Floating Turbines Can Reduce Gulf of Mexico Hurricane Threat

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I. Loop Current Dynamics

Ocean surface currents circulate clockwise (CW) in the Northern Hemisphere and counter-clockwise (CCW) in the Southern Hemisphere. The western boundary currents, guided by the continental land masses, are concentrated and fast-moving. The North Atlantic's western boundary current has a most interesting interaction with the North American coastline. Most of it passes through the Caribbean Sea and enters the Gulf of Mexico (GoM) via the Yucatan Channel. It sometimes intrudes far into the Gulf and then loops around to the right, returning to the Cuban coast, where it makes a left turn into the Florida Straits. The looping section is called the Loop Current (LC). From the Florida Straits, the current turns north and is guided by the channel formed by the Florida coast on the left and the Bahama banks on the right. This last portion is here called the Florida Current Channel, and it ends at Settlement Point on Grand Bahama Island. For the purpose of this paper, we consider this point to be the beginning of the Gulf Stream.

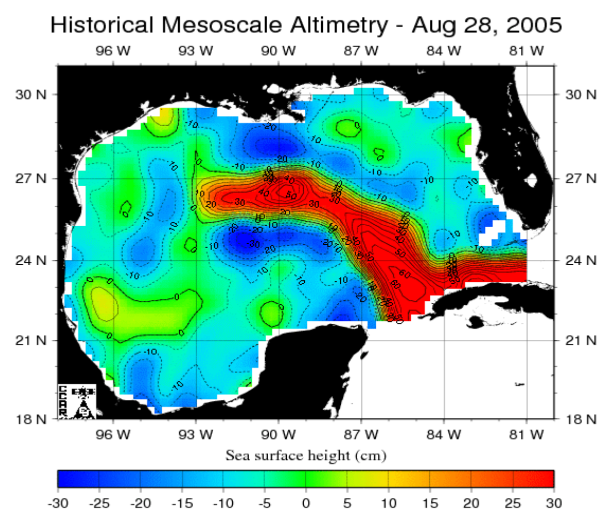

Figure 1. Sea surface height during Hurricane Katrina.

Figure 1 is reproduced from the Gulf of Mexico NearReal-Time Altimeter Viewer website [1]. Pictures for any date from the start of 1993 to the present are available. Figure 1 shows the sea surface height contours during Hurricane Katrina. Contours in the red area denote sea surface heights as much as 70 or 80 cm greater than those outside the red area. The spacing between the contours is inversely related to stream velocity. The center of the LC path is approximately where the contour lines are closest together. The scale of the figure is too small to indicate the exact location of the LC, but we can see that it runs around the outside of the hill of water collected inside the loop.

The Coriolis force creates this hill by deflecting water to the right of the LC path. The deflecting force is proportional to velocity, and due to turbulent shear friction, the fastest water is at the top of the flow. Because of thermal stratification, the lowest density and warmest water is at the top of the stream, so the hill inside the loop is topped by a layer of warm water 200 or more meters deep. The top surface of this thick layer of warm low-density water is able to stand higher than the surrounding sea surface without creating extra pressure at the bottom. The scale of the picture is 111 km per degree of latitude, so it is apparent that the deep pool of warm water can have a large area when the LC intrudes a large distance into the GoM.

The green or blue color outside the loop indicates lower surface height. The surface here may be warm due to solar heating, but the warm layer is thin and is not so effective in energizing hurricanes. Hurricanes generally increase in intensity as they pass through the red area and decrease in intensity as they pass through the green or blue areas. Katrina had only a short distance to go when it left the red area and headed for New Orleans with devastating effect.

Figure 2 shows the bathymetry that guides the current in the Yucatan Channel, Florida Straits, and Florida Current Channels. Instead of the shore lines, the edges of the continental shelves are shown. The location of the Florida peninsula is indicated by the letter F. The Bahama Banks are seen to the right of the Florida shelf. Settlement Point is indicated by SP on the west shore of Little Bahama Bank. A basic premise of this paper is that the Yucatan Channel flow, the LC, the Florida Straits flow, and the Florida Current are driven by gravity, i.e. that the mean sea level (MSL), defined as the sea level with daily tidal variations averaged out, is higher at the entrance to the GoM (measured at Grand Cayman Island, GC in Fig. 2) than the MSL at the Settlement Point outlet of the Florida Current channel. The Yucatan, Florida Straits, and Florida Current channels all have fixed side walls and a depth equal to that of the shallowest segment (no flow below that depth due to stratification) so they obey the laws of open channel flow. The hydraulic gradient is proportional to the square of the mean velocity [2]. The LC remains narrow throughout its length, and its depth is the same as the other segments due to stratification, but its path, and particularly its length can change. So when the difference in MSL between GC and SP changes, the volume transport does not seem to change. Instead, the LC length changes, and we have three years of MSL data [4] that overlaps the satellite altimeter pictures to support this hypothesis.

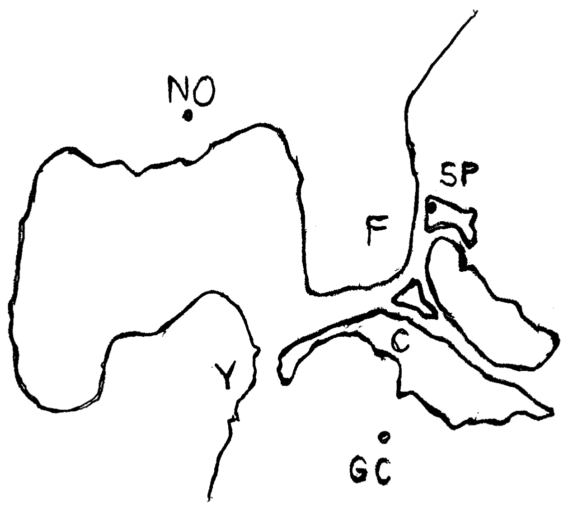

Figure 2. Bathymetry that Guides the Currents.

The justification for believing that the LC length increases and the volume transport does not change in response to increased hydraulic head (drive) is as follows: The LC is only a very short segment of two very long paths. One path encircles the North Atlantic Ocean and the other follows the meridional overturning circulation between the Arctic and the Antarctic. There are many dynamic relationships along these two paths that determine their respective volume transports (flow rates). The hydraulic head of the LC cannot be expected to exert an appreciable effect on this global transport. Because the LC cannot influence the volume transport, it changes length in response to changes in the LC hydraulic head. The turbulent friction resistance of the LC segment is proportional to its length, so the open channel flow relation between hydraulic head and the square of the volume transport can be satisfied by the length change.

The LC does not have physical side walls, but it remains narrow throughout its length. The Coriolis force tending to divert water to the right of the path is balanced by the upward surface height gradient of the hill of warm water confined inside the LC path. I believe that these two opposing forces tend to squeeze the LC into a narrow jet-like path. Turbulent shear between the moving current and the still water alongside and below the stream provides the friction resistance of the LC path segment.

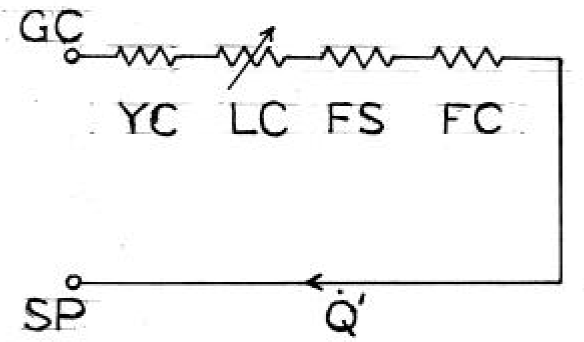

Figure 3. Electric Circuit Analog of Ocean Current System.

In the Figure 3 electric circuit analog, resistors YC, LC, FS, and FC represent respectively the Yucatan Channel, Loop Current, Florida Straits, and Florida Current segments of the ocean current path. The electric current Q' represents the volume transport (cubic meters per second) of the ocean current. The voltage difference between terminals GC and SP was intended to represent the mean sea level difference between Grand Cayman Island and Settlement Point until it was realized that Coriolis effects couple some kinetic energy from the Earth's rotation into the system. Figure 3 must be modified to include this new discovery.

In turbulent shear flow, the sea level difference is proportional to the square of the volume transport. The analog resistors are therefore nonlinear: the voltages are proportional to the square of the current. The arrow through LC indicates that the Loop Current length can change and the sea level difference driving it is proportional to its length. The other three segments do not change.

The LC length can increase gradually in response to increased hydraulic drive, but it never shrinks gradually in response to decreased hydraulic drive. Instead, the LC responds to decreased drive by pinching the sides of the hairpin loop together. Then some of the LC flows across this short circuit while the rest of the LC goes around the full path. If the drive continues to decrease, more of the current takes the short path while the tip segment closes on itself and forms a ring. The current continues its CW circulation around the ring because of inertia. The ring may separate from the LC and drift westward. If the drive increases after this separation, the shortened LC simply expands. If the drive increases before the separation is complete more water takes the longer path, less takes the short path, and the larger loop is restored. Mature LC paths usually have two or more peaks with some closed contours around them, indicating some inertial circulation.

Monthly average MSL data is available [3] for Grand Cayman and Settlement Point for 1985 through 1996. Dates of LC ring separations are available [4] for this period, in addition to altimeter plots starting in 1993. Examination of the data indicates that LC shortening events (ring separations) coincide with decreases in sea level drive. Furthermore, the sea level difference between GC and SP changes about 20 cm during each cycle. Multiplying this height difference change by the water density (1025 kg/m^3) times the acceleration of gravity (9.81 m/s^2) times the volume transport (30 million m^3/s on average) gives a power change of 60 GW.

This means that maximum intrusion of the LC dissipates 60 GW more hydraulic power than is dissipated when the LC goes directly from Yucatan to the Florida Straits. If we use floating turbines to absorb the extra 60 GW when it is available, we would have no LC intrusion and no pool of deep warm water to energize hurricanes. Assuming an equal split between useful electric power and dissipation due to drag, we would have 30 GW of useful power. This is the equivalent of 30 big nuclear power plants.

Tides flow in and out once or twice per day and the water is transported up- and down-stream by shallow-water waves. Channel depths less than 50 meters carry little water. The wave velocity for 50 meter depth [5] is 22 m/s and it is proportional to the square root of the channel depth. Therefore the 1036 km between Yucatan Channel and SP can be traversed in much less than 0.02 month, so the system should settle down between monthly average MSL samples. Therefore the MSL monthly averages can be considered to act instantaneously on the water transport.

II. Turbine Placement and Design

Turbines must be placed where the velocity is high in order to produce the greatest electrical power for a given rotor size. The Yucatan Channel, Florida Straits, and Florida Current would satisfy this requirement. These locations are vulnerable to severe hurricanes, even though a sufficient number of turbines can reduce the hurricane threat to the Gulf Coast. The high-velocity water is near the surface, so when producing power, the turbines are submerged, but not deep enough to protect them from hurricanes. Therefore, the design must include means to lower them into calmer water. Also, it may be necessary to lower them into lower velocity water to reduce drag when the hydraulic head is low. The situation is far from ideal in terms of supplying base load electric power. We get appreciable power when the hydraulic drive is high, but we get progressively less as the drive decreases and we have to reduce the turbines' interference with the current flow.

A better use for the electric power is distillation or reverse osmosis of saline water to supply fresh water for the Antilles Islands and future mainland needs. The Antilles Islands presently rely on petroleum to provide energy for desalination. The water in the island passages is too slow for turbines. They must be in the Yucatan and Florida passages where the flow is concentrated and fast. The desalination plants must be near the turbines. Articulated Tug Barges can economically transport the fresh water to where it is used. The barge can be left at the port to supply water while the tug picks up an empty barge on the way back to the desalination plant.

The shaft power available [6] from an axial-flow turbine rotor is given by

Power = (power coefficient)(0.5)(density)(velocity cubed)(swept area of rotor) (2)

The power coefficient in (2) is the fraction of the kinetic energy transport intercepted by the rotor's swept area that is actually converted into shaft power. A typical value for a good water turbine seems to be 0.45 [7]. A rotor diameter of 20 meters is a practical starting point for the design. We can count on currents of 1.8 m/s in locations where we would put the turbines. The shaft power given by (2) is 423 kW. It would require about 70,900 of these turbines to convert 30 GW of hydraulic power into shaft power. This is half of the 60 GW which we must absorb in order to prevent the LC from intruding into the GoM. The other 30 GW is assumed to be dissipated in drag of the turbines and associated equipment plus eddies shed by the mooring cables.

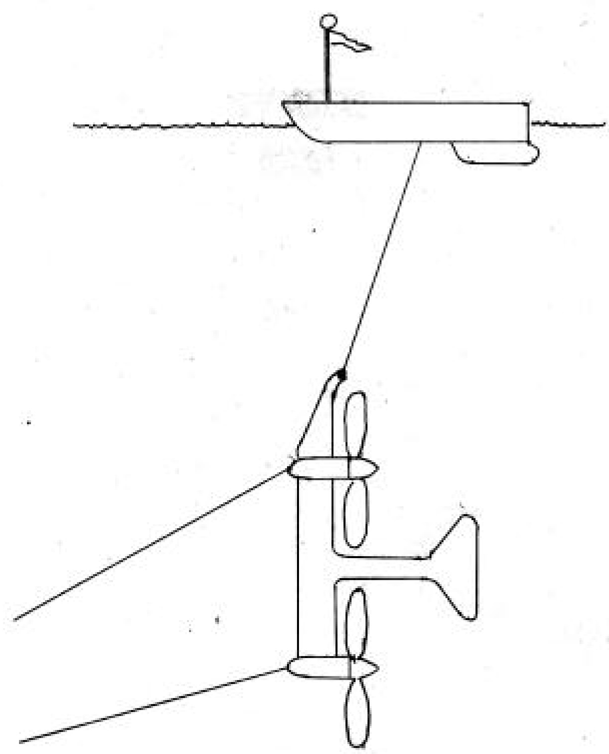

Figure 4. Side view of two-turbine floating unit.

We want to minimize the weight of the rotor because the design presently being considered uses two turbines, one above the other, suspended from a float on the water surface, as sketched in Fig, 4. Each rotor is on the downstream end of a long nacelle and the respective alternators are in the upstream ends. The gear boxes, if the alternators are not direct drive, would be somewhere in between. The rotor blades are narrow, so they must turn at sufficient speed to harvest the power passing through the circle swept by the blades multiplied by the power coefficient. A two-bladed rotor would probably be lighter than a rotor with more blades, and it would turn at the greatest speed. This minimizes the shaft torque, resulting in the least massive shaft and bearings.

The turbines rotate in opposite directions in order to cancel the torque on the assembly. The weight of the turbines hanging from the suspension point, especially the lower turbine, further prevents any tendency to roll due to torque unbalance. Automatic means must be provided to remove the electrical load from one turbine if the other one fails.

The single anchor rope is split at a point upstream of the turbines, and the two branches are attached respectively to the upstream ends of the two nacelles. Just to generate the 423 kW calculated from (2) requires a tension whose horizontal component is 423000/1.8 = 235000 Newtons. (Power = force times velocity.) Drag of float and turbine structure adds to this. The two-point attachment should stabilize the turbine assembly against pitch. The rigidly mounted vertical tail surface is intended to stabilize against yaw.

The suspension rope is wound on a winch whose motor, gears, and controls are housed in a waterproof compartment in the surface float. The turbine assembly would be near the surface when producing power, and the winch would lower it to a safe depth in preparation for a hurricane. Modern ropes have enough stretch or elasticity to act as an isolating spring to decouple the turbine assembly from the heaving and other motions of the float. Winch and control power can be provided by a storage battery charged by a PV panel on board the surface float. The PV panel must survive a hurricane but need not operate during the storm.

Fig. 4 shows a concept that has been heavily influenced by the design of *SeaGen* by Marine Current Turbines, Ltd [7]. This is a pair of turbines installed in the Narrows between Strangford Lough and the Irish Sea, just south of Belfast. It has been producing 1.2 MW for the grid. Fig. 4 amounts to *SeaGen* turned on its side and suspended from a surface float. The Fig. 4 stream velocity of 1.8 m/s is lower than their 2.4 m/s, and the power output scales as the cube of the velocity ratio. Our rotor diameter is 20 m compared to their 16 m, and the power scales as the square of the diameter ratio, resulting in 0.84 MW compared to their 1.2 MW. The longer rotor blades and lower stream velocity might have compensating effects so that the rotor weight might turn out to be similar. The same reasoning might apply to the alternators and the rest of the structure. The next task is to calculate drag forces, lift forces, and rope tensions in order to determine whether the tethered suspended structure is adequately stabilized against pitch, roll, and yaw.

III. SUMMARY

The intrusion of the Loop Current into the Gulf of Mexico is a major cause of the hurricane threat to the Gulf Coast, and it can be reduced by absorbing excess hydraulic drive power with floating turbines. The magnitude of the hardware requirement and the difficulty of its implementation require that estimates be based on reliable data. But tide gage readings on Grand Cayman Island stopped in 1996, probably because they were no longer needed for mosquito control. The readings must be resumed with funding from interested parties. The work reported here could lead to a major advance in our understanding of the LC dynamics and a valuable increase in Gulf Coast safety.

REFERENCES

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