Management of Cyclonic Activity
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Abstract

Based on realistic estimates of geophysical conditions, we demonstrate that the intensity of a hurricane may be diminished before reaching landfall, and under other circumstances, might be quenched in an incipient stage. It will be shown that with present-day technology, it is possible to mix the cold deep ocean with the warm surface layer sufficiently, and in a timely manner, in order to decrease cyclonic intensity. Two strategies will be presented: (1) In a manner similar to hurricane weakening by landfall, a virtual early landfall is created on the hurricane path, before true landfall; (2) An identified tropical depression might be quenched, by cyclonic or anti-cyclonic means, and timely intervention.

Estimates of the power needed to perform the needed ocean mixing, in a timely manner, show that this might be accomplished by employing a sufficient number of high-performance submarines. The achievement of this goal is made possible by an unusually high coefficient of performance, $O(10^4)$. The destructive power of the hurricane is a function of a hurricane’s maximal wind speed, $V_m$. It will be shown that even a 20% reduction in this wind speed produces a ~50% reduction in destructive costs.

On the flip side of these considerations, there is the possibility of using such means, under favorable circumstances, to initiate rainfall for relief of drought areas.

Novel vessel modifications are introduced to achieve the mixing process

It is the contention of this paper that a practical framework now exists for sensibly exploring means by which to reduce the tragedy and devastation caused by hurricanes.

1. Introduction

To paraphrase the description of another human calamity (Mukherjee 2010), a hurricane (cyclone, typhoon) is the emperor of all meteorological disasters. With cyclonic diameters approaching a thousand-miles, it is huge, and with estimated energies of order $10^{19}$ Joules, equivalent to roughly 100,000 medium-size atomic bombs (Monin 1972), it is a monster!

Hurricanes are fueled by radial inflow of saturated warm spray, collected at the sea surface, into the low-pressure core of the eye. This provides energy that escalates the cyclonically upward spiraling of the resulting intense vortex. The process has been likened to a Carnot cycle (Emanuel 2003; Emanuel 1991). Beyond this, the hurricane is meteorologically steered dynamically by the atmosphere. Thus a true depiction of hurricanes requires the interaction oceanography and meteorology, both well studied subjects (Pedlosky 2013). The present investigation explores methods which interfere with the fueling role of the ocean, and is thus purely on oceanographic in content. High-profile, meteorological attempts for altering hurricanes, in the last century, termed STORMFURY (Willoughby et al. 1985), were deemed to be a failure.
Any attempt to modify this monster might seem foolhardy. Nevertheless, on reaching landfall, a hurricane is removed from its energy source, and its intensity decreases. The temporal landfall decay of intensity, as measured by maximal hurricane velocity, \( V_m \), is well modeled by (Kaplan and DeMaria 2001).

\[
\frac{dV_m}{dt} = -\frac{V_m}{\tau}; \quad \tau \approx 10 \text{ hr}.
\]  

Thus, roughly 10 hours after landfall, the maximal hurricane velocity falls by more than half. Also, it is an empirical fact that a hurricane cannot form unless the sea surface temperature (SST) is greater than 26°C, (Gray 1979). The possibility of creating an artificial landfall will be explored by the cooling a specified portion of the hurricane’s ocean track, in advance of true landfall. Tropical depressions are precursors of hurricanes, and thus, a second strategy will be to interfere this development.

The aim of this study is to explore practical means for managing ocean conditions in ways that will mitigate the intensity of cyclonic events.

2. An Example Calculation

As a nominal calculation, consider a hurricane of eye of diameter ~30 miles, traveling at a speed of ~12 mph, over the North Atlantic. A warm ocean surface layer lies above a cold deep sea, and the transition from the surface layer to the cold sea below is referred to as the thermocline (Pedlosky 2013). This is depicted in the figure below for the Caribbean, the Gulf of Mexico, and the North Atlantic. The representative calculation will be performed for the case of a North Atlantic hurricane (NOAA 2009).

Figure 1. Three different thermocline locations as they typically appear in the month of August.
For illustration consider a square meter column of seawater spanning the surface layer and thermocline, as modeled in the left panel of Figure 2. The aim is to mix the column, to obtain the lower temperature uniform column shown at the right. The argument is informal and based on reasonable estimates.

Figure 2. Left column: The case of the North Atlantic, with upper layer $H_u = 20$ m, and temperature $T_u = 27^\circ$C; the lower layer $H_l = 50$ m, and at a temperature of $20^\circ$C. Right column: represents the uniform mixed upper and lower columns. Both columns have 1 m² cross-section.

If the heat capacity is taken as a constant, the mixture temperature reduction is found to be

$$T_u - \langle T \rangle \approx 5^\circ C,$$

a decrease greater than usually needed to reduce the surface layer to be less than $26^\circ$C.

The difference in potential energies of the two columns of figure 2 represents the minimal needed work, $W$, to obtain the mixed right-hand column

$$W / m^2 = (\rho_l \rho_u) g \frac{H_u H_l}{2},$$

which for $\rho_l = 1027$ kg/m³ & $\rho_u = 1025$ kg/m³ yields

$$W / m^2 = 10^4$ Joules.$$

Emphasis is on the word *minimal*, (2.3) is a lower bound on the required work needed for mixing. We will show in the following, through sound dimensional arguments, that there is good reason to believe that this is a ballpark figure.
To underline the consequences of this result, note that this is equivalent to the energy needed to light a 200 W bulb for a minute. This calculation is key to further applications, and informs us that since,

\[
(\rho_l - \rho_a) / \rho_t \approx .2\% ,
\]

relatively little work is required in the mixing. As discussed below this is due to an extremely high COP (coefficient of performance). Also see (Winters et al. 1995).

A Virtual Landfall

Consider the following quotation: “a 2.5° C decrease in temperature near the core of the storm (hurricane) would suffice to shut down energy production entirely” (Gallacher, Rotunno, and Emanuel 1989). The 10 hour duration suggested by (1.1) implies that if we consider a nominal track area of 30 miles × 120 miles ≈10^{10} m^{2}, then (2.3) implies that to achieve mixing for the proposed virtual landfall requires a minimal energy input of

\[
\bar{W} = 10^{12} \text{ Joules} ,
\]

is required. This energy is equivalent to that of a modest-sized atomic bomb.

The likely operating depth of the submarines, about 100-200 feet below the surface, and that this depth a classical result (Lamb 1945) shows that this poses little danger, making submarines ideal for delivery of the needed mixing. The Russian Shark class nuclear submarine has a power rating of ≈2×10^{8} Joules/sec (Naval-Technology.com 2011), which is representative of nuclear submarines reactors. This is equivalent to the output of the power station of a small city; a nuclear submarine is an ocean going power station. For the 10 hours (=3.6×10^{4} sec.) duration needed to create the virtual landfall, this amounts to a total energy of ≈10^{13} Joules. It follows from (2.5) that at least 10 submarines might be required to create the desired virtual landfall.

Further considerations

Cold sea water, raised from the depths, and released at the sea surface, falls back to its level, unless quickly and thoroughly mixed, say by turbulence, the most efficient mixer. Based on typical US nuclear submarine specifications (Virginia and Ohio class), a sub’s beam is about 40 feet and its speed is estimated at ~40 mph. Thus, a typical Reynolds number, \( Re \), is \( \approx 10^{8} \), which implies a fully turbulent wake starting with the 40-foot diameter of a Virginia class sub..

Nothing in the present deliberations suggests that a hurricane can be shut down, rather the present focus is on diminishing the intensity, \( V_m \) of a hurricane. To explore this further we observed that wind force is proportional to \( V_m^2 \). However, hurricane damage is proportional to the rate of work, i.e., power, and therefore proportional to \( V_m^3 \). This distinction is central to any damage calculations. For example, under the hypothesis that \( V_m \) can be diminished by 20%, then it is the case that costs are halved!
Estimated hurricane costs to world economies can vary from tens of billions to tens of trillions of dollars, depending on the criteria is used in the study (Kahn 2014; Mendelsohn and Sauer 2011). Thus, reducing costs by half takes on profound economic significance.

Coefficient of Performance

Elementary thermodynamic arguments (Fermi 1956) show that for the nominal 30-mile × 120-mile ocean area to be cooled, not by mixing, but by heat removal, say by a Carnot cycle and by 5°C, to a modest depth of 20 meters, would require an energy,

\[ dE \approx 4 \times 10^8 J, \]

up to a proportionality constant. On the other hand, the present proposal accomplishes this by making use of available deep cold water that is lifted and mixed with the warm surface water, with a calculated work \( \bar{W} \), (2.5).

This implies that the coefficient of performance is

\[ \text{COP}_{\text{cool}} = \frac{dE}{\bar{W}} \approx 10,000, \]

which is extraordinary compared to a COP of 2 or 3 for a conventional heat pump. At the heart of this energy leverage is the very slight increase in ocean density with depth.

Mixing Efficiency

The calculation of \( \bar{W} \), (2.5), is based on achieving the right panel of Figure 2, and as greatly emphasized, this only represents the least required work. To address the question of the efficiency of the proposed mixing denote the true work needed to accomplish the required cooling by \( W_T \), then dimensional reasoning suggests that

\[ \frac{W_T}{\bar{W}} = f(\varepsilon, \text{Re}), \]

where,

\[ \varepsilon = \frac{\rho_l - \rho_u}{\langle \rho \rangle}, \]

is the density factor, and \( \text{Re} \), the flow Reynolds number. \( \text{Re} \) estimates imply that the flow is fully turbulent. In the absence of a density gradient \( W_T = \bar{W} \). To see this imagine that the lower portion in the left panel of figure 2 is dyed black, and the upper is colorless. After mixing the right panel would then be a shade of gray. Dye is a passive scale or, and in view of the high \( \text{Re} \) is mixed without additional work (Sreenivasan 1991). Although this does not address the issue of efficiency, it does suggest that the additional work, needed to achieve full mixing in the presence of the density gradient as given by (2.8), under the limits \( \varepsilon \downarrow 0 \& \text{Re} \uparrow \infty \), becomes

\[ W_T \sim \varepsilon \times \bar{W}. \]

(2.10)
The appropriate proportionality constant requires experiment, but (2.10) suggests that our calculations are not off by more than a factor of 2.

**Submarine Modification**

Nuclear submarine design is highly influenced by stealth demands, i.e. the need to avoid wake detection by satellite imaging. The present application is free of this constraint, and to the contrary, there is a desire to have the largest possible wake. The only size limitation is the modest requirement that propeller tip speed must remain below the sound speed of seawater.

It is proposed that the submarine modification include a variable diameter propeller, starting with the beam diameter of \( Do \sim 40 \) feet. Therefore, turbulent diffusion and the action of the propulsion system implies fully-developed turbulence across the wake. Wake growth, \( D \), with distance downstream, \( X \), is given by

\[
D / Do = 1.25 \times (X / Do)^{22},
\]

an empirical formula (MERRITT 1972) . This predicts that after one sub length, \( \sim 450 \) feet, the wake diameter is \( \sim 100 \) feet. Under this scenario, the work done in lifting the heavier deep ocean water is subsumed by turbulence

**An Example Scenario**

Consider Dorian, the devastating 2019 Atlantic hurricane. Retrospectively, the precise hurricane path is known. Dorian’s early development was determined by the trade winds that brought Dorian, as a tropical storm on an ocean path that transformed it to a category 4-5 hurricane when it reached the Bahamas on September 1, near Abaco Island. The last leg of Dorian’s Bahamian path brought it to a stagnation point, where it lingered for two days, all the while churning up cold ocean water. This reduced its intensity, a negative feedback effect (Bender, Ginis, and Kurihara 1993) (Bender and Ginis 2000). As a result, when it left the Bahamas, it was weakened to a category 2 hurricane. This was the situation as reported by NOAA. Subsequent northerly hurricane movement, was determined by the Westerlies and other natural conditions, that ultimately restored its intensity to a category 4-5 hurricane.

Had the framework proposed here been in place, the path to the Bahamian stagnation point would have been replaced by a cooled surface layer, formed by a submarine-churned deeper cold ocean, a half day in advance of Dorian’s arrival, thus possibly then arriving as a category 1 or 2 hurricane. Further, during the last day of Dorian’s milling around near Abaco Island, submarine-pack churning of deep cold ocean water would be continued. As calculated here, the now weaker Dorian would further be reduced by half again according to (Kaplan and DeMaria 2001) and thus the devastation is reduced by \( \sim 1/8 \). In toto, the prediction is that Dorian would have left the Bahamas no worse than when it left Halifax, Nova Scotia, four days later, as a tropical storm.

3. Quelling of Tropical Depressions

The earth may be viewed as a sphere that is rotating counterclockwise in the northern hemisphere and clockwise in the southern sphere. Vortex dynamics on this sphere has been
considered in the literature, see (Newton 2013). The earth, as a rotating sphere, is a Riemannian manifold, and therefore may be regarded as made up of local Euclidean patches.

North Atlantic, Caribbean and Gulf, tropical depressions, that initiate hurricanes, may be considered as Euclidean patches. Tropical depressions, are routinely monitored by NOAA, over their evolution. Thus, and alternate strategy would be to dispatch submarines (or in this case even surface vessels) immediately from well-chosen locations, to a risk patch of ocean. For example, hurricane Dorian, was recognized as a tropical depression, on August 23, 2019; a week later it exhibited cyclonic behavior. It is proposed that vessels could have been dispatched immediately, August 3, with the mission of removing this threat.

To explore the possible means for accomplishing this goal, consider a simple inviscid fluid model. The Euler she equations for a patch of ocean, in the rotating frame of reference, at some latitude, \( \varphi \) are given by (Pedlosky 2013),

\[
\frac{\rho}{\rho} \frac{d\vec{u}}{dt} + \nabla p = \rho \left( \nabla \left( \frac{1}{2} |\vec{\Omega} \times \vec{r}|^2 - 2\vec{\Omega} \times \vec{u} \right) \right), \tag{3.1}
\]

where the 2 terms on the right-hand side represent the centripetal and Coriolis accelerations. Here, \( \vec{\Omega} \) is a vector pointing north, of magnitude

\[
\Omega = 7.3 \times 10^{-5} \text{ rad} \cdot \text{s}^{-1}. \tag{3.2}
\]

In the French language \textit{rive droit} refers to the right bank of a river, seen from the direction of flow. Hence, it is the right bank of a flow that feels the Coriolis force, everywhere in northern hemisphere.

A further simplification is to project (3.1) down to the two-dimensional tangent plane of the ocean patch. The resulting governing equations, in polar coordinates, are,

\[
C: \frac{\partial u_r}{\partial r} + \frac{\partial u_\theta}{\partial \theta} = 0
\]

\[
M_r: \frac{\partial u_r}{\partial t} + u_r \frac{\partial u_r}{\partial r} + \frac{u_\theta}{r} \frac{\partial u_r}{\partial \theta} - \frac{u_r^2}{r} - \frac{1}{\rho} \frac{\partial p}{\partial r} = 2\Omega_o^2 r - 2\Omega_o u_\theta
\]

\[
M_\theta: \frac{\partial u_\theta}{\partial t} + u_r \frac{\partial u_\theta}{\partial r} + \frac{u_\theta}{r} \frac{\partial u_\theta}{\partial \theta} + \frac{u_r u_\theta}{r} + \frac{1}{\rho r} \frac{\partial p}{\partial \theta} = 2\Omega_o u_r,
\tag{3.3}
\]

where \( \Omega_o = \Omega \sin \varphi \) is the appropriate latitudinal rotation rate. Equation (3.3) has an exact cylindrically symmetric solution given by,
\[ u_\theta = \Omega r, \]
\[ u_r = k / r, \]
\[ \frac{\partial p}{\partial r} = -\rho \left( \frac{\partial}{\partial r} \frac{u_r^2}{2} - \frac{u_\theta^2}{r} \right). \]

where \( k > 0 \), of units \( \text{m}^2 / \text{s} \), is the source strength, to be discussed below. The vorticity is given by

\[ \omega = \frac{1}{r} \frac{\partial ru_\theta}{\partial r} = 2\Omega, \]

(Pedlosky 2013).

From (3.2), the second term of the pressure term on the right, is negligible except for extremely large radii, and therefore (3.4) might serve as a model for a tropical depression. Thus, the streamlines correspond to a source, at the origin, and the curvature of the streamlines due to the Coriolis acceleration. The stream function, from (3.4) in dimensionless form, is given by

\[ \psi = k\theta - \frac{\Omega \theta^2}{2}. \]

An exemplar of the stream function (3.5) is shown in the following figure.

![Streamlines](image)

Figure 3. Streamlines for the inviscid model of a tropical depression, based on a circular region around the origin, corresponding to a radius of 30 miles as described by (3.5). The streamlines correspond to \( \theta = 0^\circ \) to \( \theta = 360^\circ \). The streamlines shown above depict a tropical depression at a nominal North Atlantic latitude. At more southerly latitudes, the streamlines tend to be radial, while more northerly latitudes the streamlines show more swirl. This may also serve as a model for the eye of a hurricane, and Mesoscale eddies see text.

From (3.4) it is seen that the motion depicted in Figure 3 is counterclockwise, \( u_\theta \), with speed that increases with distance from the origin, which may well be a model for the ocean surface flow in
the eye of a hurricane. Such a motion induces, through the Coriolis force, and outward radial flow, \( u_r \), thus resulting in a source singularity at the origin. In physical terms this result in an outflow of cold deep water to the surface. This reveals the interesting self-limiting feature of a hurricane, since cyclonic activity is sustained by warm, cold, spray off the ocean surface. That this is indeed the case is apparent on viewing the imaging of hurricane Gilbert (NOAA 2009), which left a trail of cold deep ocean water lasting weeks after its passing through the Gulf. This suggests, possibly intuitively, that a tropical depression may be quelled by a convoy of submarines traveling in the surface layer in a circle surrounding the origin. And further that this be a sustained effort until the tropical depression is no longer a threat. It is known that disturbances north of the 20th latitude seldom transform into cyclones. The reasons are complicated, but certainly decreases in sea surface temperature (SST) and Coriolis acceleration figure in the explanation (Knaff et al. 2013; Knaff, Longmore, and Molenar 2014). This over-cyclonic ocean mixing reduces SST and increases \( \Omega \), thus, simulating more northerly conditions, which imply the unlikeliness of hurricane formation.

Under the proposed strategy there is less need for precise forecasting, and possibly a need for fewer submarines. Further, the potential storm has less opportunity for accumulating moisture, hence diminishing the usual heavy rainfalls that accompanies typical hurricanes. The above deliberations can be reversed so as to enhance the initiation a hurricane, as discussed below.

Mesoscale Eddies

Also of interest, is that the flow depicted by (3.5), also appears to serve as a realistic model for the large (100 – 200 km), mesoscale, eddies spawned off of the Gulf Stream (Chelton et al. 2007), that have also been remotely sensed and monitored. These eddies are formed by an unstable loop pinching off the of the Gulf Stream. Clearly these should show clockwise preference for a northern loop, and have counterclockwise preference for a southern loop. The fact that the former are also warm, and the latter are cold, is in complete agreement with the above description of our model, adds validity to the contention that (3.5) is a reasonable model of the large eddies. Of interest to us in the present context is the fact that the “warm” eddies persist for relatively long times, even though the governing equations of forcing the circulation to be counterclockwise. While this could be verified numerically, by a three-dimensional Navier-Stokes type of model, in lieu of this the eddies model tells us that an anti-cyclonic forcing would be long-lasting. It is also noteworthy that such eddies have been identified with development (Ma et al. 2017).

7. Discussion

“How long does the newly mixed cooled sea surface layer persist?”, ironically the question is answered by satellite imagery of an actual hurricane. Hurricane Gilbert (NOAA 1988), on September 14, 1988 moved across the northwest coast of the Yucatán Peninsula, and as the imagery reveals, it churned the cold deep waters of the Gulf of Mexico, so that a wide swath of surface fell from 28°C to 24°C. The satellite imagery demonstrated that five days later, as hurricane Gilbert passed over Mexico, the prior cooled sea surface layer still persisted. Further
evidence that the cool ocean thoroughly mixes with the warm upper layer comes from (Knaff et al. 2013), who report that the cooled state can persist as long as several weeks.

Media literature contains mention of potential benefits of hurricanes, based on considerations of ecology, energy balance, needed rainfall and related concerns. In this regard, we return to the above observation that tropical depression development can be both enhanced and retarded. In case of enhancement, the accompanying rainfall, unlike cloud seeding (a case of “robbing Peter to pay Paul”), enhancement produces a new sources of rain. An ability to advance or retard hurricane formation might prove to be a valuable tool in weather management. Hurricanes are steered by ambient meteorological conditions, thus with such information in hand, and prior planning, favorable situations, might be assayed, for the time and place of hurricane occurrence. For example, the state of California, greatly in need of rain, rarely experiences hurricanes, which might change by opportunistically looking for circumstances where enhancing storm initiation might succeed. And even more likely opportunity for hurricane enhancement, would be New South Wales, Australia, which does have a history of hurricanes, and is presently experiencing a devastating drought.

The aim of this paper has been to provide, in terms of examples and realistic estimates, frameworks for mitigating and preventing the economic and human devastation caused by cyclones. The degree of feasibility is an open question, some uncertainties might be answered by experiment. Water tunnel and numerical experiments can only provide limited answers, since, large Reynolds numbers a large, and temperature and density gradients place limits on experimental modeling. Modification of a single traditional submarine, along with a test program that includes satellite imagery might provide relatively low-cost answers to some questions. On the other hand, for the second strategy, quenching potential disturbances, a testing program might be started almost immediately.

Testing costs might be immense, but the estimated world cost of cyclones over the next 10 years is greater than $1 trillion, virtually any risk reward calculation makes pursuit of this project a compelling option.

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