Detecting Coastal Upwelling Events along the NC Coast Utilizing AVHRR and In-Situ Sea Surface Temperatures and Wind Data

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ABSTRACT- **The wind-driven seaward movement of warm coastal surface water and its associated displacement by cold bottom water describes the oceanic process of coastal upwelling. As cold deep water rises to the surface, vital nutrients necessary to sustain abundant and varied sea life are replenished. Although marine ecosystems may be periodically enriched due to the effects of coastal upwelling, they may ultimately suffer harm due to adverse after effects such as rates of organic consumption exceeding available nutrients, reduction in dissolved oxygen levels due to organic decay, and the explosive growth of harmful toxin-bearing algal species. There is evidence that these negative effects can be detected in simultaneous satellite observations of sea surface temperature, wind, and chlorophyll-α concentration.**

Incidents of coastal upwelling during the summer of 2000 were identified along the northeastern coast of North Carolina (from Cape Hatteras to the Virginia Commonwealth border) by comparing archived in-situ near and offshore wind and temperature measurements with sea surface temperatures (SST) deduced from observations by the Advanced Very High Resolution Radiometer (AVHRR) on board several of NOAA's Polar Orbiting Environmental Satellites (POES). Near-shore in-situ wind direction, wind speed and water temperature data were recorded by instruments located at the Duck Army Field Research Facility and the NOAA National Data Buoy Center (Buoy #44014, positioned 60 miles off the coast). The data was used to verify the occurrence of coastal upwelling along the northeastern North Carolina coast from July 15th to the 31st of the year 2000.

I. INTRODUCTION

The research efforts conducted by student researchers Jenelle Forde, Bilan Howard, and Mario Oliver on "Historical Observations of Coastal Upwelling Events along the North Carolina Coastline," serve as a foundation for this research. Their study entailed the examination of sea surface temperature imagery over the summer months of June, July, and, August for the purpose of determining the presence of upwelling events along the North Carolina coast, specifically near the locations of Cape Hatteras and the Army Corp of Engineer's Field Research Facility Duck Pier installation. Forde, Howard, and Oliver's research suggests that average wind direction and speed are "good indicators" of possible upwelling.

The ocean is stratified in layers with warm waters on the surface and colder waters beneath. Winds from any particular direction may move surface

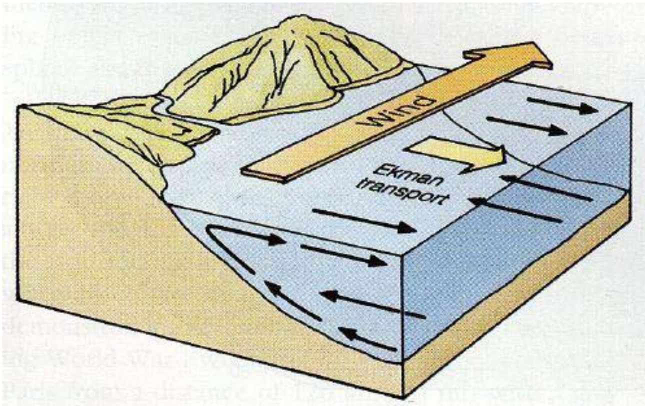

Figure 1.1. Illustration of upwelling phenomena

water (visualized as pushing if the sea is rough or dragging if the sea is smooth). However, as a result of the spherical rotation of the Earth, winds blowing parallel to a coastline with open water lying to the right of the wind direction, will force surface water to move out to sea. (This process due to rotationally induced Coriolis effects is typically called "Ekman Transport.")

In that event, warm coastal surface waters are forced away from the coast and are replaced with cooler waters from lower depths as shown in Figure 1.1. When this displacement occurs, it is said to be an upwelling. Winds must be parallel to the coastline in order for an upwelling to take place. The North Carolina coast is oriented northwest to southeast; therefore, a southeasterly wind would be the driving force for the initiation of a coastal upwelling.

This research is a continuing and more in-depth effort to study and understand the upwelling process and the environmental consequences of such events. Key factors in understanding the physical processes that contribute to coastal upwelling include, water temperature depth profile; wind direction, speed and duration; shoreline geographic orientation; local coastal bathymetry and characteristics of the continental shelf.

Upwelling can have positive and negative effects on marine ecosystems. When cold water moves to the surface and displaces warmer water, nutrient-enriched sediments are carried to the surface as well. This wealth of nutrients causes an increase in phytoplankton reproduction, which in turn triggers population increases throughout the food chain. Increased food supplies become available for local marine life and therefore commercial aquaculture harvests may be abundant. On the downside, upwelling can also cause an increase in the development of harmful algal blooms. As a result of increased marine life activity in a particular area, increased amounts of organic consumption and decay may consequently result in low oxygen levels creating harsh and harmful conditions for aquatic life.

This study is limited in scope and is focused on an examination of archived surface wind and sea surface temperature data acquired by satellite remote sensing instruments and in-situ coastal and offshore sensors. It is also focused on a detailed study of a previously identified sixteen day period (July 15-31, 2000) when upwelling events were probable. This work provides the foundation for research of historical upwelling phenomena off the NC coast and anticipates implementing real-time environmental monitoring to provide information to improve public utilization of the NC coastal environment.

II. METHODOLOGY

Level-three sea surface temperature (SST) image data (archived in jpeg format) for the northeastern North Carolina coastal waters were obtained from the Advanced Very High Resolution Radiometer (AVHRR) on board NOAA-12, 14, 15, 16, and 17 orbiting satellites. These data were acquired from Rutgers University Coastal Ocean Observation Laboratory (COOL) website: ***http://marine.rutgers.edu/cool/***

LViewPro, image processing shareware, was used to determine the sea surface temperature within approximately 25 km and 50 km East of the NC coast at 4 distinct North to South geographic locations (see figure 3.), by attempting to match the RGB triplet color values of those points on the image to triplet values on the associated temperature scales.

In-Situ water and temperature data were also obtained from the sensors located on the half km long pier at the Army's Field Research Facility (FRF) at Duck, NC (36.2 North Latitude and 75.4 West Longitude) and by sensors located on buoy 44014 operated by the U.S. National Oceanic and Atmospheric Administration's (NOAA) National Data Buoy Center (NDBC) and located at 36.5 North Latitude and 74.8 West Longitude, 64 miles West of Virginia Beach, VA. In-situ water temperature data were compiled from the uppermost of 6 temperature sensors mounted at the end-of-the Duck Pier in nominal water depths of 1, 2, 3, 4, 5, and 7 meters. Digital temperatures (which first became available July 15, 2000) were made available by scientists at the FRF.

Hourly wind direction and average wind speed data Duck Pier and Buoy 44014 were obtained from NOAA National Weather Service (NWS) instrumentation at each location and available on the Internet at:
http://www.ndbc.noaa.gov/station_history.php?station=ducn7
and
http://www.ndbc.noaa.gov/station_history.php?station=44014.

This study examined historic data from the July 15-31, 2000. Wind data were compared to SST data to establish a correlation existing between persistent wind direction and upwelling induced coastal temperature changes. sea surface temperature, and wind data were recorded on an hourly basis during the period considered.

Finally, coastal topographic data were obtained for the northeast North Carolina coast from NOAA Bathymetry charts #11555 and #12204, respectively, to determine the presence of ridge-lines orthogonal to the coast line (topographic highs) shown to be contributory to the upwelling phenomena along the NJ coast.

III. RESULTS

AVHRR images from July 15-31, 2000 were examined to determine whether visible signatures of upwelling events could be correlated with the analysis of in-situ wind and sea surface temperature data and also to determine whether any coastal bathymetric dependence could be established on the advent of upwelling.

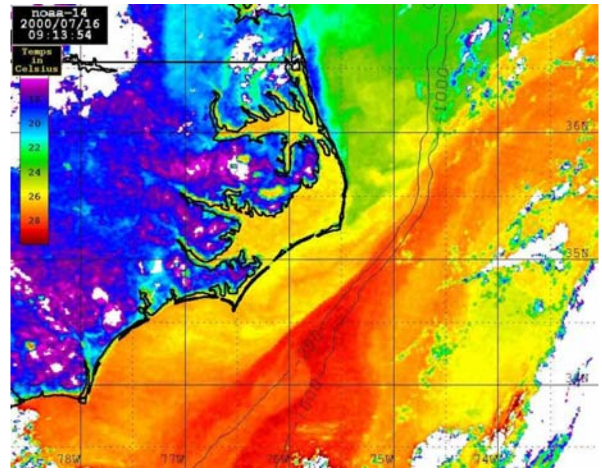

Figure 3.1. AVHRR Sea Surface Temperature (SST) image from NOAA-14 satellite for July 16 at 09:13:54Z. (from Rutgers COOL website)

Figure 3.1 depicts the occurrence of a strong upwelling event. In the figure, cooler sea surface temperatures (depicted in blue) of the water adjacent to the North Carolina coastline are seen to be surrounded by warmer water lying further offshore (shown as green and yellow tints) clearly indicating the presence of an upwelling event. The differential sea surface temperature, observed between coastal and offshore waters in the July 16th AVHRR image, were coincident with sustained winds out of the south observed for several days prior to this date. The spatial distribution of SST evident in Figure 3.1 corresponded to observed SST differentials between on- and off-shore sensors correlated with sustained Winds out of the South. Winds blowing parallel to the shoreline move the warmer surface water eastward allowing cooler water to come to the surface.

Many of the AVHRR images recorded after July 16th through July 31st were indecipherable due to obscuring cloud cover. However, the few images acquired in late July, such as that recorded on July 31st and shown in Figure 3.2, appear to depict the occurrence of a weak upwelling. The sea surface temperature differential does show cooler water located near the coastline and warmer water offshore, but the difference is less pronounced than in Figure 3.1. Moreover, in-situ data for late July including Sea surface temperature and wind measurements appear to confirm the presence of an upwelling event.

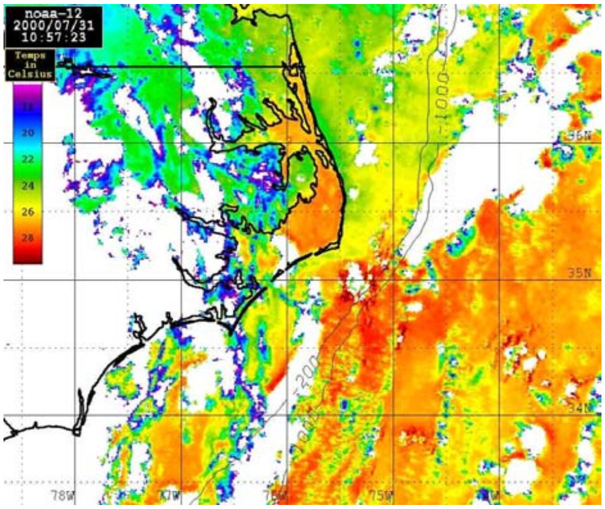

Figure 3.2. AVHRR Sea Surface Temperature (SST) from NOAA-12 satellite for July 31 at 10:57:23Z. (from Rutgers COOL website)

Figure 3.3 is a graphical comparison of hourly, in-situ measurements of coastal wind direction and Sea Surface Temperatures (SST) recorded at the Army's Duck, NC Coastal Field Research Facility. These data are compared to determine whether there is a correlation between winds blowing from the South and a decrease in the coastal sea surface temperature. The comparison includes data from July 16th through July 31st of 2000. Note that the wind direction itself is not plotted, but instead a derived parameter called "Angle-Off-Shoreline" (AOS) measured in degrees. AOS is defined to equal the absolute value of the difference between the wind direction and shoreline orientation (approximately 170º from geographic North). An AOS value of 0º corresponds to a wind blowing out of the South and parallel to the shoreline. When AOS is 0º-45º, the component of the wind parallel to the shoreline is larger than the cross-shore component and therefore most favorable to promoting an upwelling event. Winds whose AOS is between 45º-90º have a non-zero-component of the wind along the shoreline, and are therefore not as effective in producing upwelling phenomena. Winds with AOS between 90º - 180º act counter to the forces that produce an upwelling and therefore prevent their formation.

Also shown in Figure 3.3 is the result (the smooth curve) of applying a Microsoft EXCEL 2nd order polynomial trend analysis utility to the two sets of hourly data: wind direction, (relative to the shoreline) and coastal SST. Figure 3.3 illustrates that winds blowing closer to the shoreline will tend to "push" warm surface waters eastward (out to sea) and lower the coastal sea surface temperature. The trend analysis in Figure 3.3 shows more clearly that SST (shown in red) increases and decreases are correlated with increases and decreases in the AOS (shown in blue).

While Figure 3.3 does seem to indicate the existence of a correlation between AOS and SST, it does not prove that lower temperature coastal waters are correlated with warmer waters seaward. An upwelling event would be characterized by a temperature differential between offshore and onshore SST. Moreover the trend of AOS and SST should be anti-correlated. In other words, SST differential should increase as the wind direction becomes more closely aligned with the shore direction (AOS tends toward zero). This is seen in Figure 3.4 which is a plot of temperature differential (Buoy SST – Duck SST) between a coastal sensor and a buoy sensor about 60 miles due East.

To produce an upwelling, wind from the appropriate direction must be sustained for many hours (or a few days) in advance of the temperature differential becoming apparent. Thus a decrease in AOS would be seen in advance of an increase in temperature differential. This effect is indicated in both Figure 3.3 and 3.4. The sea surface temperature differential (depicted in red) increases as the angle-off-shoreline (shown in blue) decreases. A 2nd order Polynomial trend analysis of the data (such as that performed for the data in Figure 3.3) shows the distinct anti-correlation more clearly.

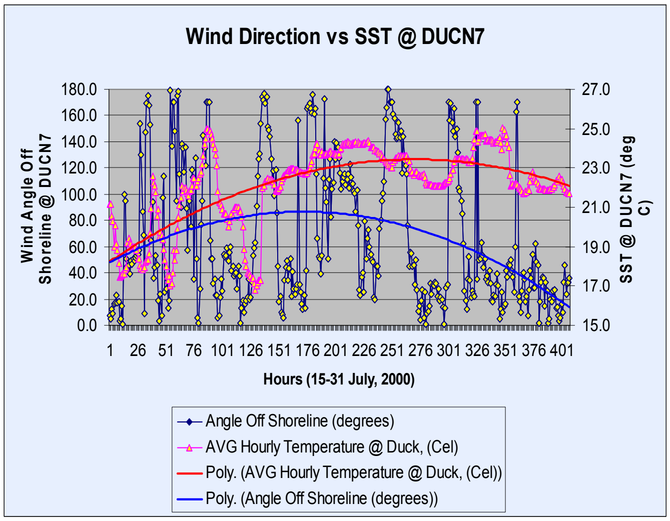

Figure 3.3 Wind Direction (Angle-Off-Shoreline) vs. Sea Surface Temperature at DUCN7 using second degree polynomial trend analysis

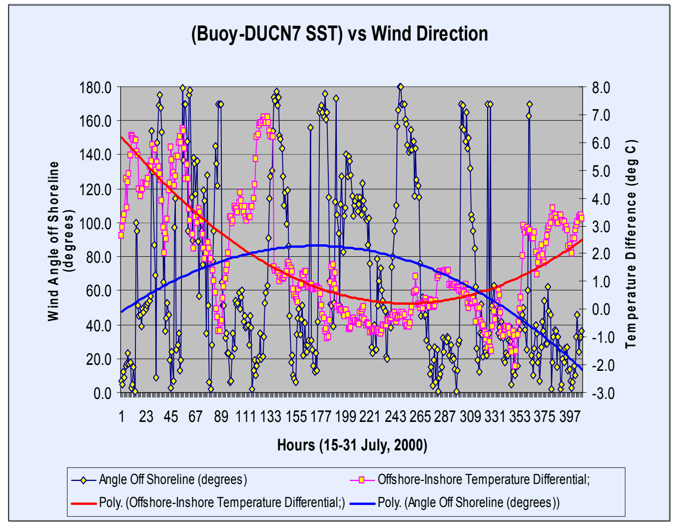

Figure 3.4 Offshore - Inshore Temperature Differential vs. Wind Direction (Angle-Off-Shoreline) using second degree polynomial trend analysis

This occurs because as the wind blows closer to the shoreline it causes the sea surface temperature to increases. When the lines are located further apart as on day two (July 16th) of the specified time period an upwelling event is occurring. This is supported by the AVHRR image (Figure 3.1) of July 16th, 2000. The behavior of these trends near July 31st on the right of the graph also supports the possibility of an upwelling as does the AVHRR image for this date (Figure 3.2).

The Plots of Sea Surface Temperature vs. Wind Direction (Angle-Off-Shoreline) suggest an occurrence of two upwelling events during the July 15th-31st, 2000 time period. The two graphs support the existence of upwelling events indicated in the AVHRR images acquired during the specified time period. The Plots of (Offshore – Inshore Sea Surface Temperature or Temperature Differential) vs. (Angle-Off-Shoreline) provides further evidence the two upwelling events. IN summary, the AVHRR images obtained from NOAA-12 and NOAA-14 satellites confirm the existence of upwelling identified by in-situ data analysis.

IV. CONCLUSION

The in-situ data and AVHRR images established a correlation between coastal upwelling events, associated sea surface temperature changes, and wind direction.

Combining the remotely sensed data with graphs of in-situ data established a method for identifying the date and locale of historical upwelling events. Identifying historical upwelling events: a.) provides a basis for correlating upwelling with chlorophyll-a concentrations, b.) Provides a (historical) means to investigate possible climate change effects along the North Carolina coast, and c.) Establishes ground work for providing near real-time marine environmental conditions effecting local commerce and tourism

V. FUTURE WORK

Along coastlines with bathymetric characteristics conductive to such events, there is evidence of a direct correlation between cold-water upwelling and increased levels of Chlorophyll-α, and the advent of harmful algal blooms (HAB). Future work would focus on developing remote sensing techniques and examining SeaWiFS data to correlate chlorophyll-a concentrations with upwelling events revealed in AVHRR SST imagery and to study multi-band ocean color data for detecting HABs that is associated with upwelling events.

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Observations of coastal upwelling of cold, nutrient rich, oceanic water have been reported along the Mid Atlantic Bight, specifically the coastlines of New Jersey and Long Island (Neuman, 1996, & Glenn et al. 1996). Analysis has indicated that upwelling along the coast of NJ and other coastal regions, wherein cold bottom water displaces warmer surface water, occur on the down-slope side of topographic "highs" or shallow ocean bottom ridge-lines (Glenn et al, 1996). The events themselves are apparently triggered by persistent surface winds blowing out of the South with a component parallel to the local shoreline. In the case of the southwest to northeast running the New Jersey coast, this is most typically seen during periods of southwesterly winds. In the case of the East to West oriented Long Island bight, upwelling seems to accompany winds out of the West.

The portion of the North Carolina Bight South of the Chesapeake Bay entrance and northward of Cape Hatteras, is oriented slightly southeast to northwest therefore, coastal upwelling is expected to be driven by seasonal winds out of the South to Southeast. If such events do occur, they might also occur downwind of topographic highs similar to the upwelling events seen further north. Another geographic similarity between the Jersey Shore and Northeast North Carolina coastline that may impact upwelling phenomena is the proximity to the large drainage plumes of the Hudson River and the Chesapeake Bay that flow out into continental shelf waters and may influence coastal upwelling dynamics.