Coastal sea level response to Hurricane Katrina

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Hurricanes cause changes in sea level through several different mechanisms including: the inverse barometer effect (static response of the sea surface to changing atmospheric pressure); a dynamic response to wind-induced currents; wave setup arising from the generation of wind waves ("radiation stress"); and surface buoyancy flux (precipitation). To evaluate the relative contribution of these factors to sea level variability during Hurricane Katrina, we examined tide gauge, atmospheric pressure, and wind data available through the NOAA National Ocean Service (NOS) data portal, and significant wave height data available from the NOAA National Data Buoy Center (NDBC) meteorological buoy data portal. We use data only from those stations for which "good" time series are available and which are widely distributed along the Gulf of Mexico and Atlantic coast of the United States. Figure 1 shows the location of these in relation to the path of Hurricane Katrina.

The impact of Hurricane Katrina was not symmetric with respect to its path. As correctly pointed out by news media during the event, the right front quadrant of any hurricane has the highest wind speeds (wind was onshore for Katrina) and generates the highest storm surge (see stations to the right of the hurricane track). The left front quadrant normally produces the heaviest rain and causes the greatest fresh water flooding. On the left side of a hurricane, the wind blows in the opposite direction to the direction of the hurricane movement so that the effective wind speed is lower. Since Katrina moved at a speed of about 5 - 8 m/s, the difference in wind speed between the right and left side of the hurricane track at landfall was likely about 25%. Of greater importance to the ensuing storm surge is the fact that, during landfall, the cyclonic winds of Hurricane Katrina were directed onshore on the righthand side of a hurricane and offshore on the lefthand side. As a result, the wind produced a marked rise in sea level to the right of the storm's path and a moderate lowering of sea level to the left of the path. This effect can be seen in the sea level plots for the tide gauges located at the coast facing Katrina's path, from Corpus Christi, Texas, to Apalachicola, Florida (Figure 2a). All stations to the right of the storm track, even those furthest from the storm centre, experienced a higher sea level rise than any station to the left of the track. Sea levels observed at stations to the left of the hurricane track increased due dropping atmospheric pressure, heavy precipitation, and wave set-up, but this effect was strongly mitigated as a result of seaward oceanic transport by the strong offshore winds.

Away from the hurricane centre, sea level change is most strongly effected by the wind stress. Even a moderate wind can produce a significant sea level change if the forcing is applied long enough. As indicated by Figure 2b (Gulf of Mexico stations), sea level first dropped 0.5 m below normal when the wind was blowing offshore, then rose 0.5 m above normal when the wind became onshore. This sequence occurred during a period when the wind speed observed at the associated meteorological stations did not exceed 10 m/s.

The highest registered sea level rise of 3.5 m occurred at Ocean Springs, Mississippi. This height was the last record before the instrument failed, just before the second landfall. There are no data for this station after this point. For Waveland, MS, the data ended even earlier, just before the fist landfall. The peak flood level was apparently missed at this location. This is confirmed by NOAA NOS "Hurricane Katrina Preliminary Water Levels Report" (see references for the web link). As a consequence, it not possible to use the coastal sea level gauges to determine the height and location of the maximum sea level for the region affected by the hurricane. At best, we can state that the maximum sea level height at the coast occurred within 100 km of the hurricane centre to the right of the path, and likely exceeded 3.5 m. According to numerical models which use wind speed and local bathymetry as input parameters, the maximum sea level rise at the Mississippi coast (around Ocean Springs) was simulated to reach 7 to 9 meters, which would be the highest storm surge in U.S. history. (cf. Experimental Storm Surge Flood Models Website of Louisiana State University at http://hurricane.lsu.edu/floodprediction/).

The relative contribution from the "inverse barometer" effect decreased with the distance from the hurricane path. This effect seems to have been responsible for 60-70% of the sea level rise observed at stations closest to the hurricane path (Grand Isle, Pilots Station East, Louisiana) but only for 10-20% of the rise observed at the stations situated ~150 km and more from the storm track. The atmospheric pressure drop was clearly much weaker in the outer regions of the storm than in the centre, although the storm surge was still significant.

Information on wind waves at nearby meteorological buoys can be found on the National Data Buoy Center (NDBC) website. However, the data from all NDBC buoys, independent of their location, have a gap between August 29 ~15:00 UTC and September 2, 2005. Since the NDBC (located in the Stennis Space Center in Mississippi) was only several kilometres from Katrina's path, the data collection facility was obviously put out of service due by the hurricane and its aftermath. Because of the lost data during the peak of the hurricane, analysis of wave impact is problematic. Nevertheless, most of the stations to the right of the hurricane path (Figure 2a) reveal a secondary sea level peak which occurred before the main surge, at approximately 00:00 UTC on August 29. These peaks coincide with the peak in significant wave height at near-by meteorological buoy 42007. This suggests that wave set-up may play a significant role in determining sea level rise during this storm.

Hourly precipitation data on U.S. stations can be obtained from NOAA National Climatic Data Center website: http://lwf.ncdc.noaa.gov/oa/climate/climatedata.html#hourly
Because there is no free access to these data, we do not use them for this report.

A formal multiple-input regression analysis is not expected to yield useful results because of the high inter-correlation of the various input signals. The considerable amount of missing data compounds the problem.

A by-product of this work is that a Matlab routine is now available for downloading sea level, tidal prediction, and meteorological data for a number of NOAA NOS stations from the Internet.

References:

NOAA National Ocean Service (NOS) sea level data:
http://co-ops.nos.noaa.gov/data_res.html

NOAA National Data Buoy Center (NDBC) meteorological buoys data:
http://www.ndbc.noaa.gov/

NOAA National Climatic Data Center (NCDC) precipitation data:
http://lwf.ncdc.noaa.gov/oa/climate/climatedata.html#hourly

NOAA NOS Hurricane Katrina Preliminary Water Levels Report:
http://co-ops.nos.noaa.gov/publications/NOS_Preliminary_Water_Levels_Report_Hurricane_Katrina_2005.pdf

USA TODAY "Hurricane Science" page (schematic diagrams and basic description of hurricane structure and terminology):
http://www.usatoday.com/weather/graphics/hurricane/2005_storms/flash_leader.htm?strmName=Ophelia&strmNum=strm16&tabName=a

Experimental Storm Surge Flood Models Website of Louisiana State University:
http://hurricane.lsu.edu/floodprediction/

Figures

Figure 1. Location of tide gauges and meteorological buoys used in the analysis. Circles denote 3-hour positions of the hurricane center with atmospheric pressure in millibars and UTC time. The diameter of a given circle is related to the category of the hurricane according to Saffir-Simpson scale. Position at the beginning of each day is shaded.

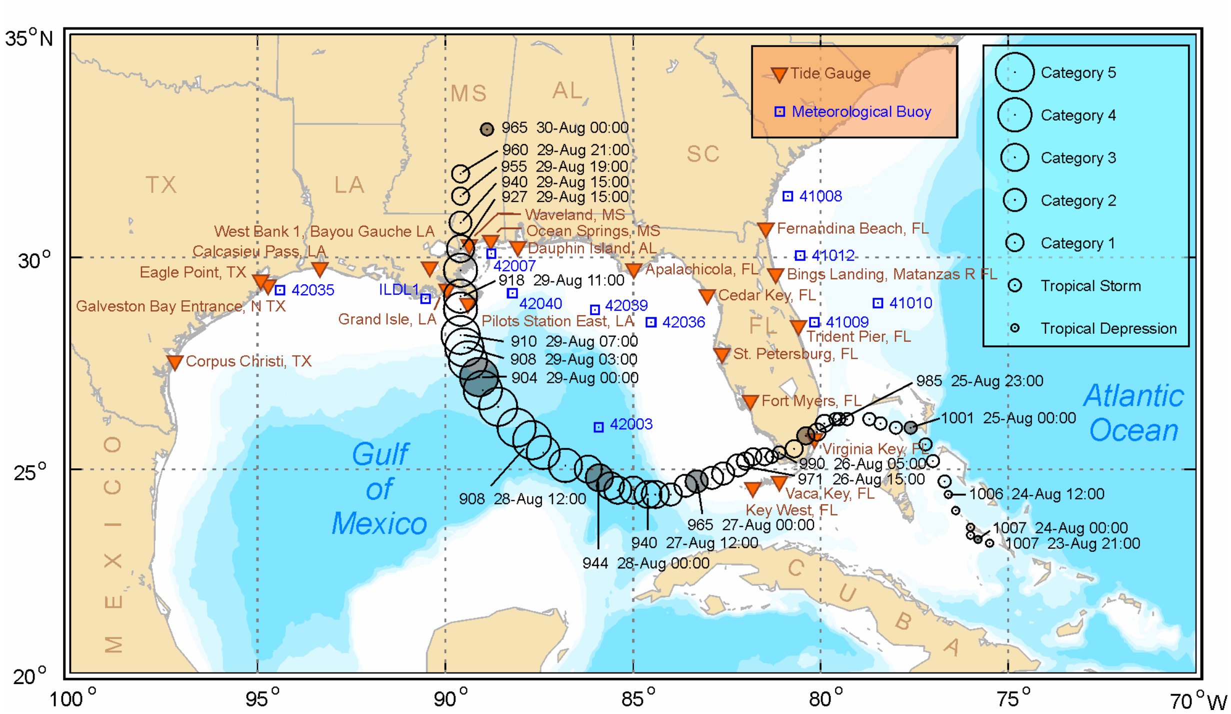

Figure 2a. Sea level, atmospheric pressure, wind, and significant wave height for selected stations along the Gulf Coast. Significant wave height is taken from the nearest meteorological buoy (buoy code is given in parentheses next to the station name). Vertical dotted lines denote landfall at Florida, transit of the hurricane over the Florida Keys (Key West), the first landfall on Louisiana, and the second landfall (around Waveland, Mississippi). Atmospheric pressure and sea level are scaled so that the change in atmospheric pressure corresponds to the sea level change that would arise from the inverse barometer effect.

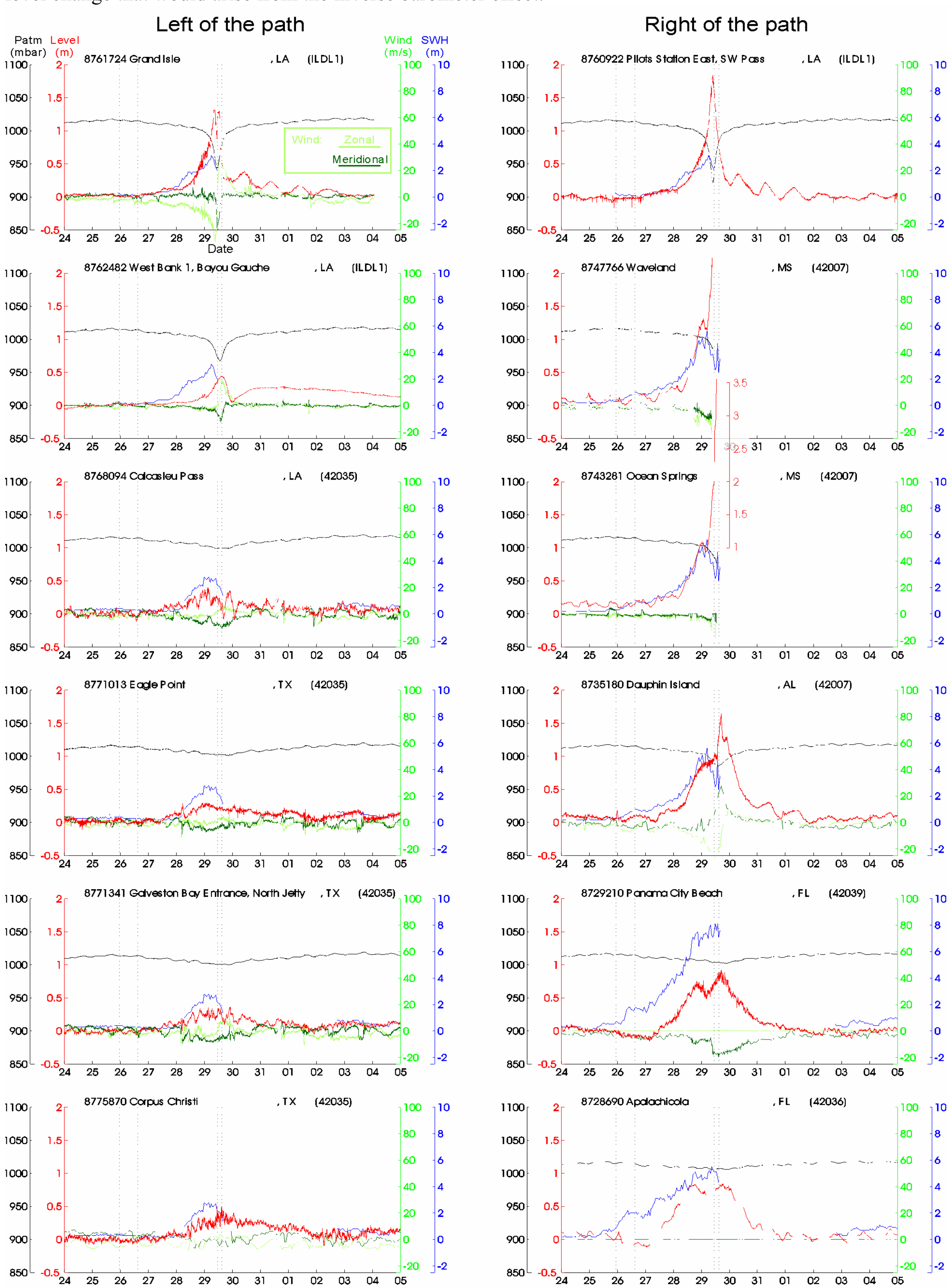

Figure 2b. Same as in (a) but for Florida stations.