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Efficient coordination of swarms of sensor-laden balloons for persistent, *in situ*, real-time measurement of hurricane development*

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Accurate long-term forecasts of the path and intensity of severe hurricanes are imperative to protect property and save lives. Extensive real-time measurements within hurricanes, especially near their core, are essential for supplementing the limited relevant information accessible by satellites in order to improve such forecasts. Current operational methods for obtaining *in situ* information, such as dropsondes and repeated manned and unmanned aircraft flights over and within hurricanes, are both expensive and limited in duration. In the present work it is demonstrated by numerical experiments how a swarm of robust, inexpensive, buoyancy-controlled, sensor-laden balloons might be deployed and controlled in an energetically efficient, coordinated fashion, for days at a time, to continuously monitor relevant properties (pressure, humidity, temperature, and wind speed) of a hurricane as it develops. Rather than fighting its gale-force winds, the strong and predictable stratification of these winds is leveraged to efficiently disperse the balloons into a favorable time-evolving distribution. An iterative bootstrap approach is envisioned in which (a) sensor balloons are used to help improve the available computational estimate of the uncertain and underresolved flow field of the hurricane and (b) this (imprecise) estimate of the hurricane flow field is leveraged to improve the distribution of the sensor balloons, which then better facilitates (a), etc. The control approach envisioned in this ambitious effort is a combination of (centrally computed) model predictive control for coordination at the largest scales, which is the focus of the present paper, coupled with a feedback control strategy (decentrally computed, on the balloons themselves), for smaller-scale corrections. Our work indicates that, following such an approach, certain target orbits of interest within the hurricane can be continuously sampled by some balloons, while others make repeated sweeps between the eye and the spiral rain bands.

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I. MEASURING HURRICANES

As evidenced by Table I, recent Atlantic hurricanes have been both costly and deadly [2]. Accurate hurricane forecasts are essential for conducting orderly evacuations, preparing emergency responses, and limiting losses. The assimilation of accurate and extensive *in situ* measurement data is essential for improving numerical weather predictions, as reviewed in Ref. [3], which provides an excellent broad view of related research. Current operational approaches for obtaining *in situ* measurements are limited in their spatial or temporal resolution or in the amount of time that they can be deployed. Such approaches include (i) aircraft-deployed, sensor-equipped dropsondes [4], which acquire GPS-registered vertical profiles of pressure, humidity, temperature, and wind speed during their 10–20 min of free fall; (ii) radar-equipped aircraft and drones [5,6] flying over (or even within) the hurricane, for at most 24 h at a time; and (iii) sea gliders [4], moving at a maximum speed

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TABLE I. Loss of life and property due to recent hurricanes (see [1]).

Hurricane	Year	Cost	Deaths
Sandy	2012	\$71B	150
Irene	2011	\$16B	50
Ike	2008	\$30B	130
Katrina	2005	\$108B	1800
Wilma	2005	\$21B	23
Rita	2005	\$10B	62
Jeanne	2004	\$8B	3000
Ivan	2004	\$14B	125
Charley	2004	\$15B	40
Mitch	1998	\$6B	9000
Andrew	1992	\$27B	65

of 25 km/day, currently being tested for sampling the important upper ocean temperature, salinity, and horizontal current velocity profiles [7].

Atmospheric balloons have already proved their usefulness for *in situ* measurements of high-altitude weather phenomena [8]. Stratospheric balloons carrying several dropsondes, known as driftsondes, can be used to profile the lower atmosphere by controlling the timing of the dropsondes released, as described in Refs. [9,10]. This strategy, leveraging numerical forecasts of the high-altitude winds, provides some level of control of the resulting measurement locations. However, the driftsondes themselves are not maneuverable after launch, thus limiting the control authority of this approach. In contrast, the control approach suggested in this work permits trajectory corrections when updated forecasts become available.

The dynamics and frequency response of buoyant objects in environmental flows have been extensively studied. These studies quantify, for example, the vertical displacement of buoyant objects from their equilibrium (neutral-density) altitudes in response to vertical winds. For application to balloons in the atmosphere, see, e.g., [11–14]; for application to floaters in the ocean, see, e.g., [15,16]. The present work assumes that the vertical location of the balloon is approximately controllable via localized feedback implemented on the balloons themselves.

In the USA, Businger *et al.* [17], in 2002 and 2005, deployed "smart" balloons at relatively low altitudes within hurricanes to acquire temperature, pressure, humidity, and optical (infrared) images to estimate sea-surface temperatures. Due to a few unfortunate technical malfunctions, these initial experiments failed to intercept their desired hurricanes; however, the general approach they followed was sound and promising. Many other balloon experiments performed by the same group in different settings have well established the possibility of deploying balloons for extended periods of time, e.g., successfully crossing the Atlantic ocean while obtaining record altitudes and flight times, exceeding 50 days. Multiple low-atmosphere superpressure balloons flights have similarly been performed by French-based teams, which have successfully intercepted tropical cyclones in the Indian Ocean, as reviewed in Ref. [18].

Businger's 2005 experiment was part of the RAINEX project, the goal of which was the acquisition of high-quality measurements of the internal structure of hurricanes [19]. Observations were performed and forecasts produced by coordinating *in situ* measurements, taken by sensor-equipped dropsondes and radar-equipped airplanes flying above and within the hurricane itself, with remote measurements taken by satellites and ground-based radar. Numerical models were used to identify, in real time, the most dynamically relevant parts of the hurricane and to plan flight paths accordingly. The RAINEX experiment conclusively demonstrated the importance of persistent *in situ* acquisition of data within the inner, most violent part of the hurricane; a similar approach has been used in subsequent hurricane measurement campaigns [4,20].

The data acquisition strategy proposed in the present work follows a similar approach, but is based on relatively low cost, buoyancy-controlled, sensor- and radio-equipped balloon swarms. Such swarms of balloons can be deployed from an airplane, ship, or ground station and can be directed into regions in the hurricane that are difficult or impossible to observe otherwise. Due to their low-energy requirements, they hold the potential to provide essentially continuous, real-time, high-resolution observations of a hurricane for several days at a time, over essentially the entire lifespan of the hurricane [17].

The present work indicates how, by controlling the balloons' vertical motions only, the balloon distribution over the hurricane might be deliberately and efficiently coordinated,[1] leveraging repeated high-resolution short-term (∼1-h) forecasts of the hurricane flow field structure. These short-term forecasts, in turn, may be obtained from all available measurement data, leveraging the hurricane forecasting approaches and codes used (and those under development) at the national weather forecasting centers. Recent work in the development of high-resolution short-term forecasts updated on an hourly basis is discussed in Ref. [22].

Note in particular that some operational approaches to initialize atmospheric models for numerical weather prediction are, in a sense, unbalanced. That is, each forecast starts with no clouds and zero vertical velocity everywhere, with these flow features subsequently developing, over a period of several hours, via the dynamics of the atmospheric model itself as the flow field is marched into the future (see [23]). This unfortunate behavior of some current short-term forecasting methods needs to be rectified for these methods to be maximally useful in the present setting. The measurements obtained from coordinated sensor balloon swarms, as considered in the present paper, could prove instrumental in significantly improving both short- and long-term forecasts of the hurricane development. That is, we envision a bootstrap estimation and control approach, in which reduced-accuracy flow-field estimates and forecasts are used to compute control strategies to steer the sensor balloons into the general areas of interest within the hurricane. As the measurements from these sensor balloons are subsequently fed back into the forecasting algorithm, improved-accuracy estimates and forecasts of the flow field will become available, which may be leveraged to distribute the balloons more uniformly over the hurricane.

The present paper demonstrates specifically how the large-scale (time-evolving, nonsymmetric) nominal flow field of a developing hurricane might be used to coordinate accurately a swarm of buoyancy-controlled balloons. This is just the first of many steps in this ambitious project. Our group is simultaneously investigating two essential related questions, summarized below, that are not discussed further in this paper.

The first such question is how the significant uncertainties in the forecast of the large-scale flow features [24], as well as the significant unresolved (smaller-scale) turbulent flow fluctuations, affect the large-scale balloon motions over time and how these effects might be mitigated via additional, energetically efficient feedback control strategies that may be applied on top of the bulk coordinating control inputs determined following the approach developed in the present paper (via model predictive control). This fascinating question is considered at length in Ref. [25].

The second question is how the balloon system will actually be sized, built, made robust, and deployed; these systems-level engineering design questions are addressed in Ref. [26] and will adapt the altitude-cycling balloon design described in Refs. [27,28]. With this approach, rather than using a ballast tank and a pump to change the mass of a constant-volume balloon, a winch is used to squeeze (and thereby change the volume of) a constant-mass balloon with a long aspect ratio. This is achieved by adjusting the length of a cable stretched along the major axis of the balloon. A balloon of such a design, once sprayed with a hydrophobic coating, can be made much less prone to accumulating ice in a very cold, wet environment, such as a hurricane.

[1]Our group's early work on this general subject area, albeit not specifically applied to hurricanes, is discussed in Ref. [21].

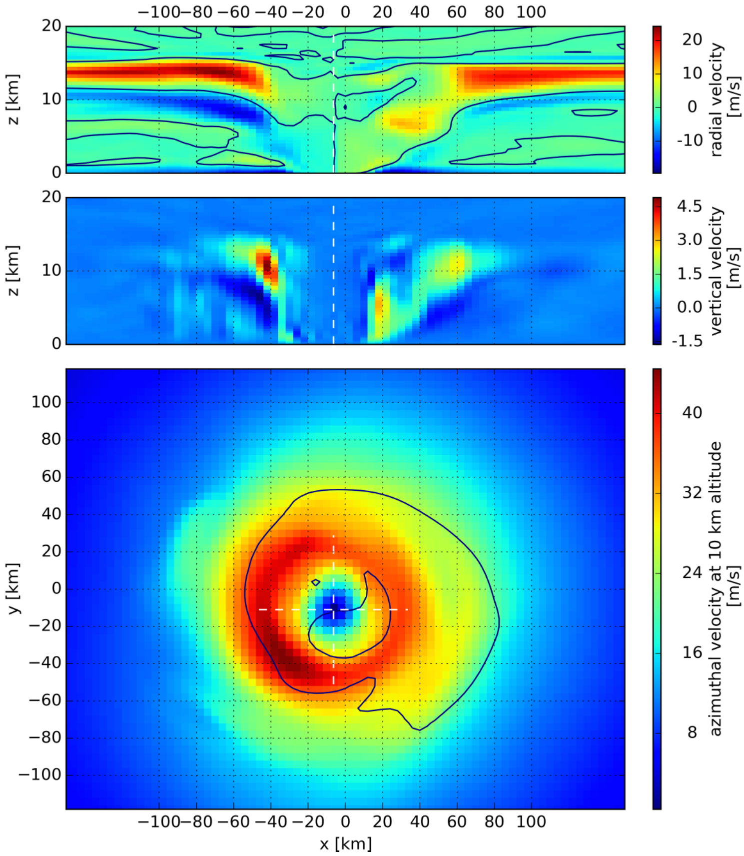

FIG. 1. Snapshot of a typical category 3 hurricane flow field from numerical simulation. The hurricane center is denoted by white dashed lines in all three panels. The top and middle panels are vertical sections through the center of the hurricane, depicting the radial and vertical velocity components, respectively; for clarity, the radial and vertical coordinates are scaled differently. The bottom panel is a horizontal section through the hurricane at 10-km altitude and depicts the azimuthal velocity component; this component reaches a maximum in the eyewall region, located roughly 30 km from the hurricane center. Contours of zero radial velocity are indicated by black lines in the top and bottom panels.

II. SWARM DYNAMICS: GOING WITH THE FLOW

With the recent explosion of interest in robotics, driven by low-cost cellphone technology and pervasive low-energy radio connectivity, it is intriguing and timely to consider what major scientific and engineering problems may best be accomplished with a coordinated swarm of 100 or more inexpensive and autonomous mobile robotic vehicles. Though academic interest in the clever coordination of robot swarms is growing rapidly (see, e.g., Ref. [29]), we believe that the present environmental sensing application represents one of the most broadly compelling scientific applications that specifically benefits from the large-scale deployment of coordinated swarms of robotic vehicles. Modern sensors and cellphone-grade technology, adopted for this particular robotic sensing application, hold the potential to substantially reduce the size and cost of the balloons required to obtain accurate measurements, thereby facilitating the deployment of many more sensor vehicles into hurricanes than previously imagined possible.

To understand how to steer buoyancy-controlled balloons in the stratified flows of interest, consider the flow structure depicted in Fig. 1, where the azimuthal and radial velocity of a hurricane are shown. At the center of the hurricane is the eye, a low-pressure, relatively calm region; the eye is isolated from the rest of the hurricane by the inner eyewall, a region characterized by exceptionally strong winds and intense precipitation. Hot, humid air enters the eyewall from near the ocean surface and moves upward and away from the hurricane center at higher altitudes and back towards the center at lower altitudes, creating a strong circulating flow in the vertical plane. Multiple eyewalls can coexist in particularly strong hurricanes, separated by a moat, which is a relatively calm region with weaker precipitation. The interaction of coexisting eyewalls plays an important role in the evolution of intense hurricanes [30].

Of particular interest regarding our ability to maintain subsets of the deployed balloons in nearly uniformly spaced formations are the manifolds of zero radial velocity within the hurricane (again, see Fig. 1). Where such a manifold is stable for neutral-density balloons (i.e., when the radial velocity in its vicinity points towards the manifold itself), the manifold acts as an attractor and a neutral-buoyancy balloon in its proximity will circle the hurricane with no control actuation required.[2] This is indeed what happened to a balloon deployed in tropical cyclone Gamede [33], in which, uncontrolled, a neutral-density balloon performed 12 revolutions around the hurricane center at almost zero radial velocity, in the vicinity of the radius of maximum azimuthal speed.

The generally outward slope of such stable zero-radial-velocity manifolds in the radial directions translate the (controllable) vertical movements of the balloons into concomitant movements in the radial direction. The relative azimuthal separation of two closely spaced balloons near a certain target orbit within such a manifold may thus be achieved as follows: The balloon in front may be commanded to descend slightly, after which it will move towards the core and travel around it more quickly, whereas the balloon in the back may be commanded to ascend slightly, after which it will move away from the core and travel around it more slowly. After the two balloons reach the desired azimuthal separation, they may be commanded to return to their target altitude and, consequently, back to their desired equilibrium radii, but now with the desired azimuthal separation. The azimuthal separation of a closed string of several balloons around an attracting orbit may be stabilized similarly.[3,4]

In addition to stabilizing the relative azimuthal separation of subsets of deployed balloons, balloons may also be commanded to maneuver quickly between different target radii and altitudes, again leveraging the flow field structure and buoyancy control only.

III. COORDINATING THE RESPONSE

The previous section described the general notion of how a distribution of buoyancy-controlled balloons is controllable within an idealized (that is, steady and axisymmetric) hurricane for an extended period of time. However, developing hurricanes, especially in their early stages (category 1 and 2), are highly unsteady and nowhere near axisymmetric. Thus, actually implementing the

[2]This characterization is precise only for an idealized steady-state hurricane for which (when viewed in a reference frame moving with the hurricane center) the streamlines and particle lines coincide; nonetheless, this characterization provides a valuable starting point to understand the controllability of a balloon formation solely via buoyancy control of the balloons. Note also that the zero-radial-velocity manifolds in such steady-state idealizations provide computationally inexpensive rough approximations of the boundaries of so-called Lagrangian coherent structures within the hurricane [31]; precise characterizations of such structures, in time-evolving flows, are sometimes of interest [32], but are not the focus of the present study.

[3]With the appropriate use of feedback, it might also be possible to stabilize the motion of constant-altitude orbits within an unstable zero-radial-velocity manifold; in practice, however, such an approach is expected to require significantly more control actuation to maintain and is thus not considered further here.

[4]This azimuthal-separation control problem is akin to the string stability problem of several automated vehicles moving at high speed and fixed (small) target separations down a highway, as studied, e.g., in the California Partners for Advanced Transportation Technology project two decades ago [34,35], and may indeed be addressed with similar control approaches if considered in the decentralized limited-information setting.

underactuated control idea notionally proposed in the previous section in a realistic hurricane flow field requires some care. Indeed, it is not initially obvious that this control strategy is even practically achievable. The remainder of this paper demonstrates with computational experiments that, in fact, this control idea, appropriately implemented, is indeed quite promising.

Our codification of the underactuated control idea proposed in the previous section leverages the receding-horizon model predictive control (MPC) framework [36–38], which we anticipate would be implemented in a centralized, high-performance-computing setting, that is, at the supercomputer center where the flow forecasting itself is also being done, not on the balloons themselves.

In this context, energetically efficient vertical control velocity schedules are determined (and repeatedly reoptimized) over a time horizon 30–90 min into the future from the present, which proves sufficient to steer the balloons towards their target azimuthal separations. A reasonable model of the balloon motion is obtained by assuming that the vertical velocities of the balloons are, via appropriate use of local feedback (computed on the balloons), approximately as commanded by the centralized MPC algorithm, while the horizontal velocities of the balloons are approximately the same as those of the hurricane itself, appropriately low-pass filtered, at the respective locations of the balloons. That is, the balloons may be thought of as, effectively, Lagrangian flow tracers in the horizontal directions. The availability of reasonably accurate short-term (30–90 min) forecasts of the hurricane's evolution is assumed in this work. Such a forecast may be obtained, for example, via the Weather Research and Forecasting (WRF) [39] model. As mentioned previously, the problem of tracking optimized trajectories in the presence of both forecast errors in the large-scale flow features and unmodeled effects (due to turbulence) in the small-scale flow features is discussed in Ref. [25]. The optimized control schedules for each balloon and the corresponding balloon trajectories based on the forecasted flow field of the hurricane are then computed as the solution of a nonlinear constrained optimization problem. The cost function used in this optimization balances the deviation of the balloons from the specified target separations with the control effort used over the forecast interval and the optimizations are performed subject to constraints represented by the nonlinear equation of motion of the balloons within the forecast flow field. For further discussion of the control algorithm implemented, see Appendix B.

IV. SIMULATION RESULTS

Our numerical tests to date have examined a number of representative scenarios, including hurricanes of various intensities and maturity, the deployment of balloons from both sea level and from airplanes at different altitudes, and the consideration of different target altitudes and radii for the balloons. Additionally, we have examined the rapid maneuvering of deployed balloons from one target attracting orbit to another. Mature, intense hurricanes present nearly steady-state, well-structured, almost axisymmetric flow fields and accurate control of balloon distributions proves to be relatively straightforward. The early stages of hurricane development, during which the hurricane intensity evolves significantly and the flow field is far from axisymmetric, provide more difficult flow fields to work with, but the results obtained are still quite compelling. Finally, we verified our control strategy with a 39-h simulation of hurricane Katrina. Results of these simulations are discussed below.

Figure 2 illustrates the maneuvering of eight balloons (four deployed from sea level and four from an altitude of 20 km) in a category 3 hurricane. The top left panel shows the separation phase in which the optimized control distribution moves the balloons to different altitudes and the corresponding radii range from 30 to 60 km. The desired azimuthal separation is obtained less than 4 h after deployment, as evident in the top right panel, where the two groups of balloons orbit the core close to the target radii of 40 and 50 km. The bottom left panel shows one of the two deployed groups sweeping across the hurricane in the radial direction toward a new 100-km target radius; note that the azimuthal separation is kept approximately constant during this maneuver. Covering the 50-km difference between the two target radii takes only about 1 h, due to the strong high-altitude

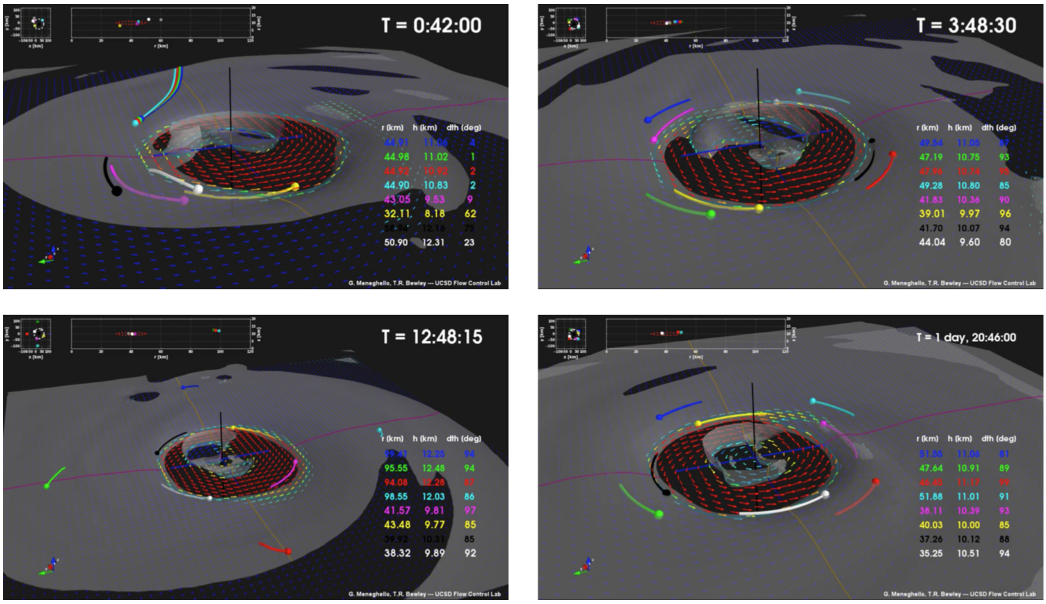

FIG. 2. Maneuvering of eight balloons within a simulation of a category 3 hurricane obtained using the CM1 numerical model. The top left panel shows two clusters of four balloons each released from sea level and an altitude of 20 km and commanded to move to uniform azimuthal separations at two different target radii. The top right panel shows that after less than 4 h, the target configuration is obtained. The bottom left panel shows that one of the groups of four balloons is directed out to a larger target radius. The bottom right panel shows that the balloons are returned to their initial target configuration. The gray surface represents the time-evolving manifold of zero radial velocity. For a time-resolved animation of this result, see Supplemental Material [40].

outflow. After one full circle around the core, the balloons are brought back towards the center of the hurricane.

Figure 3 presents two time series of the balloon distributions: The right column shows the time-resolved motion of the outer four balloons in Fig. 2, whereas the left column shows results for the more difficult case of balloons deployed in a hurricane during its development from a category 1 hurricane to a category 4 hurricane. The separation strategy is evident in the top panels: The vertically stratified radial velocity field is first used to move the balloons to different radii, as visualized in the r-z view. The different angular velocities encountered at different radii are then used to obtain azimuthal separation of the balloons, as can be seen in the x-y view. Once the desired azimuthal separations are obtained, the balloons are brought back to their target altitudes (and thus radii). The maneuvering is much faster and cleaner in the developed case (right column), because of the more structured velocity field. From the operational point of view, it is important to note that the specification of the balloons' target trajectory need only include a target radius, altitude, and azimuthal separation of a subset of balloons; the optimized control inputs and resulting balloon trajectories are then computed automatically by the control algorithm.

The bottom four panels of Fig. 3 show the radial and vertical positions, the azimuthal separation between the four balloons, and the applied vertical control velocities. Dashed lines represent the specified target. Normalized histograms on the right provide a clear indication of how well, on average, the target trajectories are maintained, as well as the associated control requirements. Note that, in the case shown in the left column, the vertical velocity of the balloons was restricted to lie between $\pm 3\ \mathrm{ms}^{-1}$; such a saturation constraint on the control velocity is easily handled by the MPC algorithm.

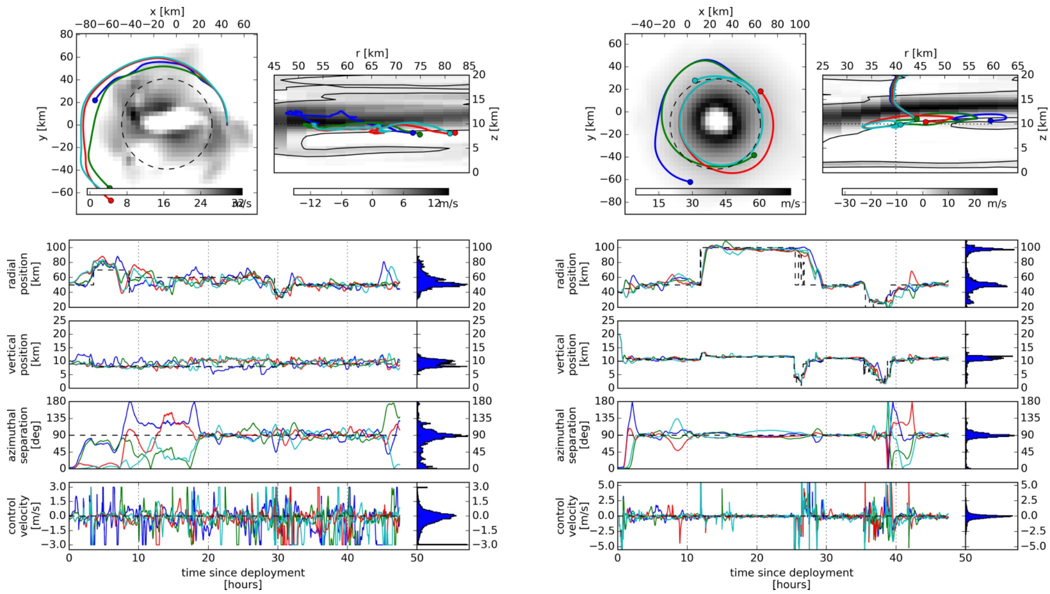

FIG. 3. Simulation of controlled balloon trajectories for a hurricane developing from category 1 to category 4 (left) and for a mature category 4 hurricane (right). The top panels show the balloon trajectories in the x-y plane and the r-z plane for the first 3.75 h (left) and 1.25 h (right) after deployment. The bottom four panels show, respectively, the radial (with respect to the moving hurricane center) position, the vertical position, the azimuthal separation, and the vertical control velocity as a function of time. Dashed lines represent the target values. Each simulation is run for approximately 48 h of the hurricane evolution.

The ability of the MPC algorithm to maintain the balloons close to the target orbits at uniform azimuthal separations, as well as to maneuver quickly to different target orbits, is especially evident in the time series of the mature hurricane case shown in the right column of Fig. 3. After deployment from an altitude of 20 km and a separation phase lasting just a few hours, the balloons stabilize close to their target radius and altitude of 50 and 10 km, respectively. About 7 h after deployment, an extended asymmetric region appears in the hurricane velocity profile. This irregularity in the hurricane velocity profile of course directly affects the azimuthal distribution of the balloons (see the red and cyan lines in the azimuthal separation plot); however, the control algorithm reacts appropriately, steering the balloons back to the target separation within the next 3 h. A maneuver is then ordered by changing the target radius to 100 km for the following 16 h, followed by ordering a dive to a low altitude at 25 h after deployment, quickly returning the balloons back to the original target orbit. These maneuvers are all executed correctly, while maintaining the desired azimuthal separations reasonably well. About 28 h after deployment, another asymmetric region in the hurricane velocity profile briefly disrupts the azimuthal separations; similar to what happened 7 h after deployment, the control algorithm reacts by quickly steering the balloons back to the requested orbit and separation. At 35 h after deployment, a smaller radius and lower target altitude are ordered; due to the severe irregularity of the hurricane velocity field close to the core, it proves to be impossible to regulate the azimuthal separations accurately in this case. At 43 h after deployment, the balloons are commanded back to the original target orbit; this is achieved quickly, thus showing that robust recovery of the balloon distribution is possible even after this distribution is significantly disrupted.

The developing hurricane case, shown on the left in Fig. 3, clearly represents a more challenging flow field for controlling the balloon distribution and the resulting balloon distribution is much less uniform. Regardless, it can be seen that following the hurricane with the balloons, maneuvering between target orbits, and obtaining a reasonable separation of the balloons on these orbits is still possible and should be adequate to obtain valuable *in situ* measurements of a hurricane using a swarm

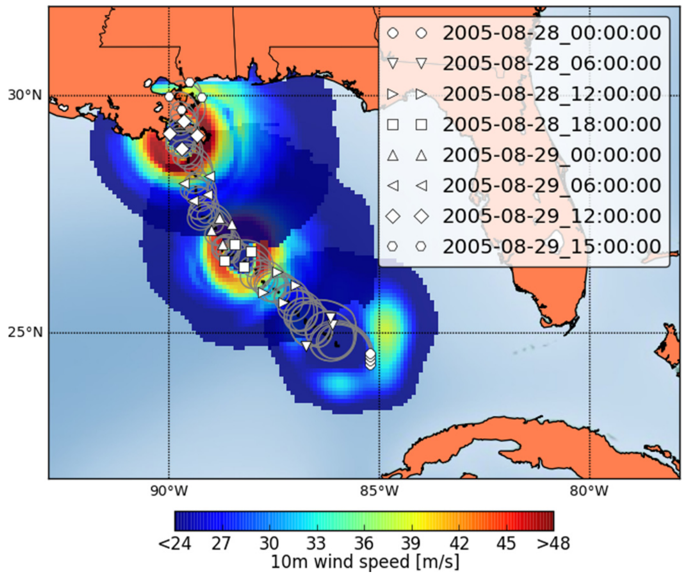

FIG. 4. Tracks (in gray) of a group of four balloons within a simulation (obtained using the WRF numerical model) of hurricane Katrina over a 39-h period, from 0000 UTC 28 August 2005 to 1500 UTC 29 August 2005. White symbols mark the location of the balloons every 6 h. Snapshots of the 10-m velocity field is presented in color every 18 h. The black dashed line represents the track of the hurricane center. For a time-resolved animation of this result, see Supplemental Material [40].

of sensor-laden balloons. Note that, depending on the mission requirements, one has the possibility in the optimization algorithm to put differing degrees of emphasis on maintaining the balloons close to a target altitude, a target radial position, or a target azimuthal separation, as discussed further in Appendix B. Note also that, in the case shown on the left in Fig. 3, almost 20 h were required to reach the target azimuthal separation, partly because the balloons overtook each other multiple times due to the irregular flow field encountered. Despite difficulties in achieving the desired azimuthal separation, the target altitude and radius are maintained fairly well. An initial separation of the balloons via different deployment times, by scheduling their release from an airplane, ship, or ground station, should greatly reduce the time required to reach the desired target azimuthal separation.

Figure 4 shows the result of our control algorithm for coordinating balloon motion applied to a simulation of hurricane Katrina, as it moved from the center of the Gulf of Mexico until landfall in New Orleans. The operational WRF model was used in producing the flow field for this simulation. Four balloons were deployed simultaneously and commanded to move with the hurricane, at 50 km from the core, while maintaining a homogeneous azimuthal separation. The full simulation reproduces the flow field from 0000 UTC of 28 August 2005 to 1500 UTC 29 August 2005, a few hours after landfall in Louisiana. The position of the four balloons every 6 h after deployment is marked by white symbols, thus visualizing the ability of our control algorithm to follow the development of an actual hurricane of interest, while accurately following the desired orbit and maintaining the desired azimuthal separation.

Note that approaches similar to that considered in this paper are being explored by our group for the related problem of the control of buoyancy-controlled underwater vehicles (also known as drifters) in oceanographic applications. Our preliminary work in this setting has shown how linear internal waves, which do not by themselves cause mass transport, can be surfed effectively by buoyancy-controlled drifters, resulting in rapid movement in the horizontal direction.

The problem of communication to, from, and between the balloons is also interesting. For the sensor balloons to be useful in real-time large-scale weather forecasting, they need to be in frequent radio contact with the National Center for Atmospheric Research or elsewhere; this is, in fact, why we are not significantly concerned about solving the difficult balloon coordination problem in a centralized fashion in this application. Note that, rather than using satellite communications, at any given time, one can form an *ad hoc* mesh communication network within the swarm of balloons and transmit relatively low-power messages over this network to the nearest ground station(s) or ship(s) or to an iridium-equipped airship or unmanned surface vessel stationed at (and moving with) the center of the hurricane core. This might, from time to time, require “data mules” to buffer certain messages for a short period of time, then travel to new positions where such data can be handed off. The manner of communicating over such an *ad hoc* network with the minimum communication energy and delays is itself an interesting research problem and is left for future research.

V. DISCUSSION

This work shows how current operational approaches for *in situ* observation of hurricanes might be significantly augmented by deploying swarms of robust, inexpensive, energetically efficient, sensor-laden, radio-equipped balloons. Despite having control authority only in the vertical direction, swarms of such balloons could be steered into useful, well-distributed target trajectories leveraging the highly stratified hurricane flow structure itself and maintained in such distributions for extended periods of time. Since developing hurricanes are not axisymmetric, the resulting distribution of balloons may be disrupted from time to time; our simulations indicate that the control algorithm developed here robustly recovers from such disruptions in realistic flow conditions. Additionally, since the balloons are equipped with buoyancy control, GPS, and radios, it should be possible to recover many of the them after the hurricane makes landfall.

The present simulations assume accurate knowledge of the hurricane flow field when optimizing the balloon trajectories; as mentioned previously, our ongoing work (see [25]) endeavors to quantify how accurate a short-term (30- to 90-min) forecast of the hurricane is required for this approach to be effective. Also, future work should target the quantification of how significantly the persistent *in situ* measurements provided by such balloon swarms could actually improve long-term forecasts of the path and intensity of major hurricanes. Given the importance [3] and limitations of dropsondes and aircraft measurements in today’s operational hurricane forecasting, this improvement is expected to be quite significant.

APPENDIX A: HURRICANE VELOCITY FIELD

The hurricane flow field used for the tests shown in Figs. 2 and 3 has been computed using the CM1 numerical model [41,42], on a $384 \times 384 \times 59$ stretched Cartesian grid. The horizontal mesh size in the region covering the center of the hurricane is 4 km; the vertical mesh size varies from 50 m close to the surface to 500 m above an altitude of 5 km.

The hurricane flow field used for the tests shown in Fig. 4 has been computed using the WRF-ARW numerical model [39], on a 10-km horizontally spaced grid with 30 vertical levels. The nested, vortex-following domains typically used in hurricane forecasts are correctly handled by our control algorithm.

In all computations performed, the velocity at each balloon’s location is obtained via tricubic interpolation of the discrete flow-field data in the spatial directions. To compute this interpolation, we use the values of the velocities and their finite-difference-computed derivatives at the eight corners of the computational cell where the balloon is located [43]. The same time step of 20–60 s is used for both the integration of the hurricane evolution and the balloons’ trajectories and no interpolation of the velocity field is required in time, provided the hurricane velocity field is saved at each time step.

The HDF5 output format [44] for the CM1 model and the NetCDF-4 output format [45,46] for the WRF model are used to save the simulation results. Included among the salient features of these output formats are seamless data compression and the possibility of loading into memory only a subset (also known as hyperslab) of the flow field, rather than the entire data set. This property is quite useful, given the large amount of data involved and the need for the MPC algorithm to sweep over the forecasted flow-field evolution repeatedly. The use of hyperslabs results in substantial savings in the computer time required to optimize the balloons' trajectories, as only a few mesh points around the current positions of the balloons are required to compute the interpolation. For the simulation presented in this work, a $12 \times 12 \times 12$ grid (including the $2 \times 2 \times 2 = 8$ corner points and their neighbors, as required to computed velocity derivatives), instead of the full $384 \times 384 \times 59$ grid, is loaded at each time step, resulting in almost two order of magnitude reduction in the time required to load the data.

APPENDIX B: MODEL PREDICTIVE CONTROL

A receding-horizon MPC framework is used to compute the optimized control (that is, the vertical velocity) sequence used to steer the balloons towards their target trajectories. The control sequences and corresponding trajectories are obtained as the solution of an optimization problem for a time horizon extending as far in the future as the current velocity field forecast (or the available computer resources) allows; our numerical results are computed with a forecast horizon of 30–90 min. The 30-min horizon corresponds to between a quarter and a half of an orbit at a radius of 40 km for the mature hurricane. The quantity to be minimized is a measure of the distance to the target trajectory (that is, the target radius, the target altitude, and the target azimuthal separation), balanced with the cost of steering the balloons. In the receding-horizon MPC setting, once the control sequence is computed, only the first time step is actually applied to the balloons and a new control sequence is optimized after shifting the start time one time step into the future.

The cost function minimized in this work is defined as

$$J(r_i,\theta_i,z_i,u_i) = \frac{1}{T}\int_{t_0}^{t_0+T}\left[\sum_i \frac{Q_r}{2}(r_i-\bar{r})^2 + \sum_i \frac{Q_z}{2}(z_i-\bar{z})^2 \right.$$
$$\left. + \sum_{ij}\frac{Q_\theta}{2}[\cos(\Delta\theta_{ij}) - \cos(\Delta\bar{\theta}_{ij})]^2 + \sum_i \frac{Q_u}{2}u_i^2\right]dt,$$

where $\{r_i, z_i\}$ are radial and vertical positions of balloon i, $\Delta\theta_{ij}$ is the azimuthal separation between balloons i and j, $\{\bar{r}, \bar{z}, \Delta\bar{\theta}\}$ are the target radius, altitude, and azimuthal separation, respectively, and $\{t_0, T\}$ are the optimization window initial time and duration, respectively. The first three terms of the cost function J represent a measure of the distance from the target radius, the target altitude, and the target separation, while the fourth term represents the cost of the control u, which for our simulations is the vertical velocity of each balloon and is additionally constrained to be less than 3 ms^{-1}. Note that $\{Q_r, Q_z, Q_\theta, Q_u\}$ are constant weighting matrices used to tune the optimization problem.

Constraints are given by the equations governing the motion of each balloon. As mentioned previously, a reasonable approximation is to impose the horizontal velocity of the balloons to be the same as the local velocity of the hurricane:

$$\dot{\mathbf{x}}_i = \mathbf{f}_i(\mathbf{x}_i) + Bu_i,$$

where $\mathbf{x}_i = [x_i, y_i, z_i]^T$ is the position of balloon i, $\mathbf{f}_i(\mathbf{x}_i)$ represents the tricubic interpolation of the discrete hurricane velocity field obtained by the CM1 or WRF model at the position of balloon i, $B = [0,0,1]^T$ is the control matrix mapping the control to the state, and u_i is the added vertical velocity component used to control the balloon. The resulting constrained optimization problem is solved using the standard approach of reformulating it as an unconstrained problem by means of Lagrange multipliers, also known as adjoint states or costates [36,38], and then solving the nonlinear system obtained by setting all gradients of the constraint-augmented cost function to zero. The Newton solver with line search and variational inequalities constraints implemented in PETSc and petsc4py is used for this purpose [47,48]. Note that the cost function J is not quadratic once it is expressed in Cartesian coordinates rather than cylindrical coordinates; regardless, assuming full knowledge of the flow field, this does not pose any additional challenges besides additional nonlinearities in the system to be optimized.

Backward differentiation formulas (BDFs) are used to discretize the time derivatives in the optimization problem. The BDF requires the solution of an implicit problem at each time step: For this reason, cheaper multistep explicit methods such as the explicit Runge-Kutta (ERK) method are often the preferred choice. Note, however, that the requirement for an implicit solution is not an issue in our case, as the optimization problem is seen as a two-point boundary-value problem (TPBVP), with boundary conditions provided at both the initial time (for the trajectories $\mathbf{x}$) and the final time (for the Lagrangian multipliers). As a result, the TPBVP should be treated as an implicit problem even when explicit time marching schemes are employed. On the upside, BDF methods have the advantage of a much larger domain of stability with respect to ERK methods and do not require the computation of the right-hand side $\mathbf{f}(\mathbf{x})$ at intermediate time steps, thus reducing significantly the number of required interpolations.

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