consecutive cross track scan lines was selected near the Duck Pier gage where the INS roll was near zero and not changing rapidly, assuming the INS and antenna roll attitudes would be nearly the same. The flight direction, the angle of the shoreline, and the yaw attitude of the aircraft were used to determine the perpendicular distance of each SRA footprint from the shoreline and the resulting individual elevations are displayed in Figure 8. The beach run up to the crest of the dune line is well defined. This area of the coast is densely packed with houses just past the dune line.

The horizontal line in Figure 8 is at -39.297 m, the average of all the points between -360 m and -60 m distance from shore, the lowest scatter interval of the SRA elevations. The scatter in the elevations increases with distance from shore both because the wave height increases and the measurement noise increases as the off nadir incidence angle of the SRA beam increases.

Using the INS roll attitude in this carefully selected segment appears justified because a straight line least squares fitted to all the points between -900 m and 0 m indicated a slope of only 0.008° and a shoreline elevation of -39.338 m, only 4 cm different from the -360 to -60 m interval average.

The Duck Pier tide gage measured the water level to be 0.275 m above mean sea level. With MSS at this position being -39.900 m, the surface elevation was -39.625 m. The SRA water elevation of -39.297 m was 0.328 m above the tide gage.

To put things into perspective, we will partition the SRA surge bias into fixed and variable components with the fixed value being -1.03 m. The variable component determined at the four tide gage locations was 0 at 1907 UTC (Charleston), 0.13 m at 2120 UTC (Cape Hatteras), 0.728 m at 2139 UTC (Duck Pier), and -0.01 m at 2251 UTC (Springmaid Pier).

A constant 1 m error in the SRA range determination is of little significance because it could be attributed to the sum of multiple sources, such as an error in the ground calibration and the variation of the speed of light. The SRA processing uses the nominal speed of light at sea level (299702547 m s^{-1}). At the 2140 m height of the SRA, that value results in the measured range being shorter (surface elevations higher) by 0.64 m relative to using the speed of light in vacuum (299792458 m s^{-1}).

The jump in the bias at the Duck Pier gage is more of a concern. It occurred about three minutes after the aircraft reversed course with an angle of bank exceeding 42 degrees, but careful analysis of the GPS trajectory gave no indication of any problem and the trajectory vertical accuracy is believed to be about 0.1 m throughout. The source of the jump in the SRA surge bias at Duck remains unknown.

Absolute range measurement is not necessary to determine the sea surface directional wave spectrum, which was the original purpose of the SRA. In that function, each SRA cross-track scan line is auto-leveled in the manner relating to Figure 5 and deviations from the least-squares fitted straight line are taken to be deviations from the local mean sea level. Storm surge requires an absolute determination of both the range to the surface and the height of the aircraft.

During ground tests, SRA range measurements to a corner reflector were stable with a standard deviation less than 0.1 m. The SRA measurement of storm surge should be independent of any tide gage. But in the case of Hurricane Bonnie, a correction to the SRA surge values was developed by linearly interpolating in time between the four observed tide gage biases and holding the bias constant outside the end points. This essentially changed the SRA from an absolute measurement to an interpolation method between tide gages.

6. Storm surge models

The NOAA storm surge model, known as SLOSH (Sea, Lake and Overland Surges from Hurricanes; http://www.nhc.noaa.gov/HAW2/english/surge/slosh.shtml) is used by NOAA to forecast storm surge heights resulting from historical, hypothetical or predicted hurricanes. SLOSH uses fixed internal parameters based on historical storms and does not tune them for any particular geographic area, nor for a particular storm. The NHC and local National Weather Service (NWS) offices use this information when issuing hurricane advisories.

The meteorology is not yet at the point where it can forecast with the necessary accuracy all the parameters required for a perfect storm surge calculation. To depict the potential flooding from an impending event to aid emergency managers in determining which coastal areas should be evacuated, SLOSH is run for hundreds of hypothetical hurricanes with various Saffir-Simpson categories, forward speeds, landfall directions, and landfall locations. An envelope of high water containing the maximum value a grid cell attains is generated at the end of each model run. These envelopes are combined by the NHC into various composites which depict the possible flooding. One useful composite is the MEOW (Maximum Envelopes of Water) which incorporates all the envelopes for a particular category, speed, and landfall direction. Another composite is the MOM (Maximum of the MEOW's), which combines all the MEOWs of a particular category.

Wind speed is not an input parameter of the SLOSH model, which calculates the wind field from the central barometric pressure and radius of maximum wind. The parametric wind model used by SLOSH was developed by Jelesnianski et. al (1992). The surface wind field is first computed via their solution of a differential equation for a symmetric hurricane. Both the wind speed and direction result from this formulation. To account for asymmetry, ½ of the forward speed is added vectorially to the wind field. The ½ factor was empirically established by examining past hurricanes. Using the full forward speed caused winds for New England hurricanes to be erroneous on both the left and right sides of the hurricane.

The North Carolina State University storm surge model (Peng et al. 2004; Xie et al. 2004; Xie et al. 2005; Peng et al. 2006), hereafter referred to as NCSU, is a mass-conserving interactive inundation and drying scheme incorporated into a three dimensional coastal ocean and estuarine circulation model. It uses asymmetric wind forcing by incorporating an asymmetry term into the Holland hurricane wind field model (Holland 1980), enhanced by using any available near-real time data to optimize the model parameters.

7. Model comparisons

SLOSH and NCSU model results were provided without knowledge of the other model output or the SRA observations. Model output was requested for the period 1700 to 2300 UTC on 26 August 1998 for the region between 79.4°W and 75.4°W and 33°N and 36°N. NCSU supplied storm surge elevations at 1-hour intervals in that domain on a rectangular grid with 2

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arc minute resolution. SLOSH was run in a hindcast mode similar to what is done in NWS operations, but with the NHC post-storm "Best Track" position, size, and intensity. The SLOSH water elevations supplied were the sum of the storm surge and a tidal component which was constant both temporally and spatially at 0.61 m in the Atlantic Ocean and 0.15 m in Pamlico Sound. Those tidal values were subtracted from the SLOSH water elevations to arrive at the surge values.

SLOSH uses telescoping grids centered in different geographical areas called basins to cover large areas with detailed land topography. SLOSH outputs were supplied for both the Wilmington/Myrtle Beach Basin and the Pamlico Sound Basin. The smallest grid element represents an area of about 2.6 square km. The largest grid cell in the Pamlico model is about 3.6 square km, while the largest in the Wilmington/Myrtle Beach model is 26.7 square km although most of the cells near shore are considerable smaller. The SLOSH outputs supplied were from standard post-storm runs and covered the period from 1100 UTC on 25 August through 1700 on 28 August with 20 minute temporal interval in the Wilmington/Myrtle Beach Basin and 15 minute interval in the Pamlico Sound Basin.

SLOSH indicated that the surge peaked at 1.5 m on the east side of Cape Fear at 1330 UTC and then slowly diminished as it shifted up along the North Carolina coast in Onslow Bay, reaching Browns Inlet (34.59N, 77.23W) at 2300 UTC with a value of 1.2 m. The SRA measured the surge in that region three times at about two-hour intervals.

The top panel of Figure 9 superimposes on the SLOSH and NCSU storm surge contours the aircraft track which began east of Cape Lookout at 1806 UTC and approached Cape Island, SC, at 1857 UTC. Two things stand out. First, the orientation of the surge elevation contours in Onslow Bay for SLOSH is about 56°, roughly 18° counterclockwise from the NCSU contours. Second, the NCSU model indicates a depressed water level west of Cape Fear where the SLOSH surge does not even diminish to 0.3 m.

The bottom panel of Figure 9 indicates the NCSU surge values along the flight track, interpolated in both time and space from the 1-hour data sets provided. The SLOSH graphical display option by which individual locations could be interrogated for elevation was used to determine the surge at the positions indicated by the circles in the top panel. Those values for SLOSH are indicated by the circles in the bottom panel and connected by line segments.

The dots in the bottom panel of Figure 9 indicate the SRA storm surge values along the flight track. It is instructive to compare the scatter of the SRA surge values in Figure 9 with the scatter of the individual elevation values from single SRA range measurements to a 37 m diameter area in Figure 8. The individual range measurements show a great deal of scatter but they are to the crest, or to the trough, or somewhere in between, of waves of several m height (when you get away from the beach). In contrast, each storm surge value in Figure 9 is the average of 400 such individual measurements (20 by 20 grid near nadir, parallelograms in Figure 5 lower image).

With few exceptions, the SRA surge values in Figure 9 cluster tightly about their mean trend. The erratic behavior of the SRA data in the region between 70 and 125 km north of 34°N is due to land contamination. The erratic behavior of the NCSU model is also because the aircraft track was near land. If the nadir point were over land, the NCSU value would be zero. If it were within one grid point (2 arc minutes) of land, the automated interpolation procedure would reduce the surge value proportionately. Since the SLOSH values were extracted by hand, they did not experience that problem.

Both models indicate a peak surge along the flight line of about 1.2 m, but NCSU suggests that the maximum would occur further north than SLOSH. The SRA indicates a maximum surge of 1.5 m at about 34°N. About 65 km of the aircraft track are nearly along the 1.2 m SLOSH contour. The SRA surge increasing along that segment suggests that the contours of constant surge were actually even more counterclockwise than the SLOSH contours.

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South of Cape Fear, NCSU indicates that the surge decreases much more rapidly than either SLOSH or the SRA. By the time the aircraft approached Cape Island (-200 km), the SRA storm surge had become negative and was about half way between SLOSH and NCSU.

Figure 10 shows the situation about two hours later. The aircraft had left F (Figure 3) and flown north until reaching 33.6°N, where it diverted slightly to the east and flew north to intercept the coast near Wrightsville Beach. It then looped around to the west and flew south-southeast back over the water before turning east. The aircraft first reached 34°N flying north at 2016 UTC.

In the two hours since the data shown in Figure 9, the SLOSH elevation contours in Onslow Bay rotated about 10° clockwise to about 46°. The NCSU contours also rotated, maintaining approximately the same angle between the two models. NCSU indicates the water depression west of Cape Fear deepened but the SLOSH surge is still positive.

The along-track distances in the bottom panel of Figure 10 are relative to the initial crossing of 34°N while flying north. The second time the aircraft passed through 34°N, flying south-southeast, occurred just past the 75 km point. The NCSU domain requested only extended to 33°N (-114 km in the bottom panel plot) and there were no SRA data in the -100 to -125 km interval because of rain attenuation. SLOSH was in quite good agreement with the SRA surge values in the interval -200 to -75 km (< 33.35°N), but was about 0.5 m low for the surge at the coastline. NCSU indicated that the sea surface was depressed at Cape Fear and to the south.

During the third interrogation of the area off Wrightsville Beach shown in Figure 11, the aircraft left Cape Lookout and flew down around Cape Fear and into Myrtle Beach. It passed through 34°N at 2232 UTC. The SLOSH elevation contours in Onslow Bay have rotated another 10° clockwise to about 36°. The NCSU contours have also rotated, maintaining approximately the same angle between the two models. SLOSH now indicates that the water surface is depressed starting about half way between Cape Fear and Myrtle Beach. The SRA surge is comparable to SLOSH near Wrightsville Beach, then plummets near Cape Fear and is closer to NCSU at Myrtle Beach and Springmaid Pier.

The rise in the SRA surge level between 125 km and 50 km suggests that the contours of constant surge level are still rotated counterclockwise relative to the SLOSH contours, similar to the situation in the bottom panel of Figure 9. The SLOSH Onslow Bay surge at 34°N decayed steadily (1.2, 1.0, 0.76 m) over the four hour interval of Figures 9-11 while the SRA surge was nearly constant initially and then decreased rapidly (1.45, 1.42, 0.8 m).

The top panel of Figure 12 shows the SRA track in Pamlico Sound, passing through 35.4°N at 2155 UTC. The NCSU contours of constant surge are rotated clockwise relative to SLOSH, but the angle between them is about three times greater than it was in Onslow Bay.

Although both models indicate a maximum surge of about 1.7 m in Pamlico Sound, the almost north-south orientation of the SLOSH contours predict an increasing surge level as the aircraft track progresses from north to south (25 to -40 km in bottom panel) which is not supported by the SRA. NCSU indicates a decreasing surge level along that segment which agrees with the SRA trend. The SRA surge in Core Sound (-75 km, 34.87°N, 76.33°W) lies between the NCSU and SLOSH values.

8. Discussion

Even with the uncertainty as to the absolute accuracy of the Hurricane Bonnie observations, Figures 9 through 12 still demonstrate that the SRA technique provides low scatter measurements of storm surge that could be of significant benefit in evaluating model performance. It appears that the SRA measurements are more consistent with the orientation of the NCSU contours in Pamlico Sound than with SLOSH, while the reverse was the case in Onslow Bay.

Since the contours of constant surge in Onslow Bay (Figures 9, 10, 11) rotate clockwise with time in both models, with an approximately constant angle between them, a timing bias was considered. Figure 13 repeats a portion of the lower panel of Figure 11 with four additional curves added to indicate the NCSU surge along the aircraft track if time were shifted earlier by 1, 2, 3, or 4 hours.

Shifted four hours earlier, NCSU is very similar to SLOSH in Onslow Bay. It also well matches the rapid decrease seen by the SRA between 0 km and -35 km, although it has a lower depression gradient in the region less than -50 km. A four hour time shift would have occurred if the NCSU data had been accidently provided in local time, but both model outputs were in UTC.

Figure 14 suggests that much of the difference in the surge values of the models may have been caused by the different tracks they used for Hurricane Bonnie. The SLOSH track (dashes) was determined by a spline fit through the NHC 6-hour interval Best Track storm positions (X). NCSU used the eye locations (dots) at two hour intervals issued in the NHC advisories during landfall. The NCSU track diverts about 25 km to the west as it approaches Cape Fear compared to the Best Track.

Dashed radials extend from the 2100 UTC eye locations on the two tracks to Springmaid Pier and to the middle on Onslow Bay. Arrows drawn from the Springmaid Pier and Onslow Bay locations at right angles to the dashed radials provide a simple indication of differences in the local downwind direction caused by the track differences.

In the middle of Onslow Bay the downwind direction for NCSU would have been rotated 30° clockwise from SLOSH, which was greater than the 18° clockwise rotation in the surge elevation contours in evidence in the top panels of Figures 9 through 11. At Springmaid Pier the NCSU downwind direction would have been 21° closer to being perpendicular to the shoreline and presumably more effective in producing a depressed water surface. Halfway between Springmaid Pier and Cape Fear, the NCSU downwind direction would have been directly offshore while SLOSH would have been 33° from being perpendicular to the shoreline.

There was not much difference in the tracks prior to 1500 UTC, but then the NHC 2-hour advisories moved Bonnie forward too rapidly in addition to diverting it toward the west. The NHC 2-hour advisories placed Bonnie at 33.7°N at 1900 UTC while the SRA aircraft suggested that it didn't reach that latitude until 2000 UTC and the Best Track indicated 2100 UTC, a two-hour spread. The NHC 2-hour advisories placed Bonnie at 34°N at 2100 UTC while the SRA aircraft suggested that it didn't reach that latitude until about 2300 UTC and the Best Track indicated 2400 UTC, a three-hour spread.

In addition to the aircraft indicating a forward speed for Bonnie between that used by SLOSH and NCSU, two of the aircraft eye locations were between the tracks used by SLOSH and NCSU. That might also help explain why the SRA surge was sometimes between the two models. Bonnie was a very large hurricane with a radius of maximum wind of about 100 km. A precise knowledge of the track would be even more important for a smaller hurricane.

During the Bonnie landfall flight it was considered useful to fly along the shoreline with land occupying half the swath, believing absolute vertical registration could be obtained by comparing the SRA terrain to lidar surveys conducted by NASA/Goddard and the United States Geological Survey. Figure 3 contains such segments between I and J, halfway between K and L, at B, and after N.

It turned out that the size of the SRA footprint and the high density of manmade structures along the coast made it difficult to compare SRA data with the high density, small footprint lidar surveys. The torsion in the airframe was only recognized after the flight and having terrain in half the swath made it difficult to determine the true boresight attitude of the antenna. It would be more effective to rely on a high quality GPS trajectory for the aircraft and fly just offshore so the swath contained only water.

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The present exercise was performed to allow both the instrumentalists and the modelers to gain experience and to indicate the potential of future model comparisons using better quality measurements soon to be available. It was beyond the scope of this analysis to delve into the model details or try to examine differences in their physics or implementations. The models were used simply to provide a context for the new SRA measurement capability.

The NASA SRA has been decommissioned and a new NOAA SRA with improved data quality and less susceptibility to rain attenuation should be operational for the 2008 hurricane season and beyond. The actuated GPS antenna mount developed by NASA after the 1998 season has been transferred to NOAA for use with their SRA so the quality of the GPS data should be better than for Hurricane Bonnie.

More tide gages are in operation now and a new MSS should soon be available that will have improved resolution and accuracy over the one employed in the present analysis. With survey-quality GPS trajectories for the aircraft and greater attention focused on absolute range measurement, the new NOAA SRA could produce targeted measurements of storm surge that would provide an absolute standard with the tide gages only used to confirm accuracy at their locations.

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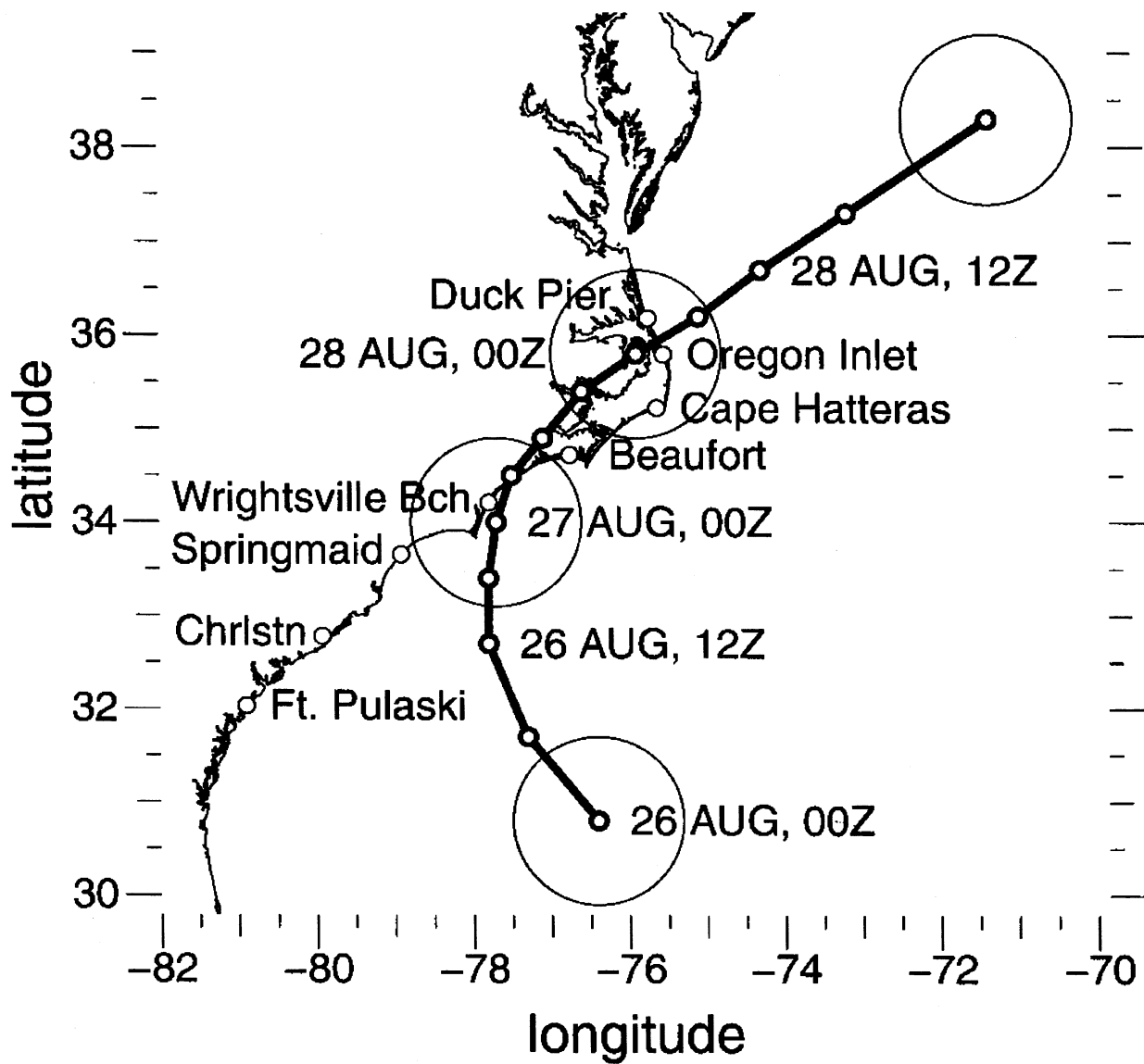
Figure 1. NHC Best Track eye locations for Hurricane Bonnie (thick circles) in 1998 (http://www.nhc.noaa.gov/1998bonnie.html). Thin circles indicate tide gage locations at Duck Pier (36.18°N, 75.75°W), Oregon Inlet (35.79°N, 75.55°W), Cape Hatteras (35.22°N, 75.63°W), and Beaufort (34.72°N, 76.76°W) in North Carolina, Springmaid Pier (33.65°N, 78.92°W) and Charleston (32.78°N, 79.92°W) in South Carolina, and Fort Pulaski (32.03°N, 80.90°W) in Georgia. The tide gage at Wrightsville Beach (34.21°N, 77.79°W) was not placed in operation until 2004.
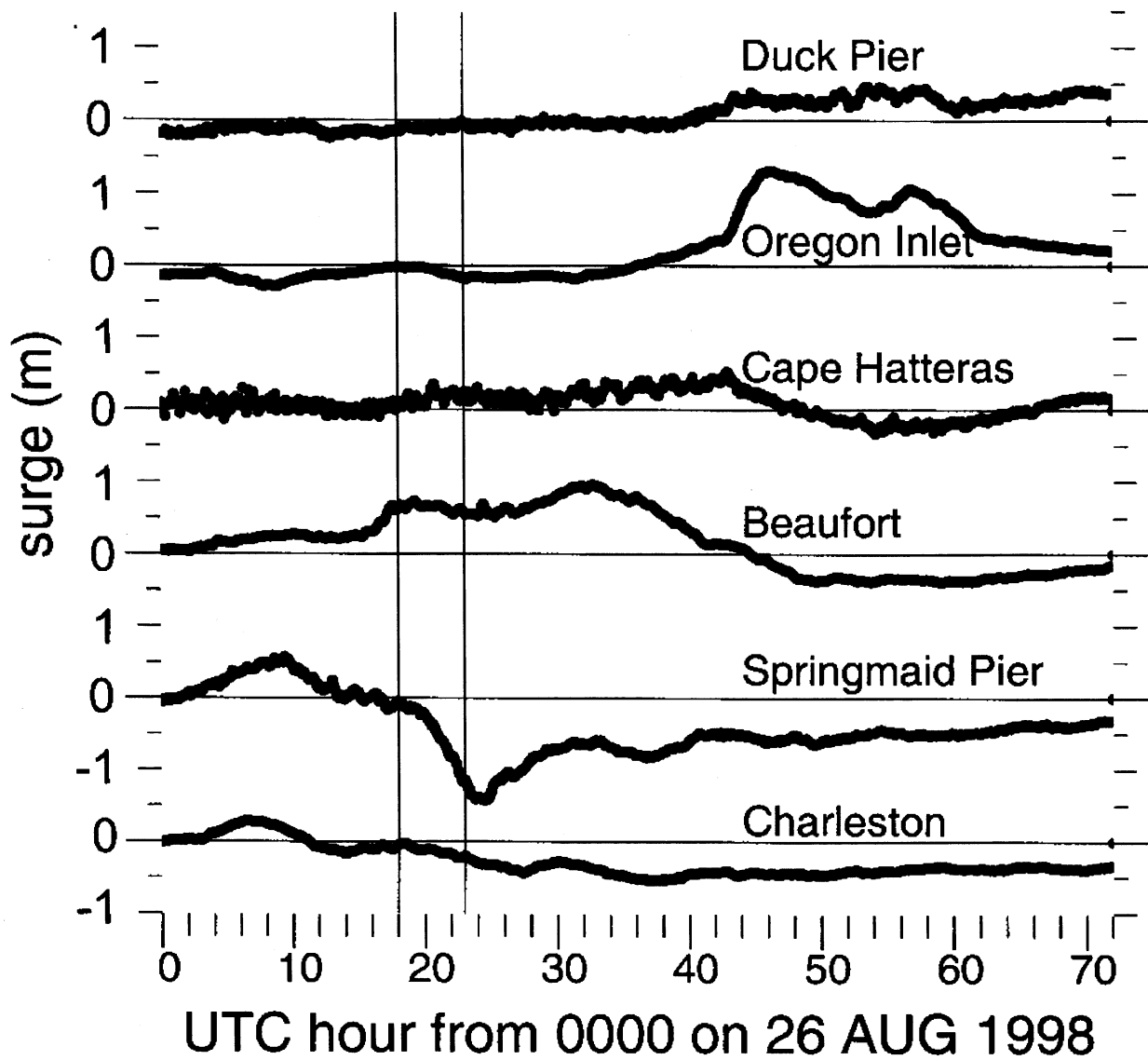
Figure 2. Tide gage surge records with the interval of the SRA observations (1800 to 2300 UTC) indicated by the vertical lines.
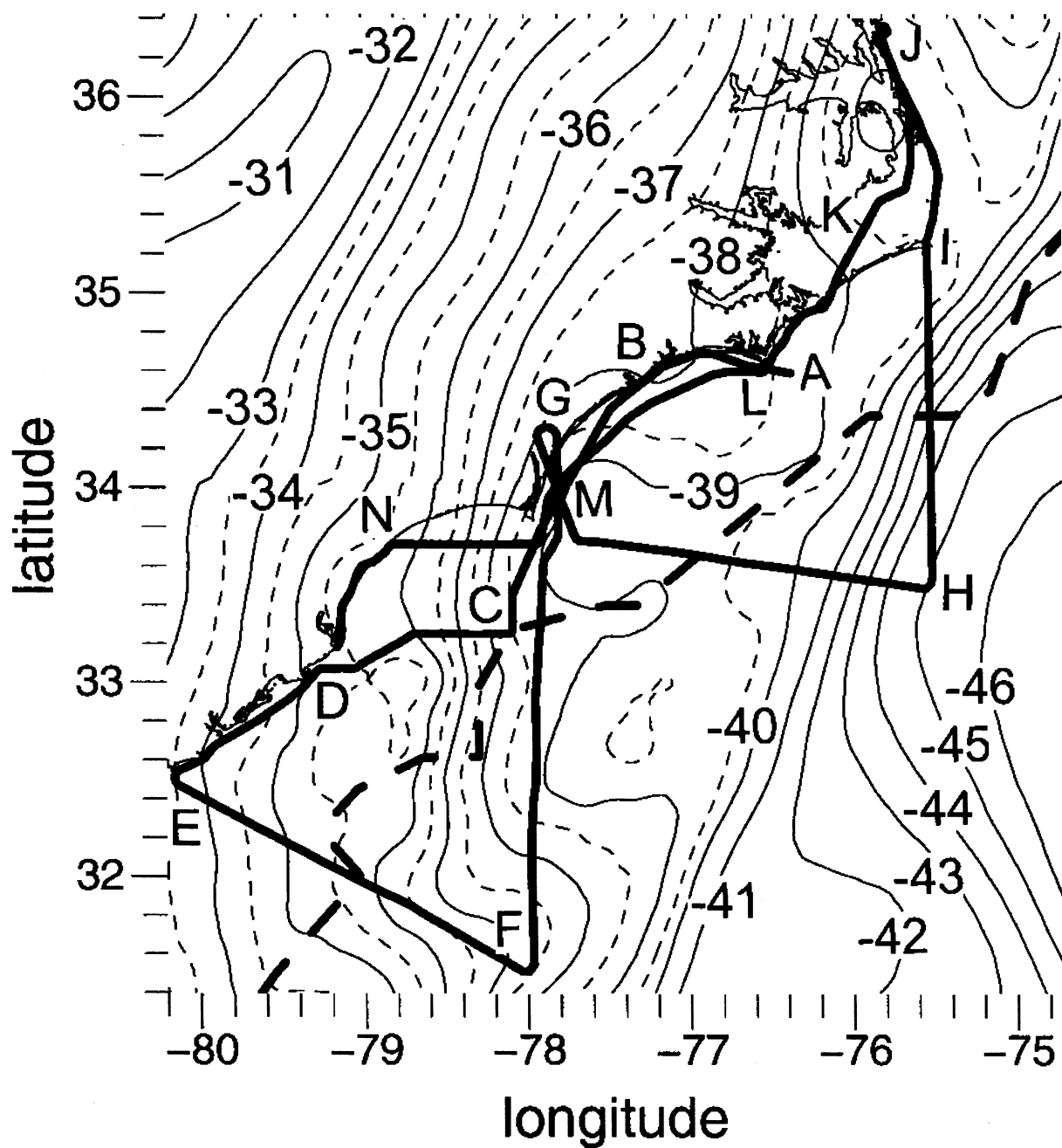
Figure 3. NOAA aircraft track (thick line) on 26 August 1998, with the letters identifying a chronological sequence of positions. Thick dashed line is a piecewise linear approximation of the western edge of the Gulf Stream. The thin solid and dashed lines indicate the elevation (m) of the mean sea surface relative to a reference ellipsoid.
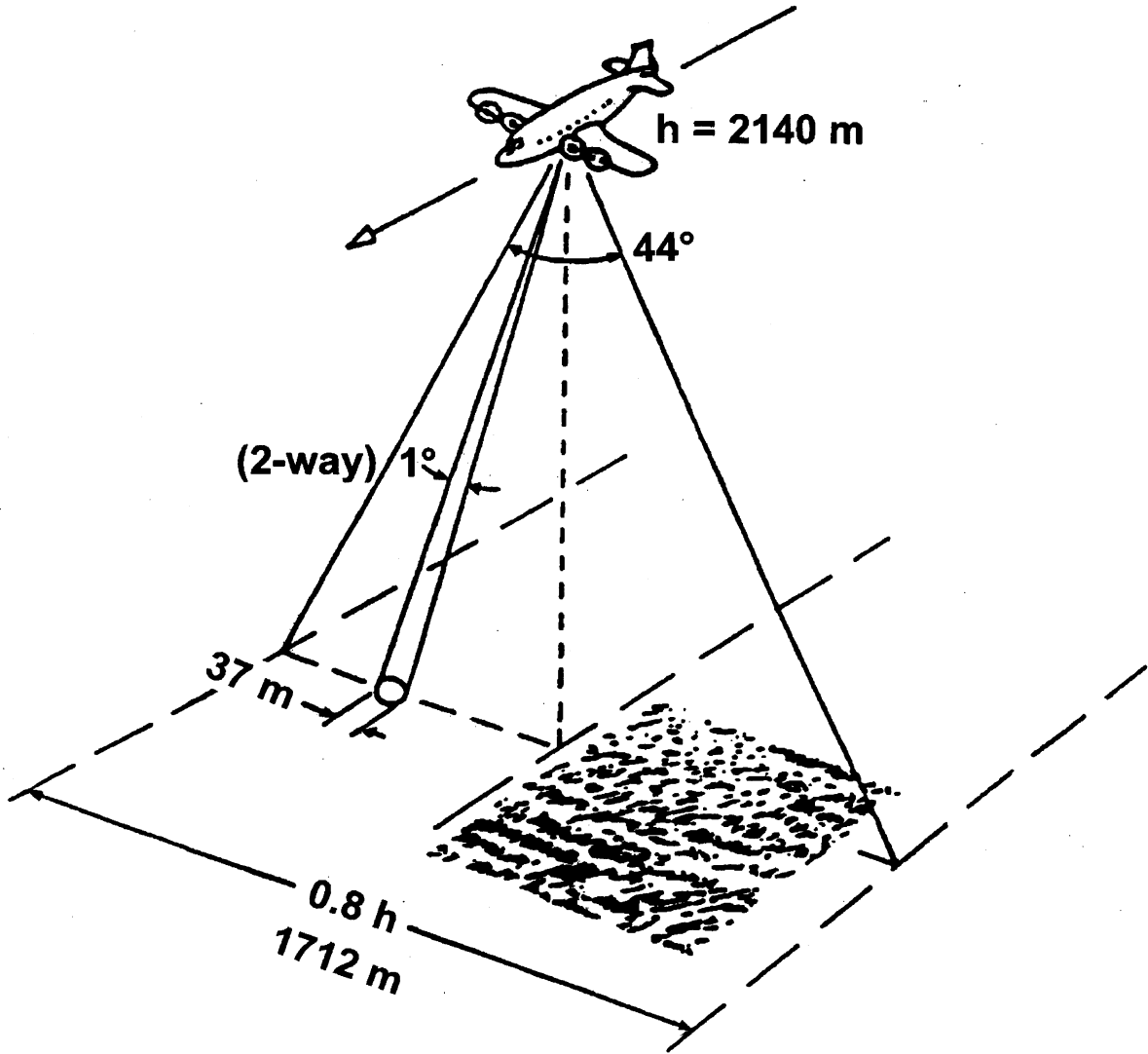
Figure 4. SRA measurement geometry.
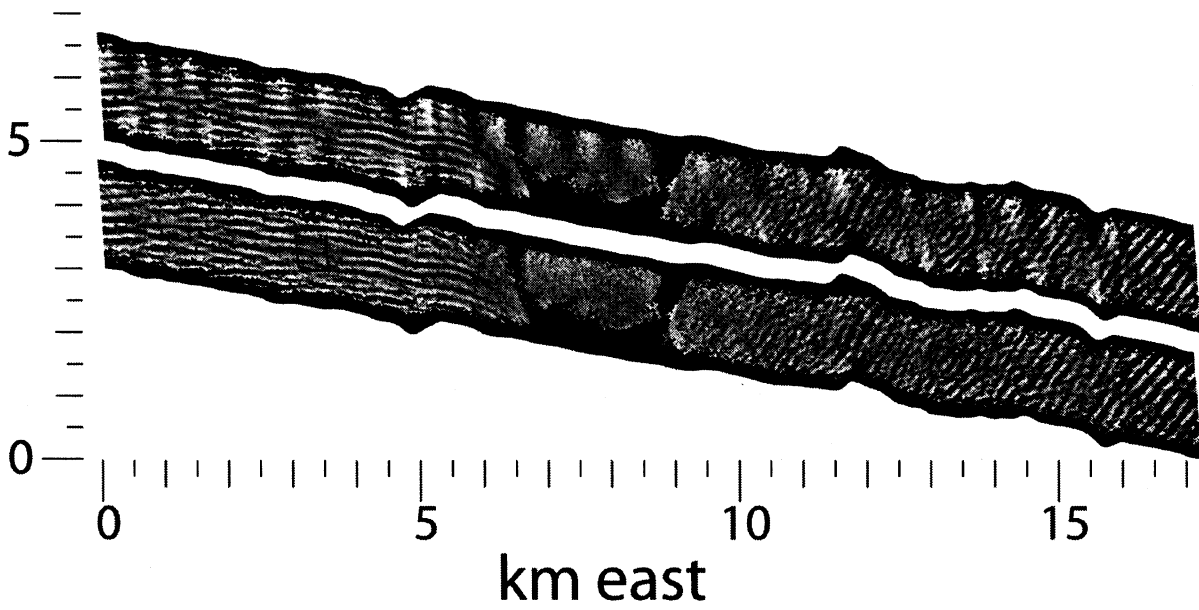
Figure 5. Grayscale-coded topographic maps produced from 687 SRA raster scan lines as the aircraft crossed Cape Lookout, processed using the inertial navigation system (INS) roll attitude (top) and auto-leveling each raster scan line (bottom). The land mass occupies the black data dropout region between about 6.5 and 9 km along the abscissa.
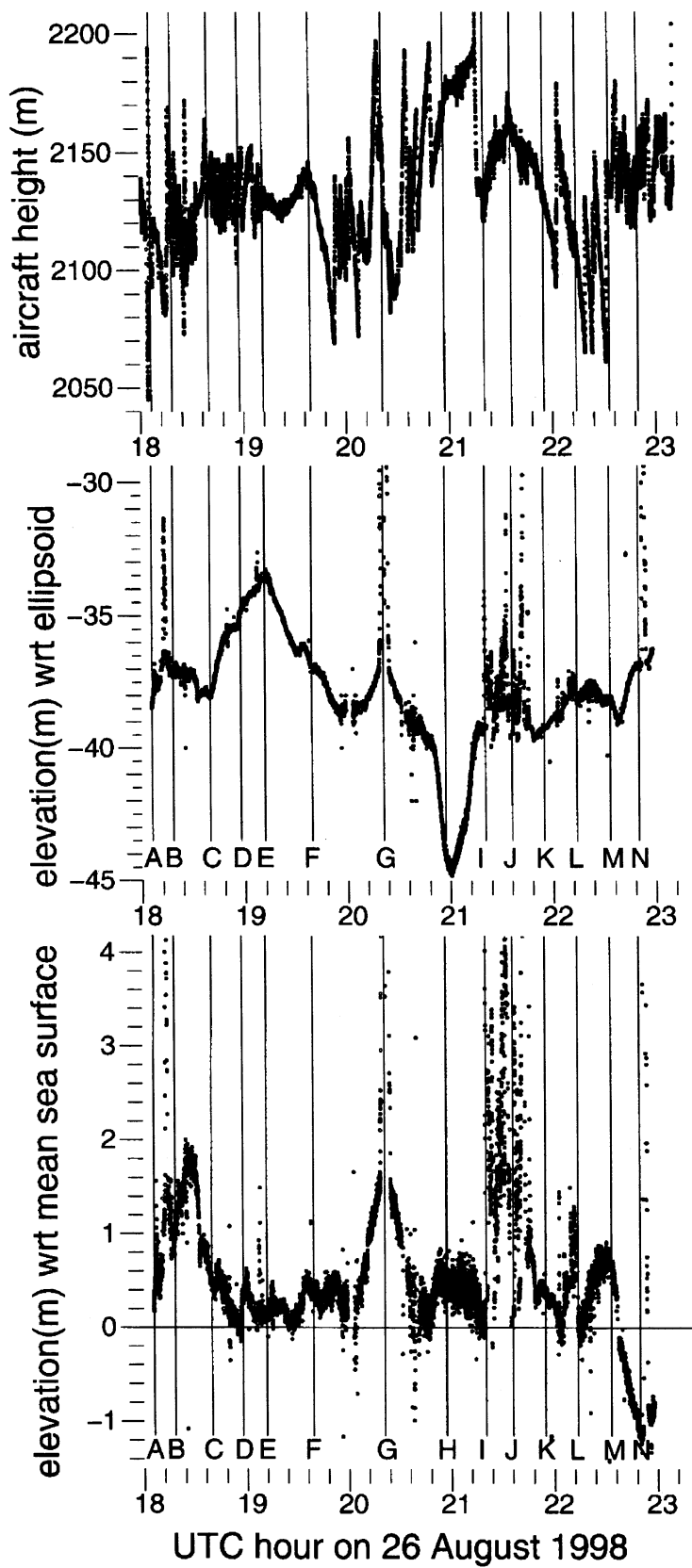
Figure 6. Aircraft altitude variation (top) along Figure 3 track, and SRA determination of sea surface elevation with respect to the ellipsoid (middle) and the mean sea surface (bottom).
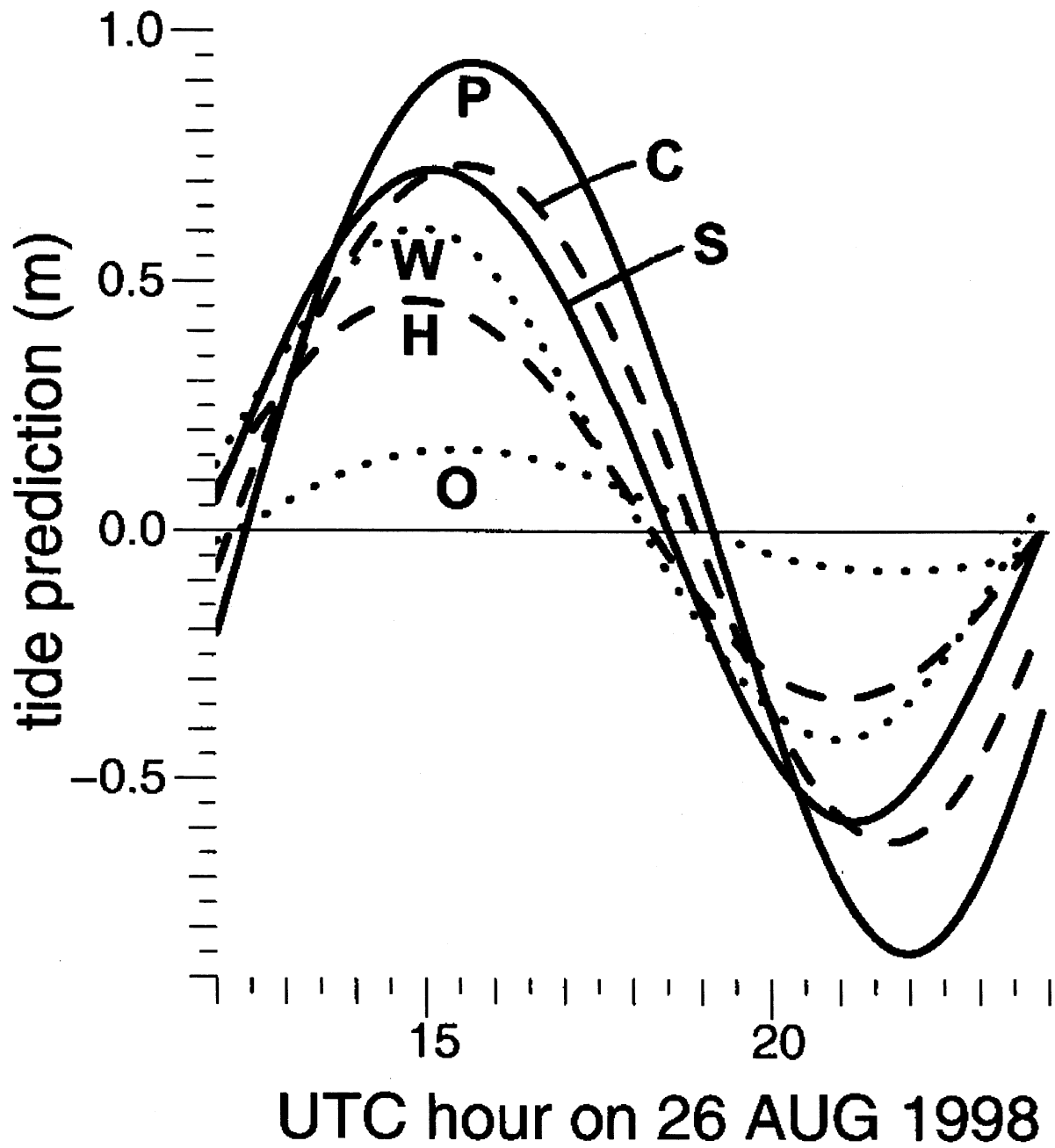
Figure 7. Tide predictions for Fort Pulaski (P), Charleston (C), Springmaid Pier (S), Wrightsville Beach (W), Cape Hatteras (H), and Oregon Inlet (O).
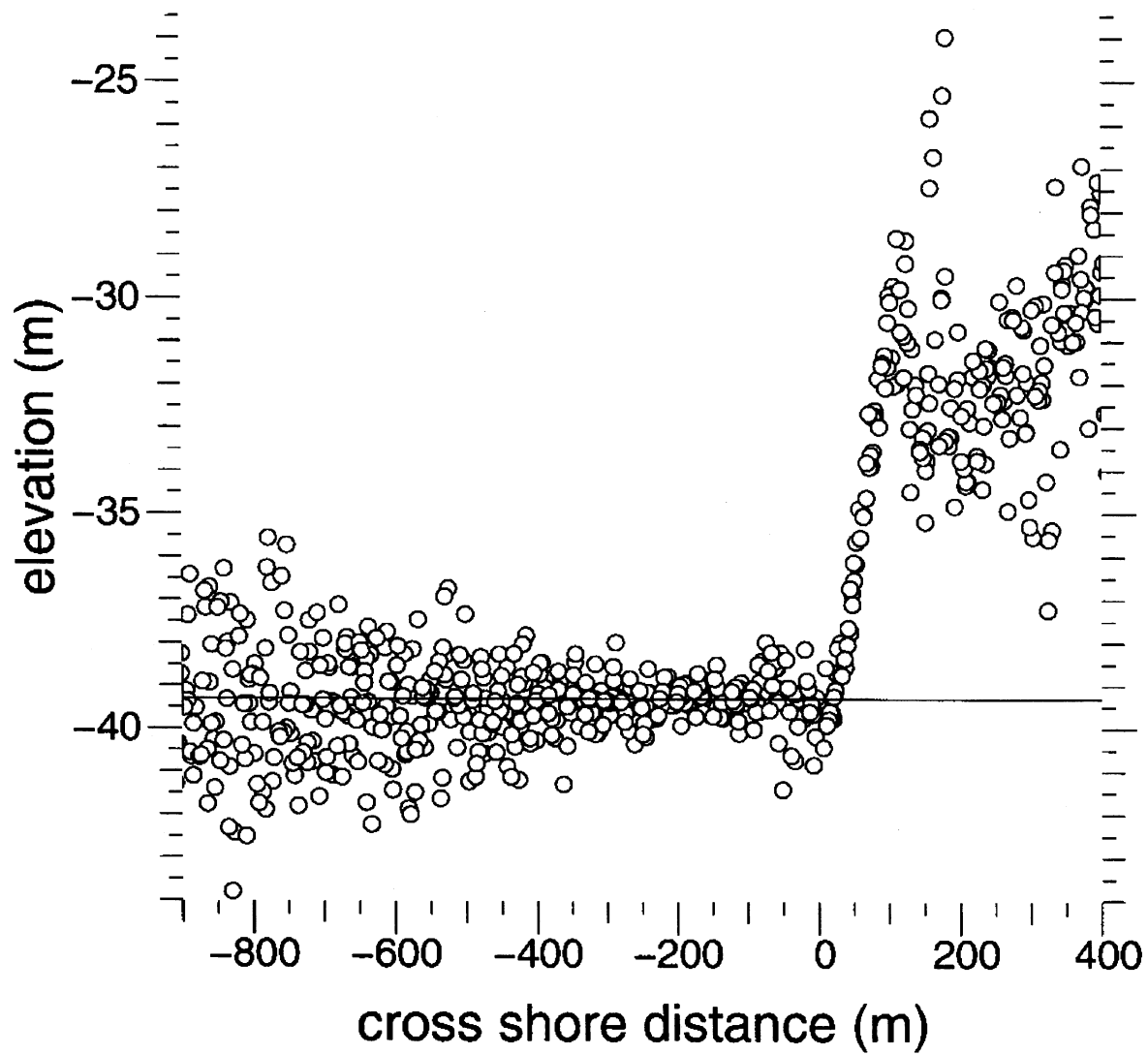
Figure 8. Individual surface elevations computed using INS roll attitude for fourteen consecutive cross track scan lines straddling the shoreline near the Duck Pier tide gage. Negative cross-shore distances are in the Atlantic Ocean.
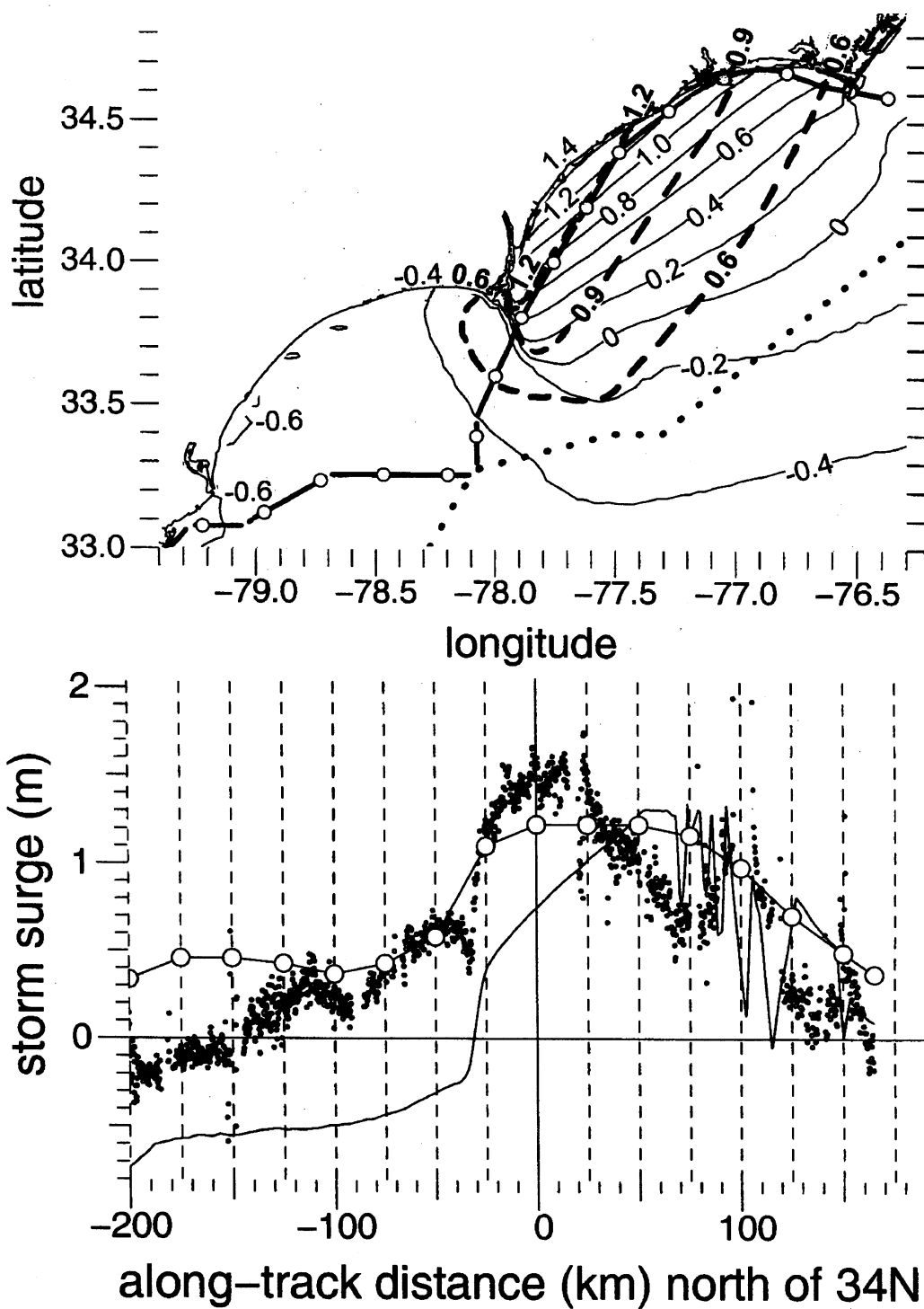
Figure 9. Circles (top panel) identify positions along the aircraft track spaced at 25 km intervals (except for the first point) along the flight line relative to passing 34°N. The thin lines indicate the NCSU storm surge contours at 1828 UTC when the aircraft passed through 34°N. The thick dashed lines indicate the SLOSH storm surge contours at 1820 UTC. Dots indicate a piecewise linear approximation of the western edge of the Gulf Stream. In the bottom panel, dots indicate SRA storm surge values along the flight track. The curve without the circles indicates the NCSU surge values along the flight track. SLOSH surge values are indicated by the circles connected by line segments.
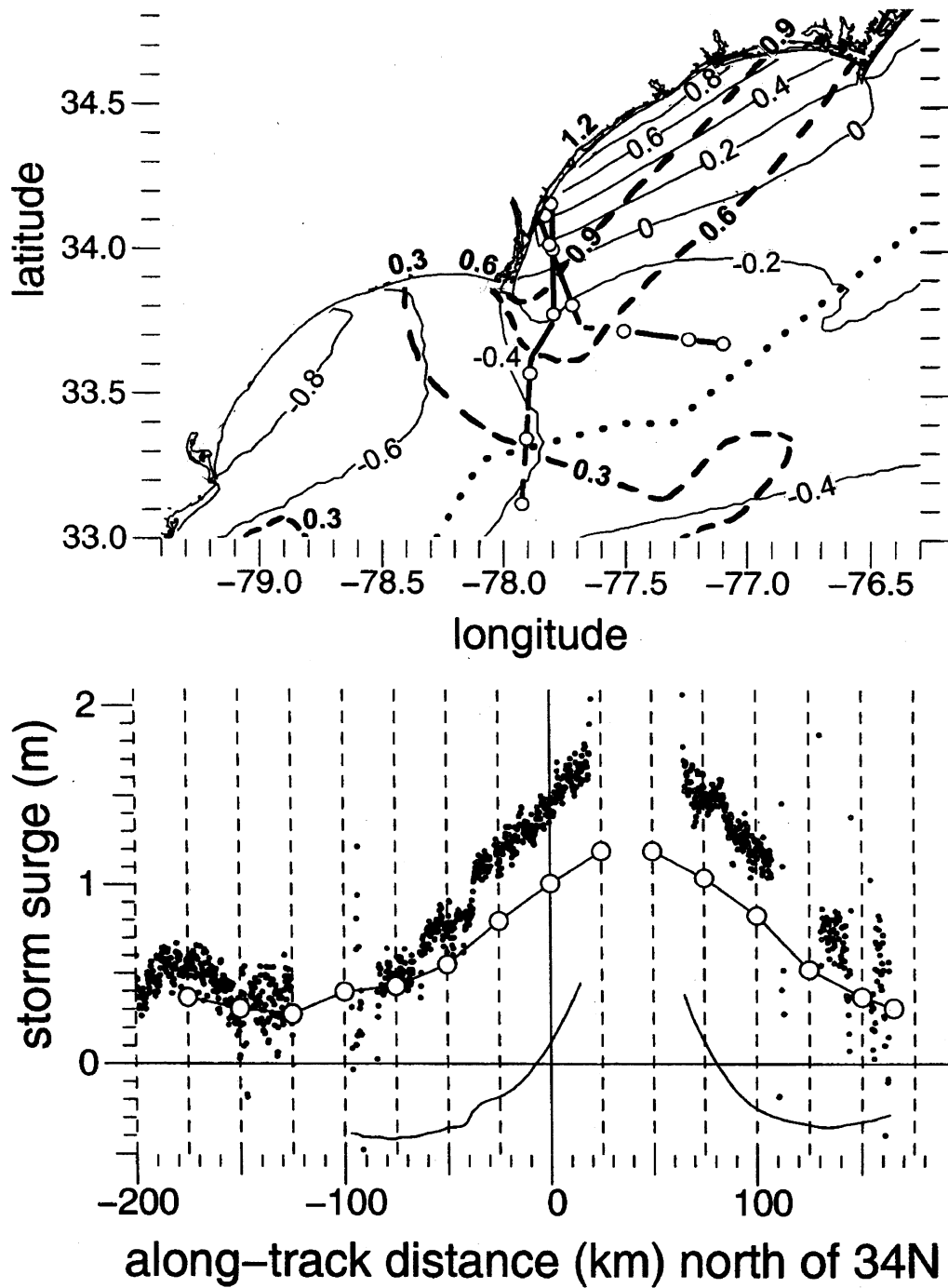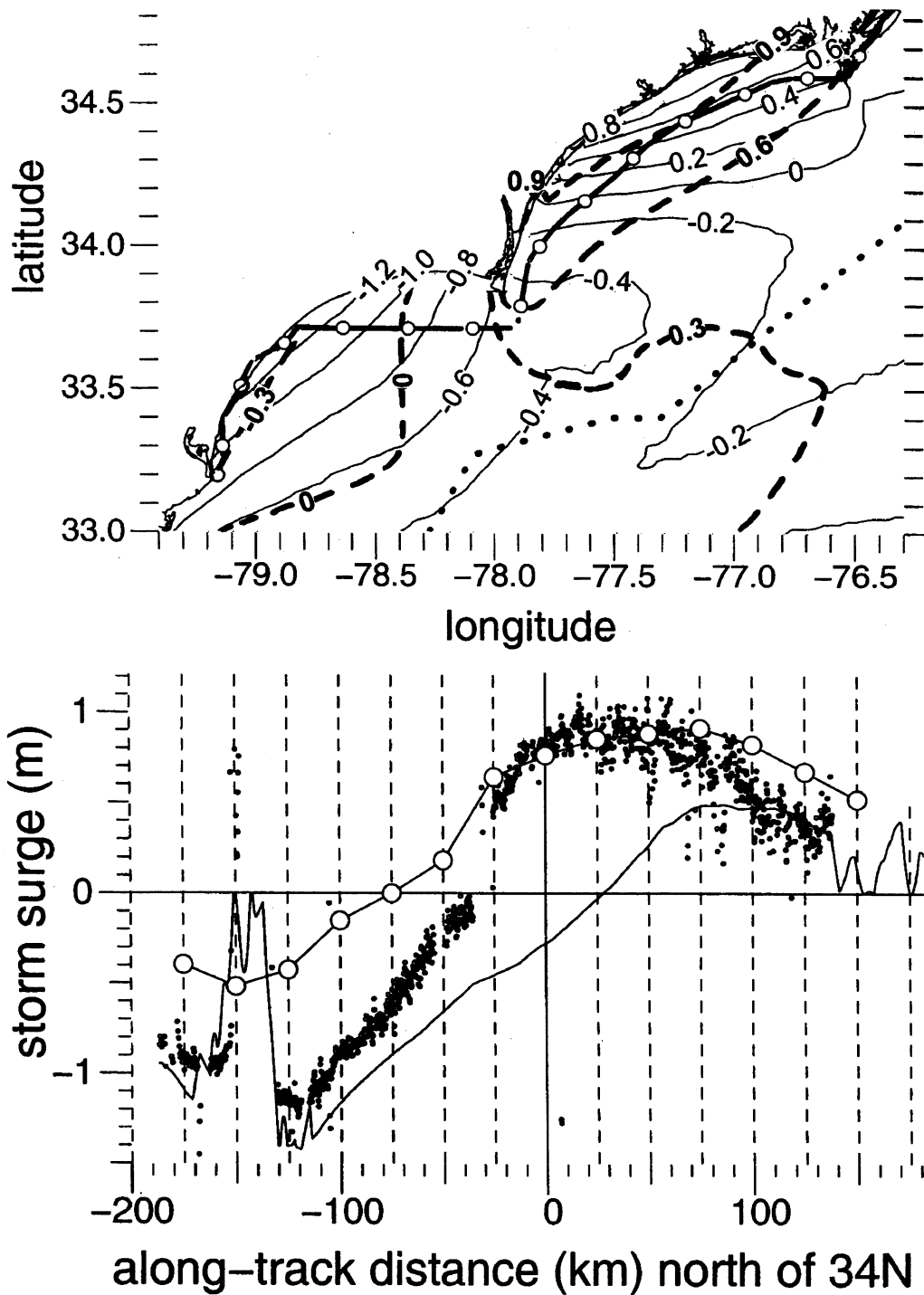
Figure 10. Top panel circles are spaced at 25 km intervals along the aircraft track (except for the last one) relative to the aircraft first reaching 34°N flying north at 2016 UTC. The thin lines indicate the NCSU storm surge contours at 2016 UTC. The thick dashed lines indicate the SLOSH storm surge contours at 2020 UTC. Dots indicate a piecewise linear approximation of the western edge of the Gulf Stream. In the bottom panel, dots indicate SRA storm surge values along the flight track. The curve without the circles indicates NCSU surge values along the flight track. SLOSH surge values are indicated by the circles connected by line segments.

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Figure 11. Top panel circles are spaced at 25 km intervals along the aircraft track (except for the last one) relative to the aircraft reaching 34°N flying south at 2232 UTC. The thin lines indicate the NCSU storm surge contours at 2232 UTC and the thick dashed lines indicate the SLOSH storm surge contours at 2240 UTC. Dots indicate a piecewise linear approximation of the western edge of the Gulf Stream. In the bottom panel, dots indicate SRA storm surge values along the flight track. The curve without the circles indicates NCSU surge values along the flight track. SLOSH surge values are indicated by the circles connected by line segments.
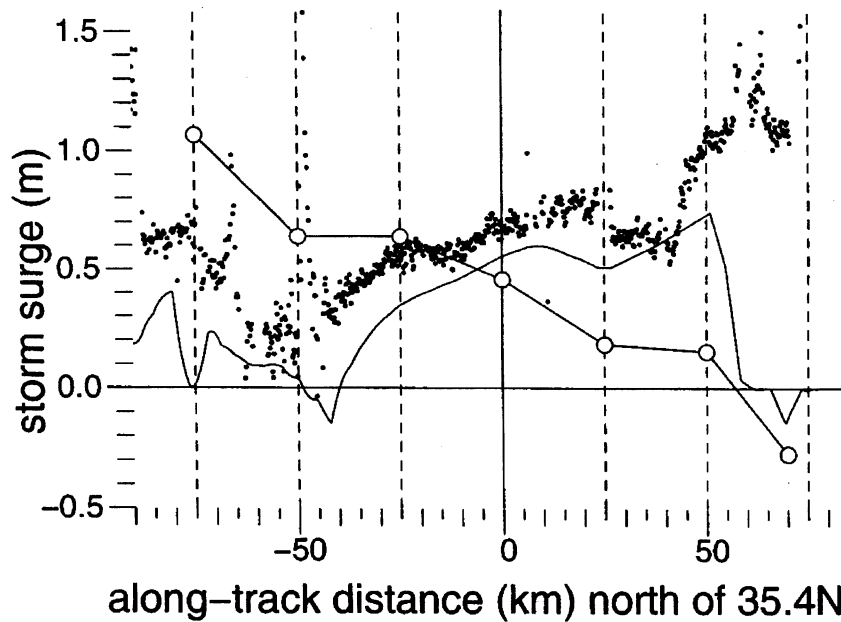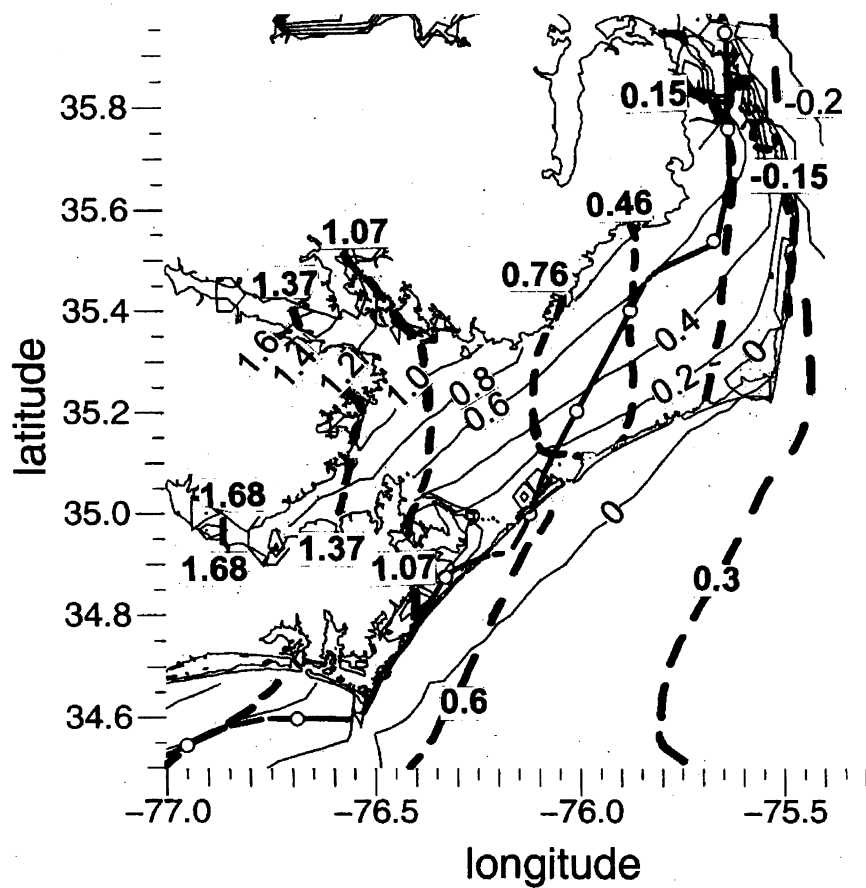
Figure 12. Top panel circles are spaced at 25 km intervals along the aircraft track relative to the aircraft reaching 35.4°N at 2155 UTC flying south in Pamlico Sound. Thin lines indicate the NCSU storm surge contours interpolated to that time and thick dashed lines indicate the SLOSH storm surge contours at 2200 UTC. In the bottom panel, dots indicate SRA storm surge values along the flight track. The curve without the circles indicates NCSU surge values along the flight track. SLOSH surge values are indicated by the circles connected by line segments.
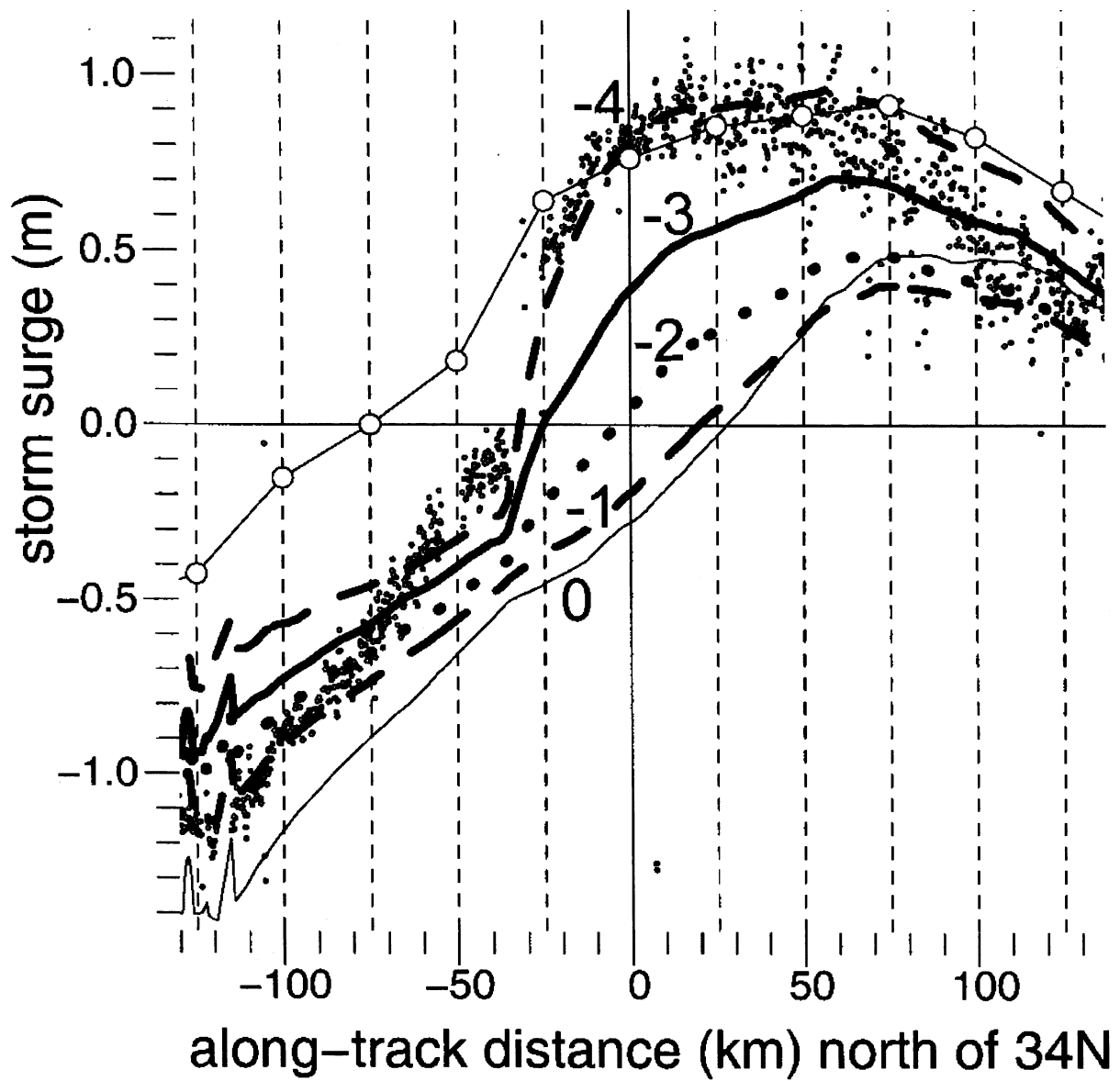
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Figure 13. Lower panel of Figure 11 with four additional curves added to indicate the NCSU surge along the aircraft track if time were shifted earlier by 1, 2, 3, or 4 hours.
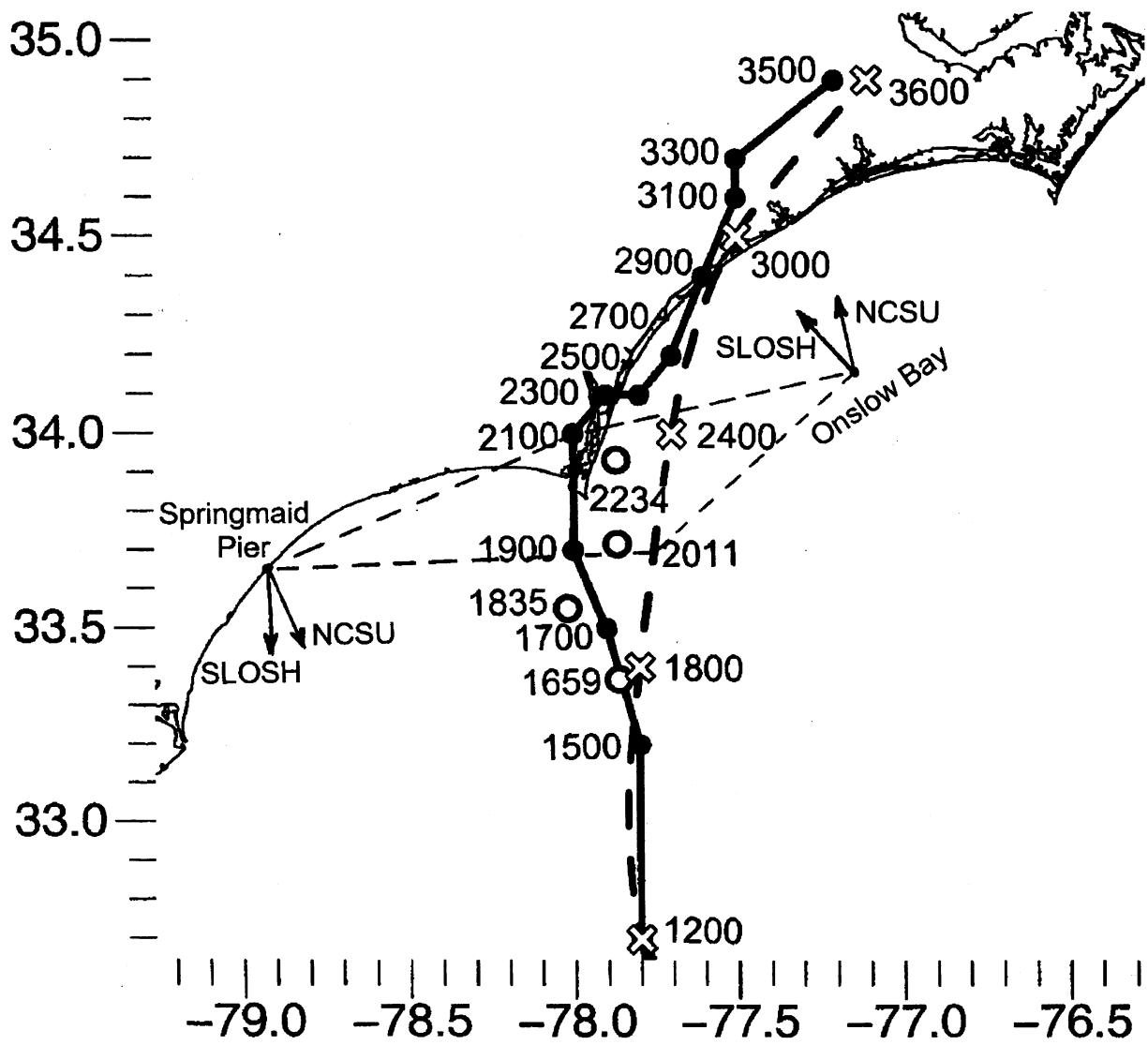
Figure 14. NHC Best Track storm positions (X) and the eye locations (dots) from NHC advisories issued during landfall with time incrementing from 0000 UTC on 26 August 1998. The four circles indicate eye locations recorded in the N43RF Flight Director's log (Barry Damiano, NOAA/AOC, personal communication, 2007) from eye penetrations at 1659, 1835, 2011 and 2234. Arrows indicate approximate downwind directions in Onslow Bay and at Springmaid Pier for the eye locations used by SLOSH and NCSU at 2100 UTC.