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Chronology of Warm-Core Ring 82B

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A chronology constructed from satellite-derived thermal imagery is presented to describe the formation and life history of warm-core ring 82B. This overview provides insight into a classification of features and discrete events associated with Gulf Stream warm-core rings and allows these events, as well as our limited shipboard observations, to be placed in a broader spatial and temporal context than would otherwise be possible without the satellite data. Events influencing the evolution of 82B include environmental factors, such as meteorological influences and Gulf Stream interactions, as well as those stimulated by encounters with changes in bottom topography. The interactions of the ring with surrounding waters are especially noteworthy, and the existence of vortex-vortex interactions is shown to be a significant cause of local water advection through streamer activity. Ring events are documented by following changes in ring size, shape, translation, and surface thermal structure. Our satellite observations are supported by extensive contemporaneous shipboard observations, including XBT, CTD, BOPS (biooptical profiling system) temperature profiles, and along-track sea surface temperature measurements. In addition, acoustic velocity profiling and drifter trajectories have been used to corroborate hydrographic features of the ring and environs. These ship and satellite data form a coherent space/time overview of the ring and its environment and show them to be closely related and continually interacting.

1. INTRODUCTION

The Warm Core Rings Experiment (WCRE) has completed the first detailed time series study of the physics, chemistry, and biology of an evolving warm-core ring (82B) over its 6-month lifetime and has compared its structure to those of other rings [*Warm Core Ring Executive Committee*, 1982]. Warm-core rings are formed in the slope water region between the North American continental shelf and the Gulf Stream when meanders of the Gulf Stream grow and occasionally separate from it [*Saunders*, 1971; *Thompson and Gotthardt*, 1971; *Gotthardt and Potocsky*, 1974]. The initial core of these warm-core rings (WCR) contains Sargasso Sea water surrounded by a clockwise-rotating remnant of the Gulf Stream: the high-velocity region. The outer boundary of the high-velocity region of the WCR is a sharp frontal boundary corresponding to the cold wall of the Gulf Stream. These rings are hydrographically distinguishable regimes, 60–200 km in diameter and a few thousand meters deep, that maintain their identity for periods of months to less than a year [cf. *Richardson*, 1983]. *Bisagni* [1976], *Lai and Richardson* [1977], *Fitzgerald and Chamberlin* [1983], and *Joyce* [1984] have presented times series summaries and general statistical descriptions of Gulf Stream WCR's. They find that several WCR's exist at any one time and that they are generally formed east of the New England seamounts, that they move roughly west southwest at speeds between 2 and 8 cm s^{-2} during their lifetime, and that all are absorbed by the Gulf Stream. WCR's evolve, in part, through interactions with the atmosphere, bottom topography, the surrounding slope water, and the Gulf Stream.

Gulf Stream WCR's have analogs in other western boundary current regimes and play a significant role in the physics, chemistry, and biology of these regions of the world's oceans. Recognizing the importance of eddies in oceanographic processes, several classification schemes have been proposed, such as open-ocean eddies, jet meanders, large ring vortices, etc. [*Oceanus*, 1976; *Koshlyakov and Monin*, 1978]. These simplified classifications tend to emphasize the isolated characteristics of individual rings. In this synoptic time series of satellite sea surface temperature imagery these eddies are shown to be dynamic features with their own identity; yet frequent complex interactions with their surroundings can have a major influence on ring evolution. Following recent practice [cf. *Fuglister*, 1977; *Joyce*, 1984], we use the term "ring" to refer to any large eddy formed from a meander of a major current system.

Oceanic processes governing the evolution of WCR's cover space/time scales that require multiplatform sampling strategies [*Steele*, 1978; *Esaias*, 1981]. In an early paper on ring studies, *Iselin and Fuglister* [1948] conclude that the averaging of ship observations blurs details that are essential to the understanding of these features. *Saunders* [1971] began the use of more detailed observations of warm-core rings by incorporating airborne infrared radiometry to observe medium-scale processes in the upper ocean. Systematic compilation of satellite observations of warm-core rings began with *Bisagni*'s [1976] report on eddies in the neighborhood of deepwater dump site 106 during 1974 and 1975. This work has continued with a number of reports by Chamberlin and coworkers [cf. *Fitzgerald and Chamberlin*, 1983] at the NOAA/NMFS Atlantic Environmental Group. More recently, *Spence and Legeckis* [1980] and *Brown et al.* [1983] have published high-resolution summaries concerned with examination of specific processes.

This paper presents the results of a satellite image time series study which yields a comprehensive synoptic overview of the formation, evolution, and demise of a WCR. A detailed classification of interactive events and a chronology of ring 82B is presented. Satellite thermal imagery plus observations from contemporaneous shipboard data are used to discuss the evolution of a warm-core ring, with particular emphasis on the dynamic, highly variable, and continuous interaction of the ring with its surroundings. We define various significant features and describe the corresponding "events" influencing ring evolution. A detailed chronology of these events is provided for WCR 82B. Such a record is essential in order to separate the various spatial and temporal processes acting on the ring and provides a descriptive context in which to discuss more detailed shipboard observations. We have examined, and summarized here, near-daily synoptic views of mesoscale

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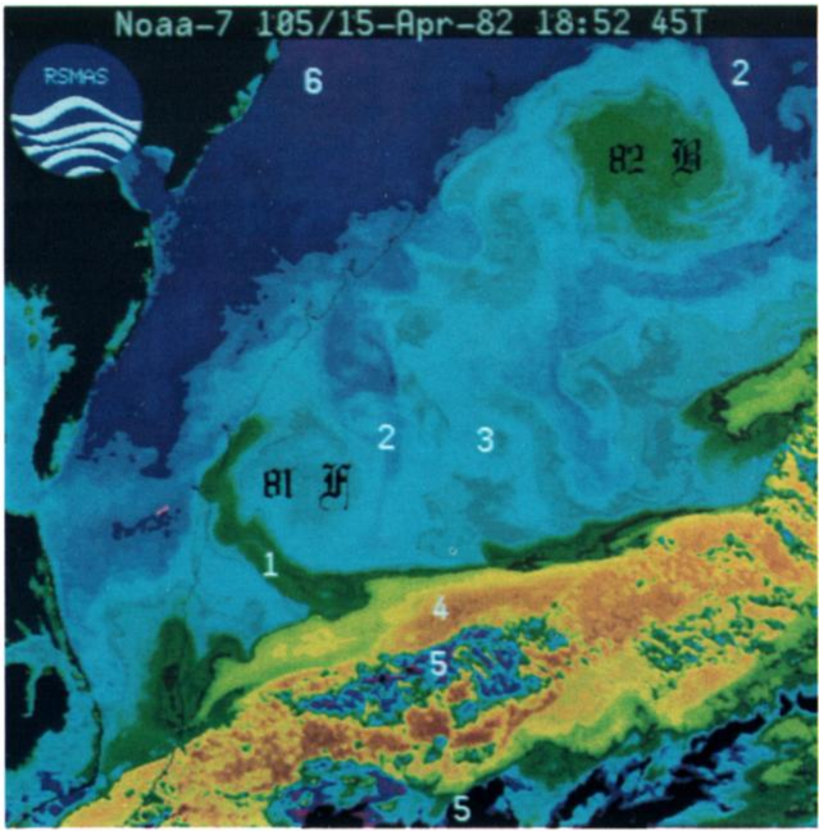

Plate 1. Sea surface temperature image on April 15 (J.D. 105) showing WCR's 82B and 81F and surrounding waters. Sea surface temperature is represented in 1°C steps (from 0°C to 29°C) with darker (blue) representing colder temperatures and lighter (yellow/orange) representing warmer temperatures. The 200-m isobath (dark line) roughly demarks the shelf (feature 6, dark blue) waters from the slope (feature 3, light blue) waters. Warm-core rings 82B and 81F as well as several features are labeled: 1, a warm Gulf Stream streamer wraping around the western edge of 81F; 2, cold shelf water streamers wrapping around the eastern edges of 81F and 82B; 3, a small cyclonic vortex in the slope region; 4, the Gulf Stream; 5, clouds (black) or the interference of relatively hazy atmosphere (blue/purple); 6, cold shelf water.

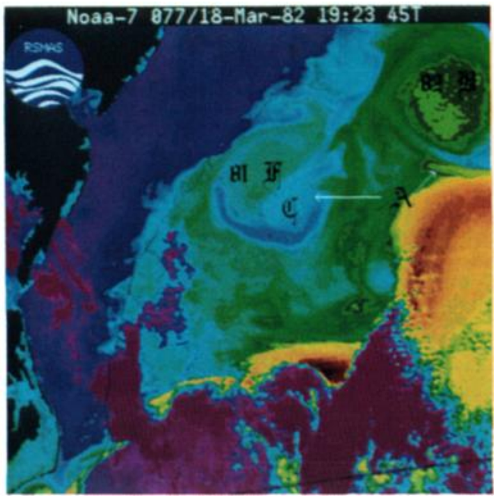

Plate 2*a*

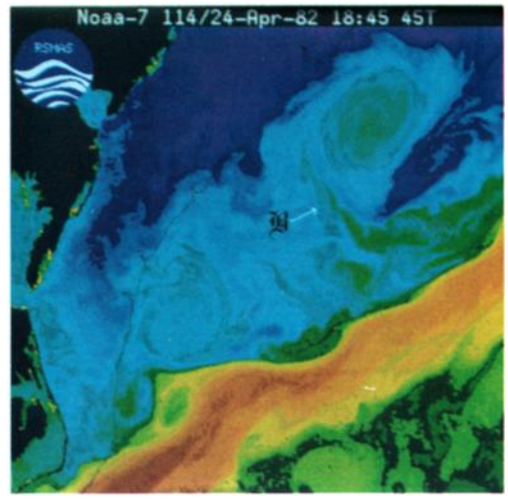

Plate 2*b*

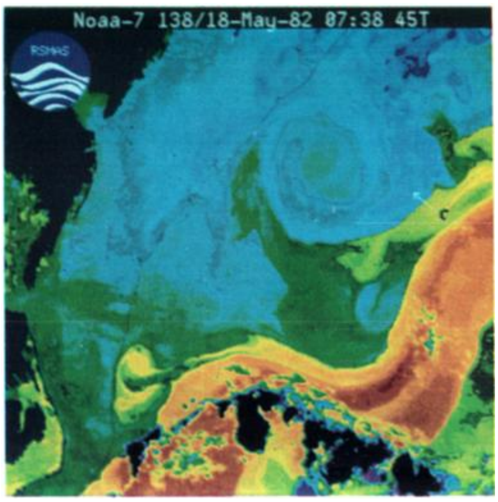

Plate 2*c*

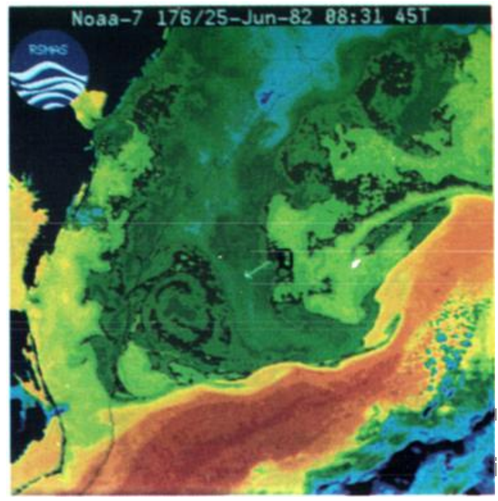

Plate 2*d*

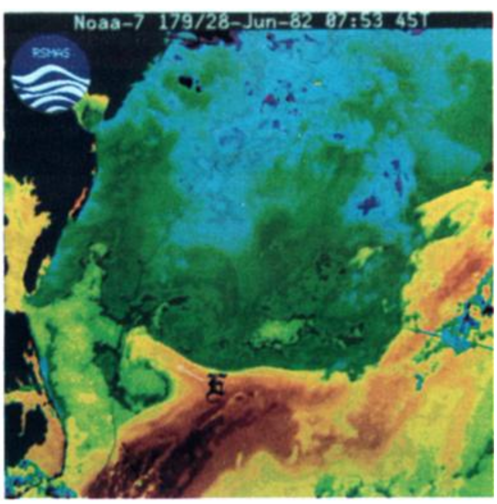

Plate 2*e*

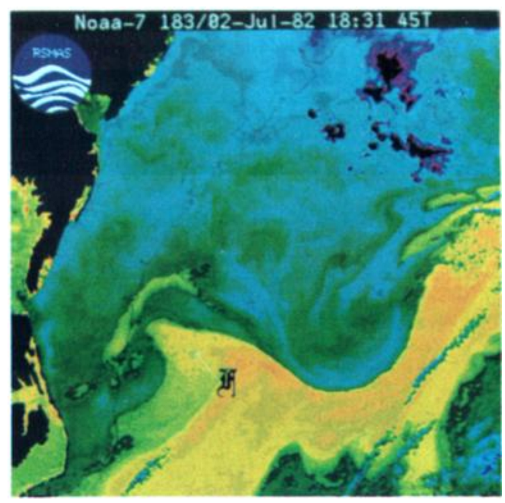

Plate 2*f*

Plate 2. Selected sea surface temperature images (1°C color steps, as in Plate 1) with blue representing colder temperatures and yellow representing warmer temperatures. Continental land mass is masked black and clouds are masked red/purple. These six images were chosen to illustrate several features and event mechanisms associated with WCR's: (*a*) March 18, 1982 (J.D. 77)—ring-ring interactive features as ring 82B survives Gulf Stream creation, ring 82B "pulls" a warm Gulf Stream streamer and 81F a cold shelf water streamer into the slope (A), and ring 81F entrains a cyclonic vortex (C); (*b*) April 24, 1982 (J.D. 114)—streamer pulled from Gulf Stream while ring exists over Hudson Canyon, cyclonic vortex in streamer field southeast of ring; (*c*) May 18, 1982 (J.D. 138)—entrainment of colder shelf water by ring 82B, first example of streamer water penetrating to ring interior, cyclone east of ring in streamer field; (*d*) June 25, 1982 (J.D. 176)—ring-vortex pairing resulting in advection of colder shelf water across slope to Gulf Stream; (*e*) June 28, 1982 (J.D. 179)—ring-vortex pairing resulting in advection of warmer Gulf Stream water, cyclone to southwest of ring; (*f*) July 2, 1982 (J.D. 183)—ring–Gulf Stream interaction during which a meander overwashes the ring, surface thermal expression is not governed by ring circulation.

thermal variability on scales of 1–1000 km provided from ship data and satellite imagery that includes 145 advanced very high resolution radiometer (AVHRR) thermal images acquired for the purpose of studying warm-core ring 82B during 1982.

2. Methods and Definitions

2a. *AVHRR Images*

Remote sensing measurements used in this study are derived from the NOAA satellite series AVHRR instrument. The NOAA satellite platforms are in sun-synchronous polar orbits at altitudes of 833 and 870 km, with ascending passes at either 0730 or 1400 local sun time. The AVHRR scans at a rate of 360 swaths per minute with an effective ground resolution of 1.1 km (at nadir) in five coregistered spectral bands [*Schwalb*, 1978]; two visible bands (550–680 nm, 725–1100 nm) and three infrared bands (3.55–3.93 μm, 10.3–11.3 μm, 11.5–12.4 μm). The satellite-sensed radiances are processed by a standard procedure to produce a navigated, atmospherically corrected, and mapped sea-surface temperature image. Navigation procedures earth locate each satellite picture element to within 1 km [*Brown and Evans*, 1982]. Radiance data are corrected for varying water vapor concentrations in the atmosphere by using a two-channel (10.3–11.3 μm and 11.5–12.5 μm) algorithm [*McClain et al.*, 1982]. The atmospherically corrected image is then mapped onto a standard projection. Sea surface temperatures processed in this manner have a nominal 0.7°C rms scatter when compared with research ship, continuous flow, surface temperature observations [*Brown et al.*, 1985]. In this work, over 5000 contemporaneous ship and satellite observations were obtained during the course of the WCR program; corrected satellite sea surface temperatures exhibit a nominal scatter of 0.7°C rms. The final imagery is scaled from 0°C to 29°C in 0.125°C steps and covers an area from 35°N to 40°N and 70°W to 76°W in 1-km increments.

2b. *Image Interpretation and Definition of Events*

A number of interactions influencing the evolution of WCR's can be seen in thermal imagery. The wealth of detail, space/time variability, and the several types of features and "events" associated with WCR's observed in Plates 1 and 2 necessitate a systematic scheme of definitions and interpretation. For the work reported herein, each image has been analyzed for spatial structure and temporal evolution evidenced by the surface thermal field. The difference in surface temperatures of the shelf, slope, and Gulf Stream in spring and early summer provides a discrimination of shelf-slope and slope–Gulf Stream fronts. Thermal contrast between the slope and its surrounding waters during this time period also permits a clear discrimination of advective events, such as streamers, when these features are present at the surface. Vortices are differentiated from the slope water either by feature temperature or by the presence of surrounding streamers which may be warm, cold, or a combination of both. Each feature can be defined by using various measures, such as size, location, orientation, and temperature.

While the detection of a surface feature such as a WCR is relatively straightforward when sufficient temperature contrast is present, quantitative determination of specific aspects of a feature, such as the ring center position, is complicated by the complex and constantly evolving structure of the surface signature. Quantitative estimates of ring center position as a function of time determined from satellite imagery utilize the thermal contrast associated with the boundary of the high-velocity region [*Brown et al.*, 1983]. Ring center location is shown in Figure 1 relative to the bottom topography; letters are placed adjacent to the location of major events, which will be discussed below. The ring center, and a measure of its perimeter ellipse (not shown), are used as reference for location of the ring with respect to various features and corresponding events that affected the evolution of WCR 82B.

Examples of major types of features that are discussed in this work are identified in Plate 1 by white numbers. While not in temporal sequence with the images presented in Plate 2, Plate 1 exhibits nearly all the features discussed in this work and thus provides an excellent framework to present the feature definitions and their associated surface signatures. A detailed discussion of the time history of these events/features is presented in section 3.

Entrainment is defined as the incorporation of fluid into the ring by advection, and it can cause rapid changes in the ring center temperature. We define streamers (1 and 2 in Plate 1) as strong advective features delineated by sharp frontal boundaries where the along-feature dimension greatly exceeds the across-feature dimension. In Plate 1, warm Gulf Stream streamer 1 can be seen wrapping around ring 81F from the southwest. This same image shows cold slope water streamers 2 wrapping clockwise around 82B and 81F from the northeast. One form of entrainment is the special case of a streamer that penetrates into the interior of the ring (cf. Plate 2*c*).

A Gulf Stream meander can be regarded as an instability in the stream and is evidenced by an undulation in the "north wall" temperature contrast in the Gulf Stream imagery (e.g., Plate 2). Not only do these meanders loop and become detached to form new rings, they also can interact significantly with existing rings. When an encounter between ring and meander is more intense, the upper layer of the ring can be replaced by Gulf Stream water, and there is usually an accompanying loss of mass and size change [*Joyce et al.*, 1984]. Plates 2*e* and 2*f* show this type of encounter between the Gulf Stream and ring 82B. Such an event will be termed an overwash and is distinguishable from streamer entrainment in the satellite images by the areal extent of the interaction and subsequent changes of ring size, shape, and location. An overwash has been observed to affect the upper 200–400 m of the ring [*Joyce et al.*, 1984], whereas streamers initially observed on a ring's periphery are confined to depths more equivalent to the ring's upper layer (order 50 m, cf. Figure 1 and 2) [*Schmitt and Olson*, this issue]. Streamers are usually found in the ring's high-velocity region, although on occasion they are observed to "spiral" into interior surface waters.

Vortices associated with WCR's are smaller isolated components of a flow field with a closed circulation of their own. This association of a large anticyclonic feature with small cyclonic circulations differs from those observed by *Lai and Richardson* [1977], who report on WCR's in close proximity to cold core rings. An example, labeled 2, is on the northeast quadrant of 82B (Plate 1) and can be identified by the time-varying spatial patterns in the slope waters that lie between the warm Gulf Stream (4 in Plate 1) and the colder shelf waters (6 in Plate 1). Isolated vortices (3 in Plate 1) are frequently observed in the slope. Clouds (black areas) or artifacts from a relatively hazy atmosphere are labeled 5 in Plate 1. A relative color scale has been adopted to enhance Plates 1 and 2. Cooler temperatures are represented by blue tones, intermediate temperatures by greens and yellows, higher temperatures by reds. The color-to-temperature map is varied as time progresses from March to June in order to enhance specific features and show significant gradients that would otherwise be obscured by seasonal warming and the attendant loss of thermal contrast.

Interactions are identified in this analysis by their effect on the specific region under study. This effect can take the form of a modification of temperature, areal extent, shape, motion, or any remotely observable characteristic. For example, in the case of a ring we operationally define an event to be a topographic interaction when a change in ring shape, size, or translation speed occurs simultaneously with a change in bottom topography. Figure 2 presents a speed history for 82B derived from the ring center of mass track (Figure 1) [*Hooker and Olson*, 1984]. Examination of Figure 2 finds several instances when dramatic changes in ring motion are evident. Some of these changes are due to topographic influences, others to Gulf Stream effects.

3. Event Classification of Gulf Stream Warm-Core Rings

The evolution of a ring is a function of relatively predictable processes, such as interactions with changes in bottom topography, and stochastic processes, such as ring–Gulf Stream interactions and meteorological events. Bottom topography effects are seen to alter the ring track location and govern its along-track speed. Stochastic processes, such as ring–Gulf Stream interaction, can produce pronounced changes in ring size. It is the temperature, location, and geometric features of rings that can be readily observed and effectively monitored by satellite infrared imagery. A time series of satellite imagery gives a synoptic overview of these physical characteristics governed by meso- and large-scale processes acting on the ring.

This discussion makes frequent reference to an abbreviated set of images selected as representative of the complete time series and which are illustrative of the features and events discussed (Plates 1 and 2). While we are primarily concerned with the life cycle of 82B, it will be seen that the behavior of 81F is frequently a precursor for the subsequent events occurring to 82B, as well as, at times, influencing 82B directly. Prior to this discussion we should reemphasize that our conclusions with respect to the behavior fo WCR's and their environs are based upon analysis of 145 satellite images [*Evans et al.*, 1984] and data from several ships over a period of several months (cf. Figure 2), whereas only a limited subset of these images can be shown in the report. As a consequence the authors have the advantage of observing detailed temporal sequences that only can be summarized for our readers here.

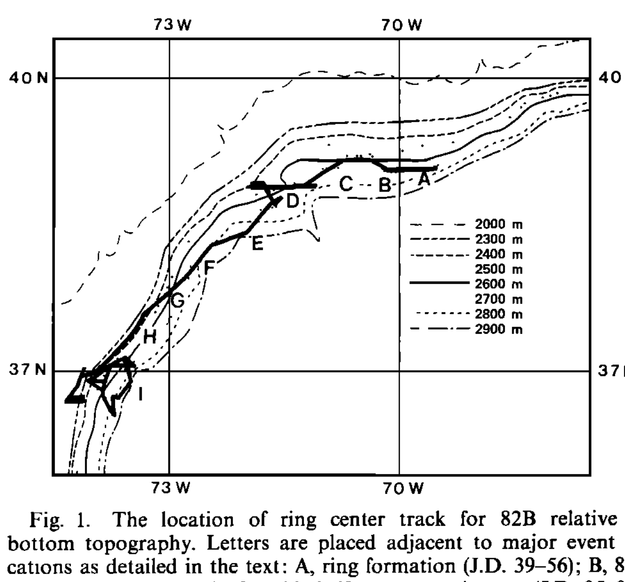

Fig. 1. The location of ring center track for 82B relative to bottom topography. Letters are placed adjacent to major event locations as detailed in the text: A, ring formation (J.D. 39–56); B, 82B GS encounter (J.D. 77); C, cold shelf water entrainment (J.D. 85–95); D, Hudson Canyon passage (J.D. 109–123); E, cold shelf water entrainment (J.D. 132–139); F, GS streamer entrained into 82B; G, start of Wilmington-Delaware Canyon passage (J.D. 153); H, cold entrainment period (J.D. 168); I, Cape Hatteras area, GS encounters with 82B (J.D. 183, 202, 218, 222, and 238).

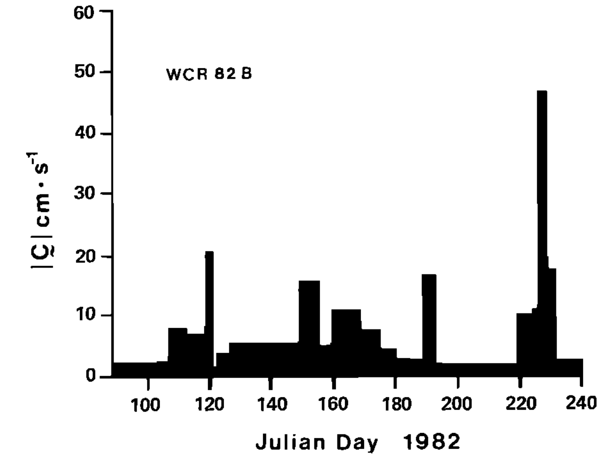

Fig. 2. WCR 82B absolute translation speed versus time. Center of mass positions shown in Plate 1 are differenced in time to derive a ring motion history.

3a. *Descriptive History of WCR 82B*

Between 1982 Julian days 39 and 56 (which we will write as J.D. 39–56), ring 82B forms from a northward flowing Gulf Stream meander centered at 70°W, 38.5°N (Figure 1, position A). The meander that formed 82B had a close interaction with warm-core ring 81F (J.D. 39)—located northeast of the meander at 70.6°W, 39.3°N—that may have contributed to this formation process. Separation of 82B from its meander (i.e., its formation) was complete by J.D. 56.

Between J.D. 56 and 80, rings 81F and 82B remain in close proximity, with their high-velocity regions as little as 15 km apart; separations from the Gulf Stream are of the same order. Plate 2*a* illustrates this time period and shows features associated with ring-ring interactions. During this period, the westward motion of 81F is retarded as it crosses the Hudson Canyon area. A small cyclonic vortex formed between the two rings (J.D. 70) is then advected by the flow field of ring 81F (Plate 2*a*, feature C). The surface expression of this vortex subsequently becomes entrained into 81F, covering approximately 40% of the ring's surface area with cooler water. Surface advection associated with this event rapidly cools 81F's surface water, modifying and obscuring the surface temperature pattern. By J.D. 90 the hydrodynamics of ring 81F has reestablished a surface signature, and it was again recognizable as an anticyclonic circulation with a surface temperature characteristic of the surrounding slope water (Plate 2*b*).

During this same period, a ring–Gulf Stream interaction occurs as ring 82B survives a near Gulf Stream (GS) encounter when a meander passes within 15–30 km of the high-velocity region between J.D. 71 and 82 (Plate 2*a*; Figure 1, position B). This is the first Gulf Stream (GS) encounter for 82B after formation and stimulates streamer activity, which pulls warm GS water into the slope area (Plate 2*a*, arrow A north to 82B).

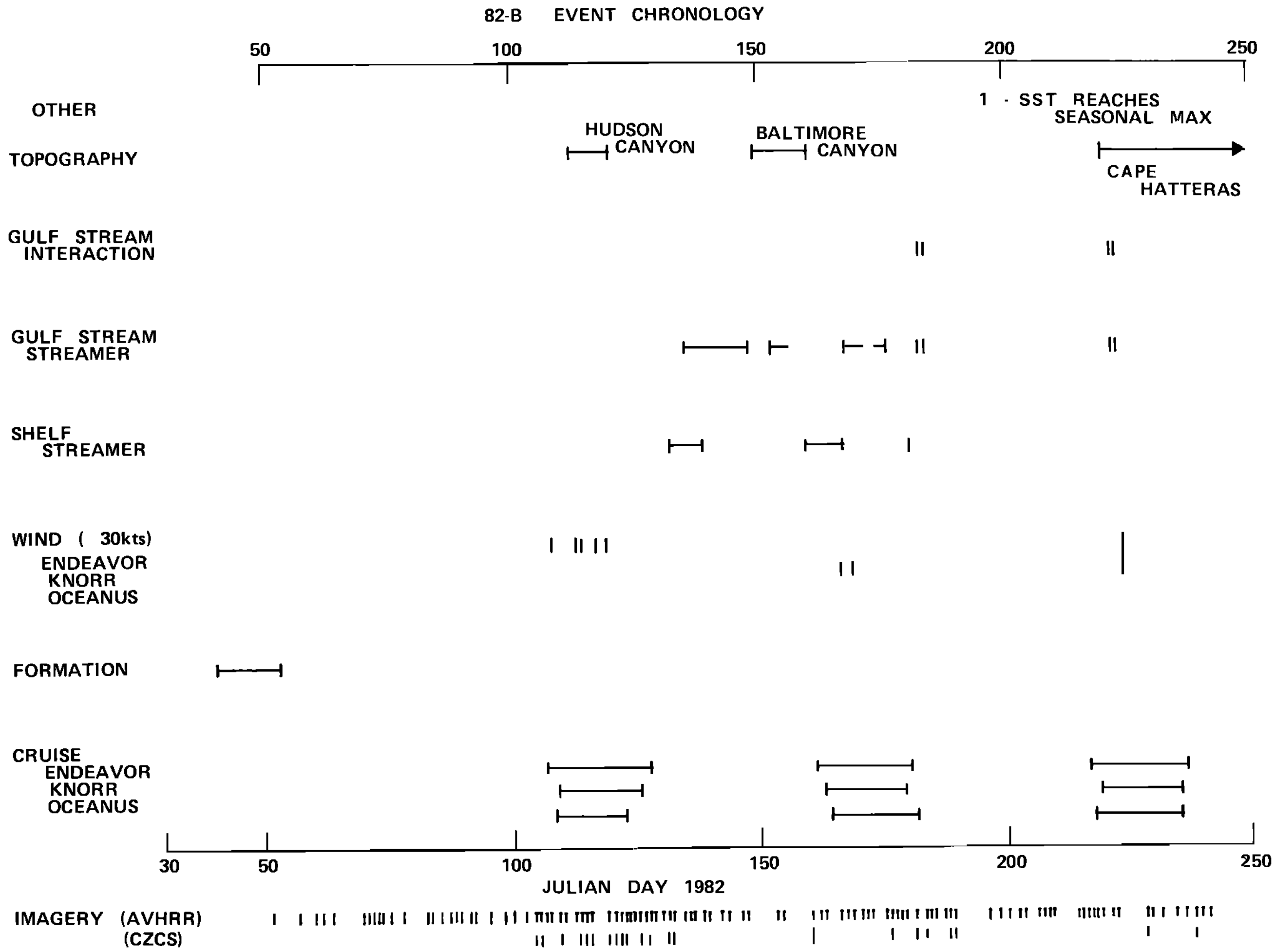

Fig. 3. Event chronology versus time (Julian day) for warm-core ring 82B. The three ship-sampling periods are noted. The days on which imagery is available are also listed.

Following this close interaction period (J.D. 56–80), rings 81F and 82B move farther apart (several ring diameters) and appear to have less influence on each other. From formation (J.D. 56) until the beginning of the interaction with the Hudson Canyon (J.D. 91), 82B translates to the west along the 2700-m isobath at approximately 4 cm s^{-1} (Figure 2); it then changes direction and begins movement toward the southwest.

Between J.D. 80 and 123, ring 82B apparently is cooled by surface entrainment of shelf/slope waters and by a storm while at the same time, interacting with the bottom topography of the Hudson Canyon (Figure 1, position C). Plates 1 (J.D. 105) and 2*b* (J.D. 114) are illustrative of this period. Early during this period (J.D. 83–95) satellite images show cold shelf/slope waters wrapping around 82B from the northeast. This is followed (J.D. 96–97) by a major storm that further lowers the surface temperature of 82B. Streamer activity continues both from the GS (Plate 1, feature 1, ring 81F; Plate 2*b*, feature B, ring 82B) and from the shelf/slope (Plate 1, features 2; Plate 2). Also during this period, cyclonic vortices with associated streamers are observed to the north, east, and south of 82B (Plate 2*b*). These vortices are most noticeable when presented in temporally sequential images due to their low thermal contrast with surrounding waters. Warm-core ring cruises on the R/V *Endeavor*, R/V *Knorr*, and R/V *Oceanus* begin during this time period and last from J.D. 108 through J.D. 128 (Figure 3).

From J.D. 109 to J.D. 123, 82B's center track exhibits a loop at the mouth of the Hudson Canyon, ring ellipticity increases, and 82-B's major axis orientation shifts from north-south to east-west (Plate 2*b*). The Hudson Canyon is also the site where a ring-cyclone interaction originates on J.D. 123 and continues to J.D. 132 as 82B moves down slope from this bottom topography (Figure 1, position D).

It is at the beginning of this period (J.D. 80–123) that minimum sea surface temperatures are observed in the shelf, slope, and ring and that restratification of the surface layers of the shelf and slope probably begin. Indeed, by J.D. 104 there is evidence that the shelf waters are beginning to warm. As a consequence of this restratification a phytoplankton bloom occurs [*Brown et al.*, 1985] on the shelf and slope during the period from J.D. 104 to J.D. 125. During this period, ring 81F has moved to a position where it is "squeezed" between the 200-m isobath and the GS (Plate 2*b*) from whence it begins a series of GS interactions leading to its coalescence in much the same manner that the more completely observed ring 82B will follow.

Between J.D. 123 and J.D. 140, the first streamer penetration to the core of 82B is observed, and 81F undergoes major GS interactions. Plate 2*c* (J.D. 138) is illustrative of the end of this period. On J.D. 132 a cyclonic vortex to the northeast of 82B is associated with a strong streamer that wraps cold shelf water around the east side of 82B. This streamer of shelf water then appears to spiral into the center of ring 82B, entraining cold shelf water in the surface layers of the ring (Plate 2*c*, feature C; Figure 1, position E). The sea surface temperature of areas surrounding 82B (Gulf Stream, shelf, and slope) begin their seasonal warming during this interval and continue to increase more or less continuously until J.D. 210–215. Also, ring 82B returns to a track following the 2800-m isobath and a southwest speed of approximately 7 cm s^{-1} (Figure 1, position E, also Figure 2).

During this period (J.D. 123–140), ring 81F is involved in a series of Gulf Stream interactions that continues until it is finally absorbed by the GS (about J.D. 154). Plate 2*c* shows 81F, having been overwashed by the Gulf Stream, as a small warm ellipse at the vertex of the 200-m isobath and the north-wall of the GS. Also from J.D. 125, and perhaps related to 81F GS interactions, Gulf Stream meander amplitude is observed to increase.

Between J.D. 140 and 176, the whole slope area is warming, and ring 82B moves south southwest toward its final position off Cape Hatteras. Plates 2*c* (J.D. 138) and 2*d* (J.D. 176) illustrate the beginning and end of this period, respectively. Following a cloudy period (J.D. 140–145), 82B is observed, on J.D. 146, to have warmed several degrees in this several-day period. This suggests that a warm streamer event, perhaps stimulated by a Gulf Stream meander observed in the satellite imagery, has overridden the surface layer (Figure 1, position F). The presence of a 10-m warm surface layer warm is confirmed by XBT surveys during a ship-of-opportunity cruise, *Knorr* 94.

On J.D. 153, ring 82B experiences a near GS encounter when a meander crest passes within 15 km of the ring high-velocity region. Following this near encounter, 82B begins a period of GS and topographic interactions and ring center returns to the 2400-m isobath (Figure 1, position G). Between J.D. 150 and 160, 82B crosses the Wilmington-Delaware Canyon area, and a cyclonic vortex is formed north of 82B. Between J.D. 160 and 168, strong shelf/slope streamers associated with the cyclonic vortex to the northeast wrap around the east of 82B as it passes the Wilmington-Delaware Canyon area. This cyclone interaction precedes a period of cold shelf water entrainment that penetrates to the ring interior (Figure 1, position H, J.D. 168). A major storm passes over 82B on J.D. 169, erasing the surface temperature expression of small-scale horizontal structure.

On J.D. 176 a prominent cold streamer is evident in the temperature imagery (Plate 2*d*, feature D). Examination shows this feature to be associated with a pairing of ring 82B with a cyclonic vortex to the northeast (darker green feature north of the arrowhead). This ring-vortex activity is seen to advect shelf water across the slope water to the Gulf Stream, where it then continues downstream (Plate 2*d*). This period (J.D. 140–176) ends as ring 82B becomes nearly stationary after J.D. 175 when it reaches the vicinity of Cape Hatteras. At this point, 82B—like 81F before it—is located at the vertex formed by the 200-m isobath and the north wall of the GS (Figure 1, position I); subsequent ring translation is dominated by ring–Gulf Stream interaction.

Between J.D. 176 and 240, ring 82B increasingly interacts with the GS Plate 2*d* (J.D. 176) shows 82B at the beginning of this period, while Plates 2*e* (J.D. 179) and 2*f* (J.D. 183) illustrate interactions during this time. Ring-vortex coupling produces first cold streamers then warm streamers, as is illustrated in Plates 2*d* and 2*e*, respectively. The cold streamer has been discussed above. In addition a small cyclonic vortex to the southwest of the ring generates pronounced warm streamers from J.D. 177 to 180 (Plate 2*e*).

Strong interactions between the ring and the Gulf Stream, with Gulf Stream water displacing ring surface and upper core water, are frequently seen throughout this period. An overwash event, for which the R/V *Endeavor* obtained verifying data, is illustrated in Plate 2*f*. The location of the ring can change markedly during such encounters as the ring moves rapidly to the north and then returns to the southwest, following the passage of the meander. Encounters between the ring and the Gulf Stream are centered on Julian days 183, 202, 218, 222, and 238 (Figure 1, position I).

Sometime during the intercruise period (J.D. 183–217), ring 82B suffered a major GS interaction in which its diameter was reduced from 110 km to 70 km, the thickness between the 15° and 16°C isotherms was reduced from 350 m to 200 m, and its depth to the 10°C isotherm was reduced from 550 m to 440 m [*Olson et al.*, this issue; *Joyce and Kennelly*, this issue]. Also during this period, rapid surface warming of the shelf and slope waters (through J.D. 199) reduced the thermal contrast between 82B and its surrounding environment. The ring boundary becomes more evident on J.D. 203 and J.D. 206 as Gulf Stream water was entrained by the ring during a meander encounter. Thereafter the ring surface thermal expression remains indistinct through the end of the time series of J.D. 241.

Figure 3 presents an event chronology for ring 82B that summarizes the above discussion. The cruise periods for the three ships involved in the WCRE are shown as well as the days for which satellite imagery is available.

3b. *Topographical Interactions*

The influence of bottom topography on the Gulf Stream front has been explored [*Warren*, 1963; *Legeckis*, 1979]. Observed tracks of eddies relative to bottom topography suggest that they tend to follow single contours [*Bisagni*, 1976; *Halliwell and Mooers*, 1979]. Topographical influences have been oberved to modify the size and shape of rings as well their motion. Our satellite and ship observations studied the region west of 67° longitude that is bounded on the south by the Gulf Stream. The bottom topography of this region is shown in Figure 1, where letters are placed at the locations where major events occurred.

For reference we have divided this region into the following areas: the north slope, referring to the area where the 200-m isobath runs east-west (Figure 1, positions A–C); the Hudson Canyon regime, which includes the area of the Hudson Canyon (Figure 1, position D); the south slope, referring to the area where the 200-m isobath runs southwest (Figure 1, positions E–H); the Wilmington-Delaware Canyon regime (Figure 1, position G–H); the Cape Hatteras regime, referring to the area formed by the vertex of the 200-m isobath and the north wall of the Gulf Stream (Figure 1, position I).

The ring translation, i.e., the motion of the center of mass of a ring, is approximately 4 cm s^{-1} in the north slope area (Figure 2). However, steady ring translation is disrupted by bottom canyons. Once a ring reaches the south slope, its translation accelerates to 7 cm s^{-1} as its path is progressively pinched between the 200-m isobath and the north wall of the Gulf Stream (Figure 2). Its southerly progress is impeded as it reaches its southern limit near Cape Hatteras, where interactions with the Gulf Stream significantly modify and eventually assimilate the ring.

In our study of satellite imagery we have observed that as a

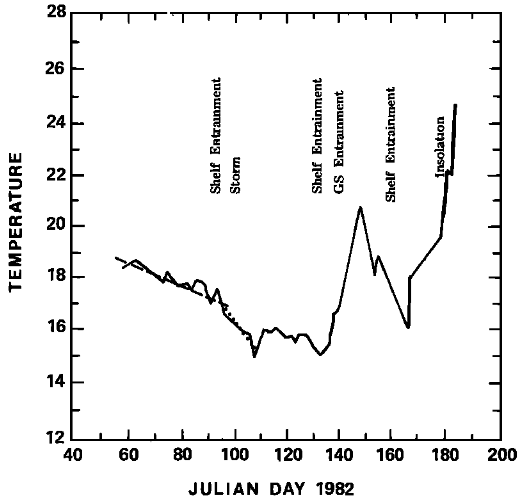

Fig. 4. The sea surface temperature (°C) of the 82B ring center as measured by satellite versus time (Julian day). Dashed line for J. D. 59–95 is a period where ring core temperature cools at a rate of 0.035°C d^{-1}, dotted line covers a period of rapid cooling during storm passage, J.D. 96–97.

ring moves toward shallower topography there are often cyclonic vortices generated in the lee of the ring. Such vortices often appear to the northeast of warm-core rings as they encounter canyons or approach Cape Hatteras. Plates 2*b* and 2*c* have been shown to illustrate this type of event. The vortex is usually advected clockwise around the ring until the line between the ring and vortex centers is nearly perpendicular to the ring translation velocity, at which point entrainment is often observed. This ring-northeast cyclonic vortex type event was found to occur repeatedly during the history of both rings 81F and 82B [*Kennelly et al.*, this issue].

3c. *Temperature Evolution of 82B Ring Center*

Figure 4 presents the sea surface temperature evolution for 82B as observed by using a time series of infrared imagery. Formation of warm-core ring 82B from a Gulf Sream meander leaves a new ring with a core (ring center) surface temperature between 18° and 18.5°C on J.D. 56. A steady decrease in ring central core temperature of approximately 0.035°C d^{-1} is observed from J.D. 59 to J.D. 95. Use of this thermal time history with in situ observations of core volume [*Schmitt and Olson*, 1984] permits estimate of total air-sea heat flux over ring core waters during this time period. The observed cooling rate of 0.035°C d^{-1} (the dashed line) corresponds to a heat loss of 400 W m^{-2}. Toward the end of this initial cooling period (J.D. 85–95), streamers penetrate the high-velocity region, advecting cooler shelf and slope waters into the outer core area, which results in shrinkage of the central warm area. A major storm occurs over the region during J.D. 96–97; ring 82B is seen to abruptly cool to 15.9°C.

Surface temperature remains nearly constant from J.D. 110 until J.D. 136, when warming commences, suggesting cessation of deep convection in the central core. Ring 82B is observed to warm, presumably from entrainment of a warm Gulf Stream streamer following a ring–Gulf Stream interaction, between J.D. 142 and 145. From J.D. 160 to 168, ring center is cooled by entrainment of cold shelf streamers. Ring 82B surface waters begin an uninterrupted trend of seasonal warming—at a rate of 0.38°C d^{-1}, after passage of a storm on J.D. 169—that lasts until J.D. 190. Ring 82B surface temperature is moderated by a series of Gulf Stream interactions and streamer events from J.D. 190 until coalescence with the Gulf Stream around J.D. 280.

3d. *Shelf/Slope Exchange*

Plates 1 (features 2) and 2*d* (feature D) illustrate advection of cold shelf water into and across the slope. Eddy entrainment of shelf water has been previously observed [cf. *Saunders*, 1971; *Morgan and Bishop*, 1979; *Halliwell and Mooers*, 1979]. When an anticyclonic ring is situated close to another frontal boundary (such as a small vortex), the strong horizontal shear present enhances lateral fluid transport. In most of the present observations, cold streamers are associated with, and sandwiched between, a warm anticyclonic ring and a cooler cyclonic vortex. Location of cyclonic vortices to the northeast of an anticyclonic warm ring enhances advection of cold, fresh shelf waters into the slope. Conversely, when cyclonic vortices are located in the southwest quadrant, there is intense advection of warm Gulf Stream water into the slope. We classify these phenomena as cold and warm streamer events, respectively.

Besides providing an agency for modification of slope waters, ring-vortex-enhanced advection also is an effective mechanism for modification of ring central surface waters. The modification of WCR's as a result of entrainment is progressive, developing slowly in time (days to weeks). Streamer effects are limited to the upper 100 m of the ring; XBT, BOPS, and CTD observations find little effect below this level. In contrast, ring entrainment of a vortex has the potential to cause an impulse change in water mass properties affecting the upper ring. Cyclonic ringlets observed during April have radii the order of 30 km. A ringlet observed on the northern periphery of ring 82B during a June R/V *Endeavor* CTD transect exhibits a low-temperature region between 25 and 75 m that may be a trapped region [*Kennelly et al.*, this issue]. If this fluid is incorporated into the ring when a cyclonic vortex is entrained, a volume equivalent to order of 25% of the ring surface area times the vertical extent of the entrainment is rapidly injected into the ring. While no in situ observations are available for ring 81F following a vortex entrainment, satellite observations indicate that the observed 81F surface temperature and chlorophyll became equivalent to the values of the surrounding slope waters.

3e. *Ring–Gulf Stream Interactions*

Satellite imagery shows that the initial survival of a ring as a separate mass is dependent, in part, upon the spatial relationship of the Gulf Stream and the meander that created it. A series of wave crests (or meanders) of the GS are likely to pass the same location once a ring has formed. Consequently, a subsequent crest may absorb a newly formed ring or significantly modify its structure.

Once a ring is formed, ring–Gulf Stream interactions can result in streamer activity (Plate 2*a*, feature A), in overwash phenomena (Plate 2*f*, feature F), and significant modification of ring structure and location. Ring–Gulf Stream interactions are also location dependent; once a ring reaches the vicinity of Cape Hatteras, significant interactions with the Gulf Stream occur approximately every 3–4 weeks. Meander amplitude has been observed to increase following an interaction. This process can aid in the formation of other rings.

4. CONCLUSIONS

Although each warm-core ring will have a unique event chronology, it appears similar events occur to most rings. Although topographical events are somewhat predictable, environmental events such as Gulf Stream interactions are stochastic. They are observed to have the potential of altering the ring velocity, temperature, and size. Further, these events are shown to impact the entire slope water region.

A ring does not exist in isolation. The classification of discrete ring events is a description of interaction types. It is clear that interpretation of a single ring event requires a synoptic mesoscale overview of an area. The overview provided by this satellite imagery series generates a general catalog of events influencing the surface field of rings. This event classification provides a context within which to interpret past and future limited data sets that do not have the benefit of such extensive satellite coverage and in situ observations.

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