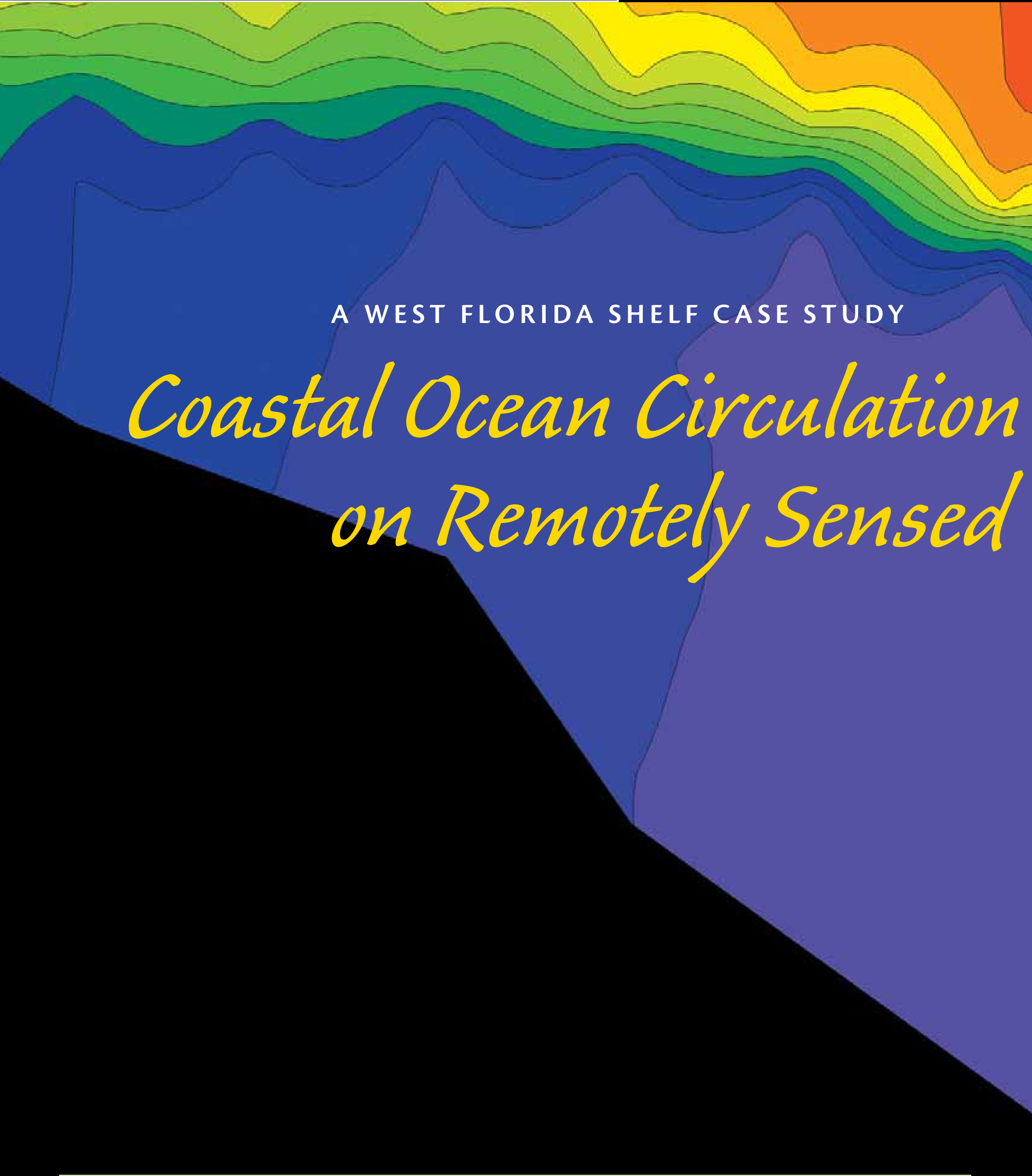
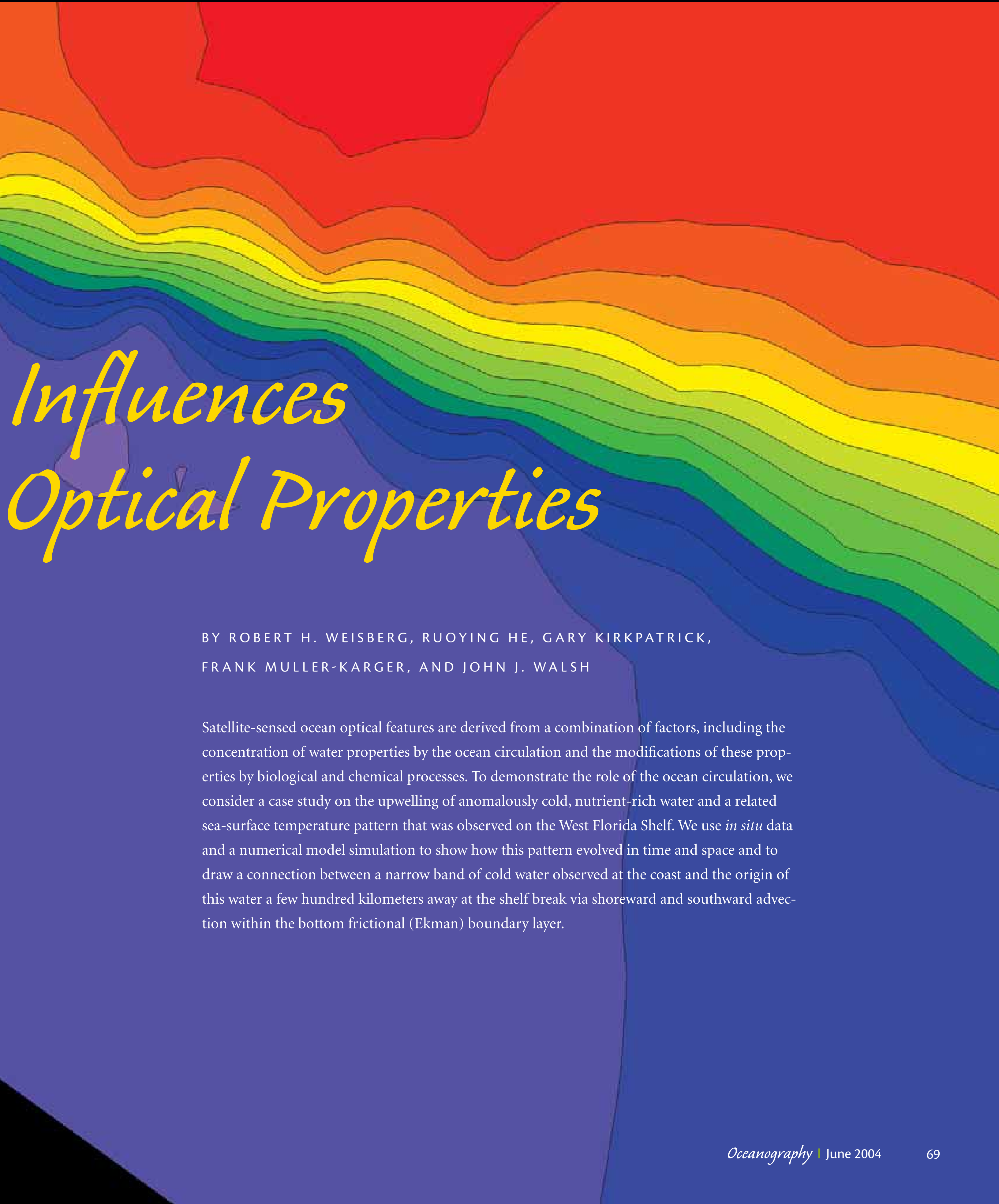


A WEST FLORIDA SHELF CASE STUDY

Coastal Ocean Circulation on Remotely Sensed



Influences Optical Properties

BY ROBERT H. WEISBERG, RUOYING HE, GARY KIRKPATRICK, FRANK MULLER-KARGER, AND JOHN J. WALSH

Satellite-sensed ocean optical features are derived from a combination of factors, including the concentration of water properties by the ocean circulation and the modifications of these properties by biological and chemical processes. To demonstrate the role of the ocean circulation, we consider a case study on the upwelling of anomalously cold, nutrient-rich water and a related sea-surface temperature pattern that was observed on the West Florida Shelf. We use *in situ* data and a numerical model simulation to show how this pattern evolved in time and space and to draw a connection between a narrow band of cold water observed at the coast and the origin of this water a few hundred kilometers away at the shelf break via shoreward and southward advection within the bottom frictional (Ekman) boundary layer.

INTRODUCTION

The ocean margins present a highly variable radiation spectrum to space-borne sensors. Rendered by the analyst, it is then passed on to the ocean scientist, who must decipher the resulting ocean color tapestry. The colors may represent stationary features such as shoaling topography or fixed macrofauna, moving continua of chlorophyll-containing microfauna or particulate or dissolved matter from river runoff, or simply the infrared signature of sea surface temperature (SST). Time- and space-dependent variations of these features may occur for a variety of reasons, depending on the material being sensed. For quantities such as chlorophyll or SST, the governing equations include advection by the ocean currents; diffusion or mixing by circulation-induced turbulence acting on the concentration gradients; sources or sinks by biological, chemical, or geological processes; and property fluxes across bounding surfaces. Additionally, the color tapestry may result from either two-dimensional processes occurring at the surface, or from fully three-dimensional processes occurring throughout the water column. Given the interplay of these variables and processes, interpreting the nature of ocean color remotely sensed from space is a complex problem.

Of the remotely sensed variables that are subject to advection by ocean currents, SST may be the most easily interpretable. This is because temperature, with provision for surface heating and cooling, is a conservative variable, as contrasted with pigment-related variables that may be highly non-conservative. The interpretation of SST remains complex, nevertheless. Net surface warming or cooling by incoming short and long-wave radiation, outgoing long-wave radiation, and latent and sensible heat fluxes occurs over a broad range of time scales, including the diurnal cycle, the seasonal cycle, and the passage of synoptic weather systems.

For instance, under light wind conditions, SST may change by several degrees C from dawn to dusk, as the effect of solar infrared radiation concentrates in the upper meter of the water column in the absence of mixing. Similarly, with the passage of a cold front, the entire water column (in shallow regions) may cool by several degrees C due to sensible and latent heat losses. Along with these surface-induced changes there may also occur changes by subsurface processes. Under stratified conditions, even if the net surface heat flux is zero, large SST variations may occur either by upwelling or vertical mixing, or by a combination of these.

This paper provides a case study in which the fully three-dimensional ocean circulation leads to a large change in SST via coastal upwelling and mixing. We choose a period in May 1998 when the interpretation of a satellite Advanced Very High Resolution Radiometer (AVHRR) SST image is supported both by *in situ* data and a numerical model simulation of the coastal ocean circulation (using an adaptation of the Blumberg and Mellor [1987] Princeton Ocean Model, POM). By describing the evolution of this feature, we demonstrate the complexity of ocean color interpretation, and we reinforce the need for fully three-dimensional considerations of the coastal ocean circulation, if we are to interpret the more complex range of color signatures evident by space borne sensor systems.

THE OCEAN SETTING, THE DATA, AND THE MODEL INTERPRETATION

The spring and summer of 1998 was a period of anomalous water properties on the West Florida Continental Shelf (WFS) (Figure 1). Despite a relatively hot and dry spring season and a resultant warm SST, cold-water outcrops were found to commonly occur along the coast. For example, Figure 2 shows one such period in which we see a narrow strip of cold water at the surface extending from Tampa Bay in the north to Charlotte Harbor in the south. Contrasted with this are the warmer nearshore waters to the north and south and the waters of the Gulf of Mexico Loop Current (LC), seaward of the shelf break to the west. While this surface coastal feature waxed and waned with the passage of synoptic-scale weather systems, a subsurface feature that persisted well into summer was concurrent with it. As a subsurface temperature example, Figure 3 shows a temperature cross-section sampled offshore of Sarasota, Florida (just south of Tampa Bay) on May 18, 1998. At mid-depth, we see a sharp thermocline with the near bottom waters being some 8°C colder than the near surface waters. This thermal contrast in the

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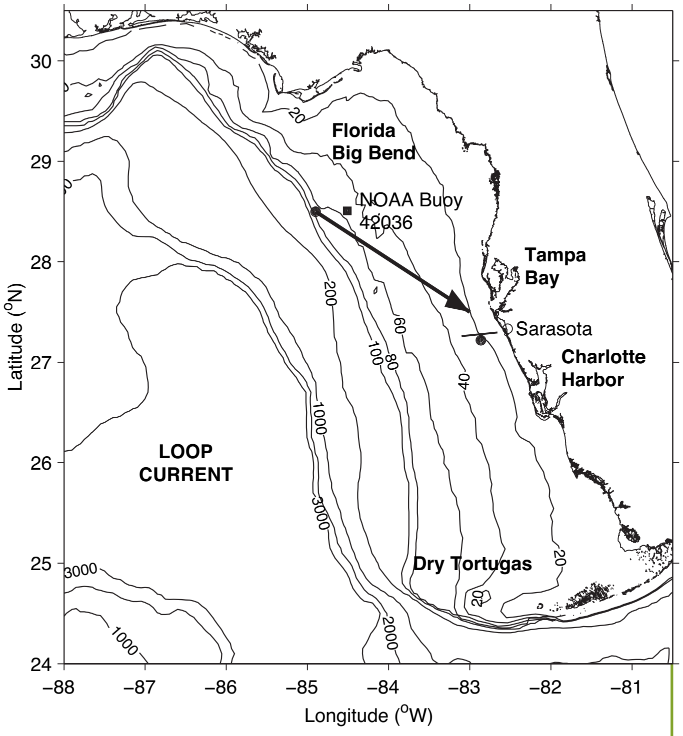

Figure 1. The west Florida continental shelf is a broad, gently sloping region about as wide as the State of Florida. Shown are bottom depth contours, the various locations referred to in the text, and the measurement sites. Attention should be focused on the region between Tampa Bay and Charlotte Harbor, where cold water is observed to outcrop, and the Florida Big Bend region, where these outcropping cold waters are thought to have originated by deep-ocean water broaching the shelf break. The arrow indicates the approximate pathway taken from the shelf break to the near shore. The line segment and the solid dot offshore of Sarasota denote the positions of the Figure 3 temperature section and the Figure 5 velocity data, respectively. The small, closed, 20-m contour region toward the bottom of this Figure encircles the Dry Tortugas.

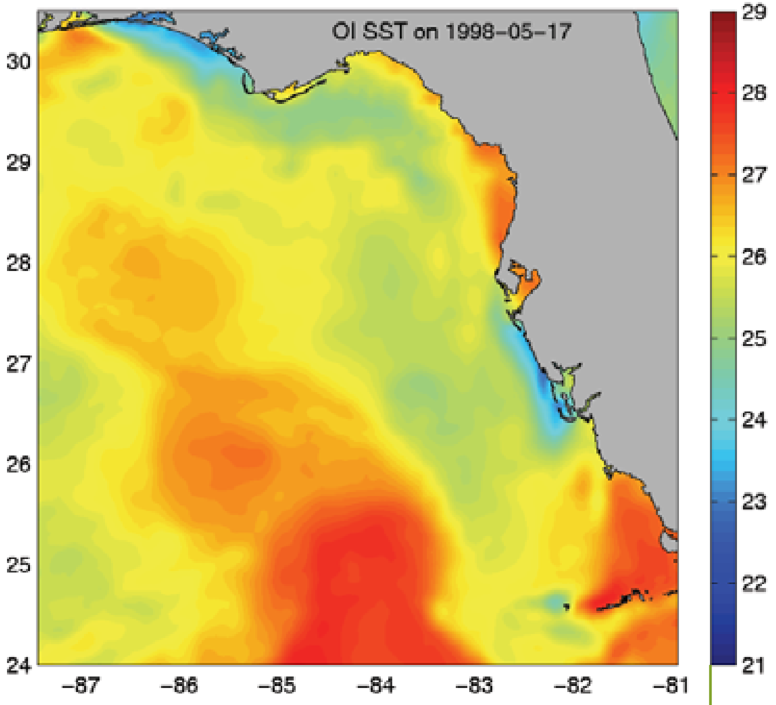

Figure 2. An outcrop of cold-water (blue) is evident along the coast between the Tampa Bay and Charlotte Harbor estuaries in this OI SST image (after He et al., 2003) on May 17, 1998. In contrast with this nearshore, cold temperature feature, we see that the surrounding surface waters are warmer (with temperature increasing from blue to orange) on the WFS, and we see the warmest waters within the Gulf of Mexico Loop Current located seaward of the shelf break.

vertical also had an associated near-bottom chlorophyll fluorescence signature that led to changes in surface pigments in satellite imagery (Figure 4).

Weisberg and He (2003) described the spring and summer 1998 responses of the WFS to both the local effects of winds and surface heat flux and the remote effects of the deep-ocean LC using observations and model simulations. The appearance of anomalously cold water on the shelf was caused by a combination of these local and remote factors. An impact by the LC on the shelf slope near the Dry Tortugas caused the isotherms (together with other material isopleths) to tilt upward along the entire shelf slope to the north and west of the impact region, bringing deep, relatively cold and nutrient-rich water closer to the surface at the shelf break. Along with this preconditioning effect of the deep ocean, the synoptic-scale wind fluctuations were anomalously upwelling-favorable. As a result, during the upwelling phases of the weather system passages, the magnitude and duration of the winds were sufficient to cause these elevated deep-water material isopleths to broach the shelf break, depositing cold, nutrient-rich waters on the broad, gently sloping shelf. With the alongshore currents on the shelf having a net southward set over much of this time, the bottom frictional (Ekman) boundary layer, by turning the flow leftward toward the

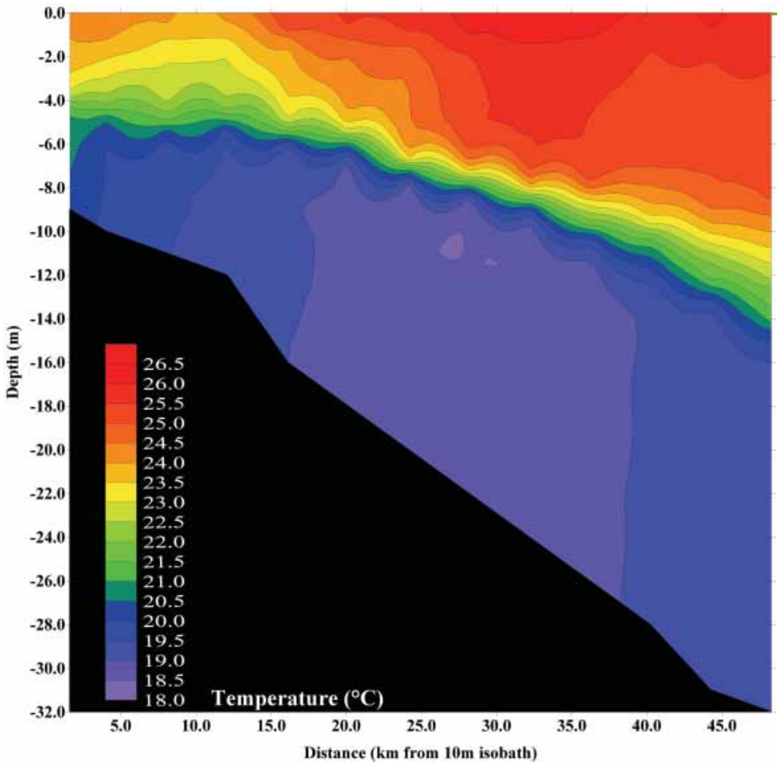

Figure 3. A temperature cross section sampled offshore of Sarasota, Florida on May 18, 1998. It is believed that the cold-water core originated a few hundred kilometers to the northwest by upwelling across the shelf break in the Florida Big Bend region (Figure 1; Weisberg and He, 2003; Walsh et al., 2003).

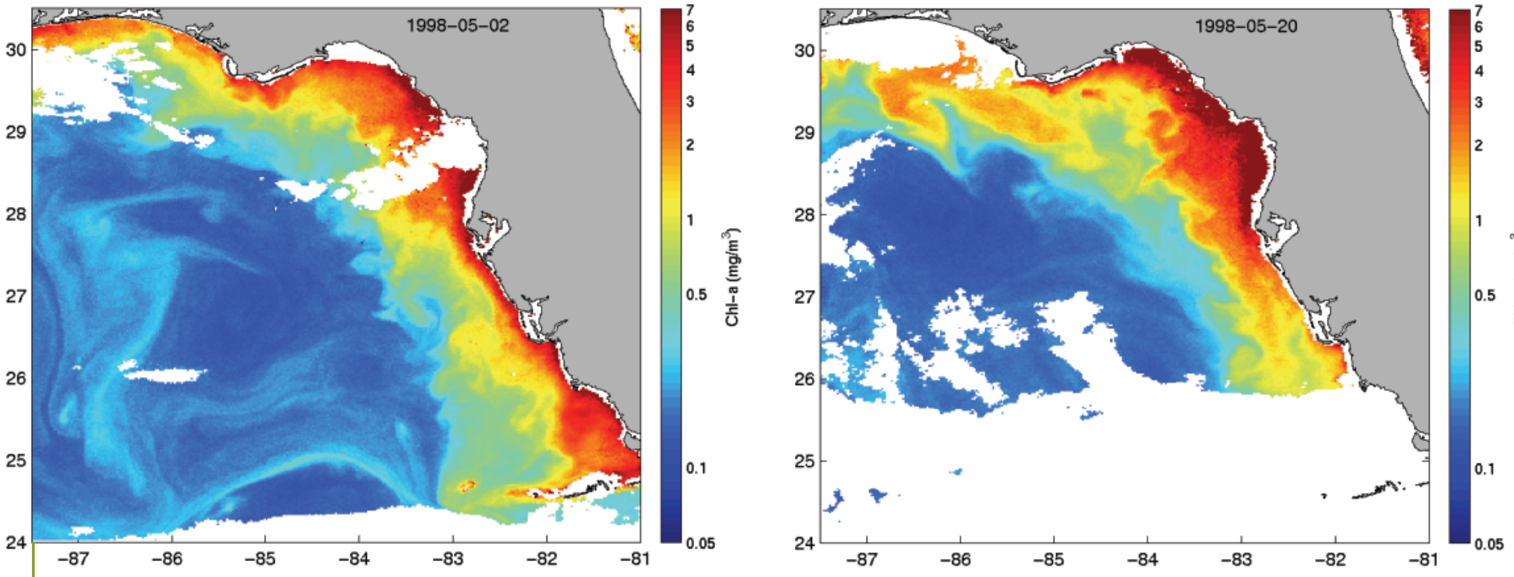

Figure 4. SeaWiFS color images for May 2, 1998 (left panel) and May 20, 1998 (right panel) demonstrate the effects of upwelling on pigment related ocean color. The SeaWiFS data (from Orbimage, Inc.) observed by satellite at six different wavelengths are converted to chlorophyll concentration estimates as indicated in the color scale to the right. Red designates areas of high concentration and blue designates areas of low concentration. The first of these images, acquired prior to the outcropping of cold water at the coast (Figure 2), shows high chlorophyll concentration between Tampa Bay and Charlotte Harbor, confined to a narrow, nearshore band. Subsequent to the outcrop in the second of these images we see the translation of high-chlorophyll water both offshore and to the south, consistent with an upwelling-induced circulation.

shore, provided the conduit for these cold, nutrient-rich waters to reach the coast. The way in which these physical factors led to the observed phytoplankton evolution during this time was described in a companion paper by Walsh et al. (2003).

The role of the bottom Ekman layer in the shoreward transport of materials is evident in velocity vectors sampled over the water column on the 20 m isobath offshore of Sarasota, Florida (Figure 5). The alongshore flow was toward the south for the entire month of May, leading up to the Figure 2 satellite image, and a marked left-hand turning in the near-bottom relative to the near-surface flow demonstrates the upwelling nature of the across shelf transport. The fact that the winds were not the sole cause of upwelling, however, is clear from the upper panel, where we see downwelling-favorable winds (southerly) over the beginning of May. For the largest of these downwelling sequences, we see onshore flow in the surface and offshore flow at depth (May 8th and May 10th), despite the net southward along shore flow induced by the LC impact (described and simulated for spring and summer 1998 by Weisberg and He [2003] and discussed theoretically by Hetland et al. [1999]). Not until the winds reversed on May 11th did the wind and LC effects add constructively, causing a reversal in the upper and lower across shelf transports and

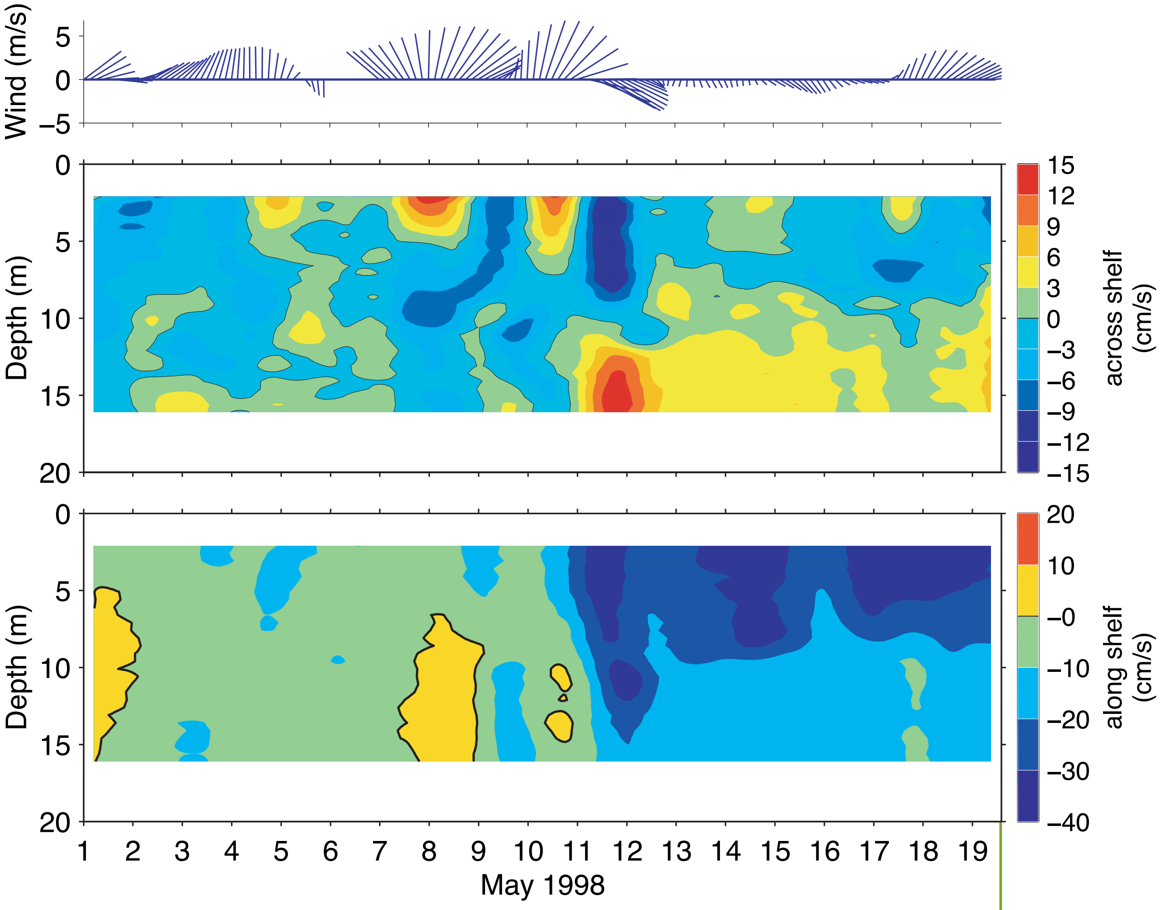

Figure 5. The effects of both local and deep-ocean forcing are evident in the along shelf and the across shelf components of velocity sampled on the 20 m isobath offshore of Sarasota. The along-shelf component in the lower panel has positive values directed toward the north-northwest. The across-shelf component in the middle panel has positive values directed toward the coast. Shown as a function of depth and time, these measurements, made with a bottom-mounted acoustic Doppler current profiler, are low-pass filtered to remove oscillations at times scales shorter than 36 hours. The upper panel is a similarly filtered set of wind vectors measured at NOAA buoy 42036 located in the Florida Big Bend. We see a predominant southward set to the along shelf current, despite the variations in wind velocity, which is a consequence of remote deep-ocean influences. With the onset of upwelling favorable (northerly) winds around May 11th, the local wind and remote deep-ocean effects add constructively to produce strong, vertically sheared currents with offshore flow near the surface and onshore flow near the bottom (middle panel), leading to the outcrop of Figure 2.

the subsequent outcrop of cold water at the coast. This situation continued throughout the entire spring and summer seasons. Lurking beneath the warm surface and the sharp thermocline was cold, nutrient and biota rich water that occasionally outcropped to the surface at the coast.

These subsurface waters originated along the shelf break region of the Florida Big Bend, located a few hundred kilometers northwest of Tampa Bay (Figure 1). This was determined through Lagrangian trajectory analyses by seeding the numerical model with particles at various depths and locations and tracking these over the period of simulation (Weisberg and He, 2003). This theme of across-shelf transport from the shelf break to the coast in a bottom Ekman layer conduit is further advanced by considering the model simulated vertical velocity as sampled on May 15th (Figure 6). In a mid-depth planar view (upper panel), sampled on sigma level 12 from this 21 level sigma coordinate (in which the sample depth is normalized by local water depth) model simulation, we see the region of maximum coastal upwelling beneath the satellite sensed cold SST feature (Figure 2). In the Sarasota, Florida, cross-section, we see that the positive vertical velocity (upwelling) is generally confined to the bottom Ekman layer (due to the turning of the horizontal velocity vector in the across isobath direction) with the outcrop to the surface occurring only near the coast.

DISCUSSION AND CONCLUSIONS

Why and where the outcrop occurs requires further explanation, and for this we must consider both the geometry of the WFS and the anomalously strong stratification of May 1998. A previous upwelling case study (Weisberg et al., 2000) discussed a purely wind-driven event in May 1994, as contrasted with the joint-wind, LC-driven event discussed here. In May 1994, the upwelling outcrop occurred at about the 25-m isobath and was isolated from the coast. It followed the rapid onset of strong, upwelling-favorable winds subsequent to a period of quiescent winds, permitting an analogy to be drawn with an initial value problem. The *in situ* data for that event suggested a classical Ekman-geostrophic route to coastal ocean spin up. In this situation, an offshore surface Ekman layer transport caused sea level to drop, which caused an alongshore geostrophic interior flow and an onshore bottom Ekman layer response to this interior flow, all developing over the course of a pendulum day. It was argued that the location of maximum upwelling, and therefore, the outcrop of cold water at the 25-m isobath just south of Tampa Bay, occurred as a consequence of the bottom Ekman layer and the steering effect of the curving coastline to the north.

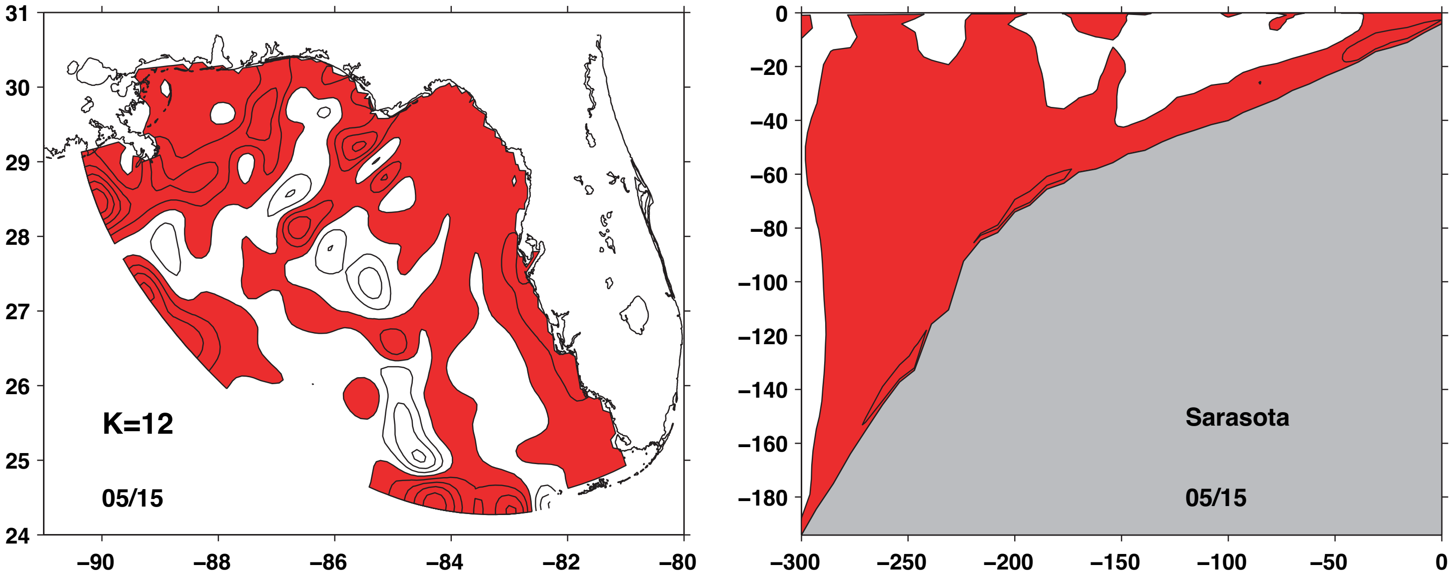

Figure 6. Model-simulated vertical velocity component sampled on May 15, 1998, both in planar view at mid-depth (left panel) and in a Sarasota, Florida cross section (right panel). Note the local vertical velocity component (upwelling designated in red) maximum at the outcrop between Tampa Bay and Charlotte Harbor in the planar view and the near-bottom distribution of upward motion in the cross-section. Since the model employs a sigma coordinate in the vertical (in which the position within the water column is normalized by the local water depth), mid-depth is always at the middle of the water column as indicated by the index K=12 being the 12th layer in this 21 layer model.

The confluence of these two effects, occurring just to the south and offshore of Tampa Bay, led to the outcrop there. Two idealized model simulations were performed in support of this hypothesis. The first considered constant density for which the maximum upwelling region occurred as observed, with southwestward directed vectors from the curved shoreline and southeastward directed vectors from the bottom Ekman layer converging at the point of maximum upwelling. The second considered stratified conditions for which the region of maximum upwelling shifted both southward and shoreward.

Stratification affects the results in two ways. First, by affecting the vertical distribution of turbulence, stratification affects the vertical structure of the (surface and bottom) Ekman layers resulting in a larger onshore component of flow in the bottom Ekman layer. The effect of this stronger bottom Ekman layer flow is to overpower the weaker southwestward flow issuing from the curved shoreline in the north. Second, by stabilizing the water column, stratification provides a buoyant inhibition to upwelling such that fluid must enter a shallower depth before turbulent mixing is sufficient for it to reach the surface. The May 1998 event, in which the LC caused anomalous stratification, when contrasted with the purely wind driven May 1994 event, supports these arguments on the WFS regions of locally maximum upwelling. In May 1998, the stratification was strong enough for the thermocline to literally outcrop at the beach. This situation persisted well into summer, much to the joy of hot summer bathers, but to the chagrin of recreational scuba divers who complained of poor visibility and cold water at depth.

Several conclusions may be drawn regarding the interpretation of remotely sensed images and the *in situ* coastal ocean-observing systems that are necessary to support this. Foremost is the recognition that coastal ocean surface features generally result from fully three-dimensional coastal ocean processes, and that these processes may entail a combination of locally and remotely (deep-ocean) forced phenomena. While some WFS surface phenomena are traceable back to apparent source regions such as intensified ocean color at the shelf break (i.e., the "Green River" phenomenon of Gilbes et al., 1996) or Colored Dissolved Organic Material (CDOM) signatures from the Florida Big Bend rivers (Jolliff et al., 2003), even these are manifestations for the fully three-dimensional circulation. Isolated outcrops like the one reported here are fully dependent on the circulation transporting materials from what may be very distant locations. If this is what fuels biological productivity, then inferences drawn from satellite sensed surface images alone may be limited. Given the nature of the problem, *in situ* observing systems must, at a minimum, be concerned with the vertical structure of the flow and other material property fields. Along with high-frequency (HF) radars for surface currents there is a need for moorings to document the vertical structure of the currents and in particular the near bottom currents that can transport deep ocean properties from the shelf break to the near shore. There is also a need for temperature and salinity measurements in the vertical by some combination of moorings, profilers, and other vehicles, since the vertical structure of the flow field, and where outcropping of materials may occur, depends on the three-dimensional density field. Interpretations of the anomalous WFS behaviors in spring-fall 1998 could not have been made without such fully three-dimensional *in situ* data.

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