Atmospheric Balloons for Persistent In-Situ Measurements in Hurricanes

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Goals

Severe hurricanes are both costly and deadly. Accurate long-term forecasts of their path and intensity 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 the hurricane, are both expensive and limited in duration. In the present work, it is demonstrated how a swarm of robust, inexpensive, buoyancy-controlled, sensor-laden balloons can be deployed and controlled in an energetically-efficient, coordinated fashion, for days at a time, to continuously monitor relevant properties (pressure, humidity, temperature, windspeed) over the hurricane as it develops. Rather than fighting the gale-force winds in the storm, their the strong and predictable stratification is leveraged in order to disperse and mantain the balloons into a favorable, time-evolving distribution over the hurricane.

Balloons Model

The problem is formulated in the Model Predictive Control framework. The objective is to minimize the average distance from a target trajectory $(\bar{r}, \bar{z}, \Delta\bar{\theta}_{ij})$. The objective function

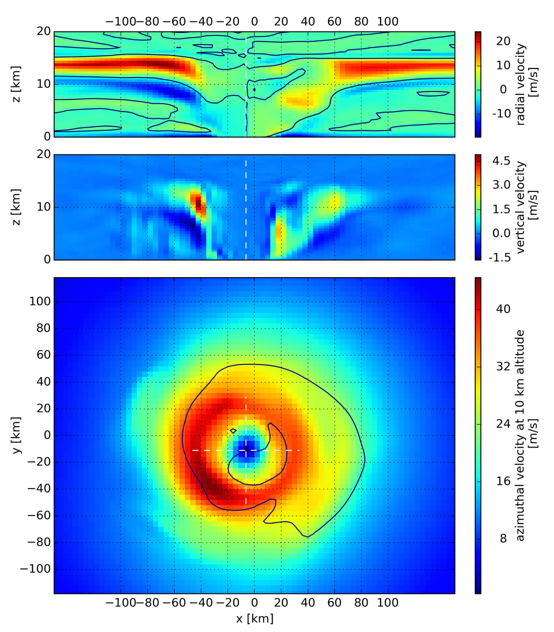
$$J = \frac{1}{T}\int_{t_0}^{t_0+T} \sum_{ij} \frac{Q_\theta}{2}\left(\cos(\Delta\theta_{ij}) - \cos(\Delta\bar{\theta}_{ij})\right)^2 + \sum_i \left[\frac{Q_r}{2}(r_i-\bar{r})^2 + \frac{Q_z}{2}(z_i-\bar{z})^2 + \frac{Q_u}{2}u_i^2\right] dt$$

weighting the distance from the target and the control cost, is minimized subject to the equation of motion

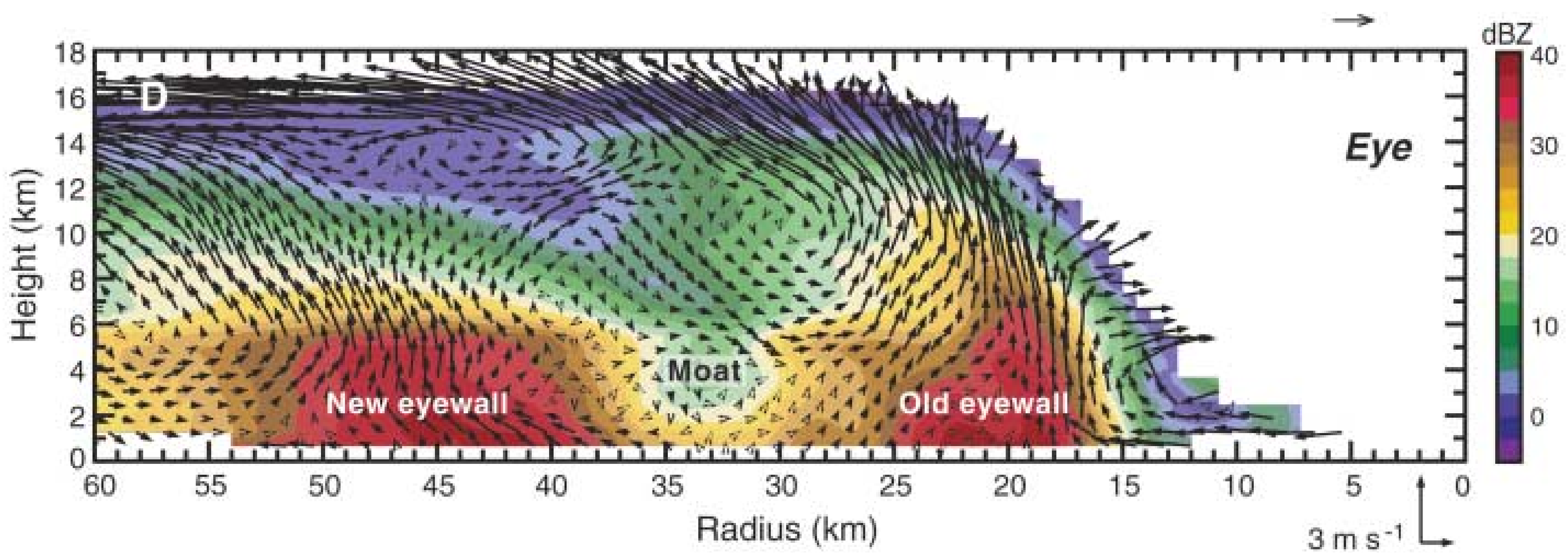
$$\dot{\mathbf{x}}_i = \mathbf{f}_i(\mathbf{x}_i) + Bu_i$$

where $f(\mathbf{x}_i)$ is the flow velocity at the balloon location $\mathbf{x}_i$, $B = [0,0,1]^T$ and u_i is the control (vertical) velocity of each balloon. The flow velocity $f(\mathbf{x}_i)$ is obtained by repeated, short term forecasts ($\approx 1h$) obtained using operational weather numerical models (e.g. WRF).

Hurricane Model



NUMERICAL MODEL



EXPERIMENTAL OBSERVATIONS (HOUZE 2007, SCIENCE)

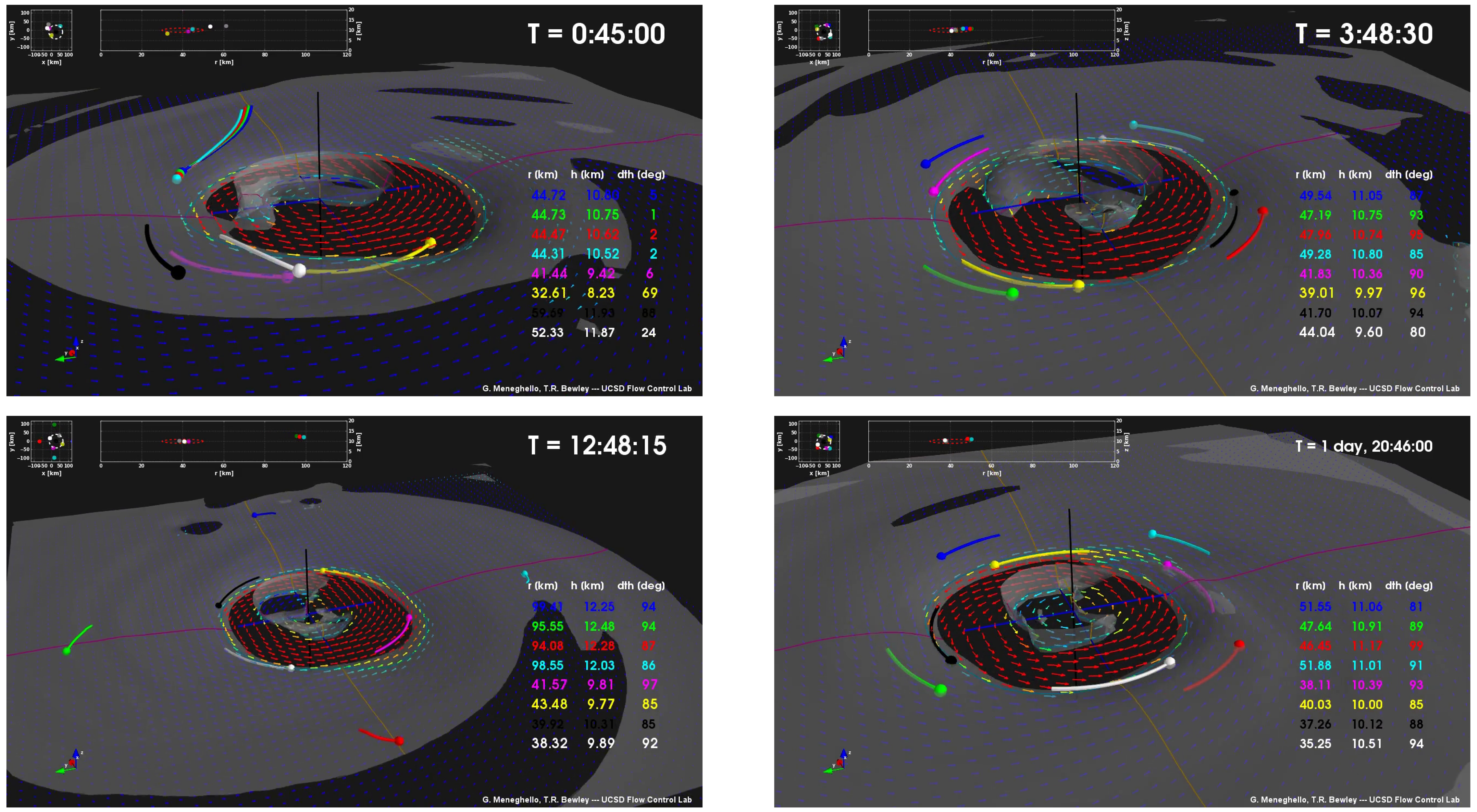
The balloons are controlled by acting on their vertical position and leveraging the flow stratification to control the horizontal position. Of major importance are regions of zero radial velocity[a] (black lines in the left plot): a balloon on these lines will approximately circle the center of the hurricane. A balloon above or below these lines will move outward or inward in the radial direction.

LEFT: snapshot of a hurricane flowfield obtained using the CM1 numerical model (Bryan and Fritsch 2002; Bryan 2002). The top and middle panels are vertical sections through the center of the hurricane, depicting the radial and vertical velocity components, respectively. The bottom panel is a horizontal section through the hurricane at 10km altitude, and depicts the azimuthal velocity component.

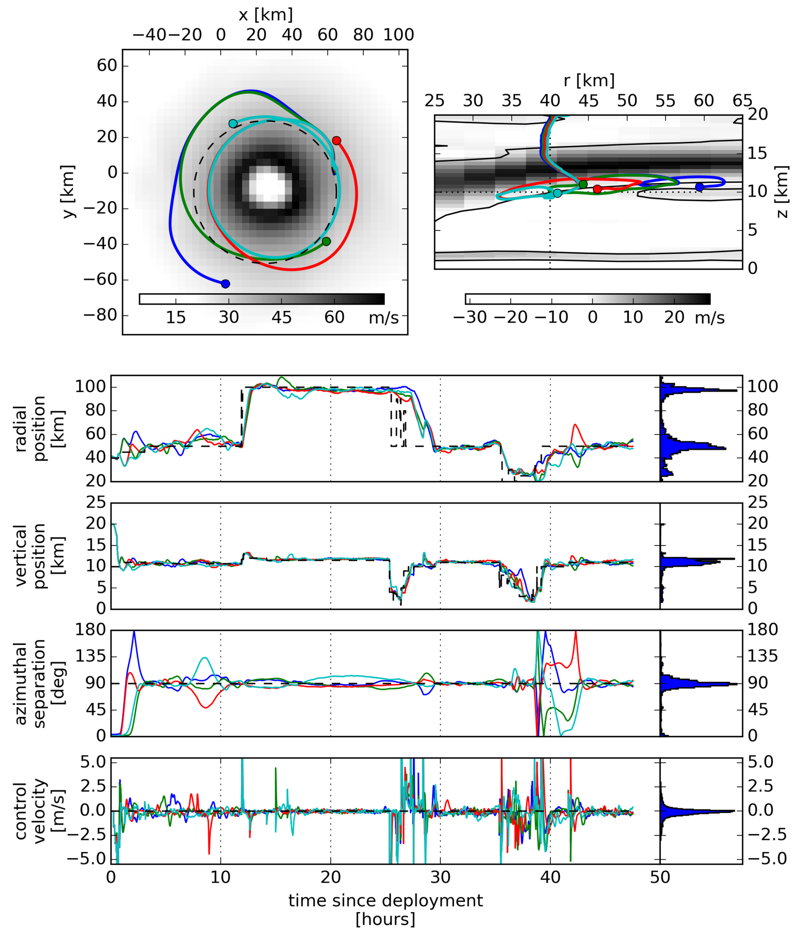
RIGHT: "Aircraft data collected in Hurricane Rita between 1800 and 1820 UTC 22 September 2005 [...] comprehensive mean of dual-Doppler storm-relative winds derived from ELDORA data" (Houze 2007, Science)

[a] these are computationally inexpensive approximation of coherent Lagrangian surfaces

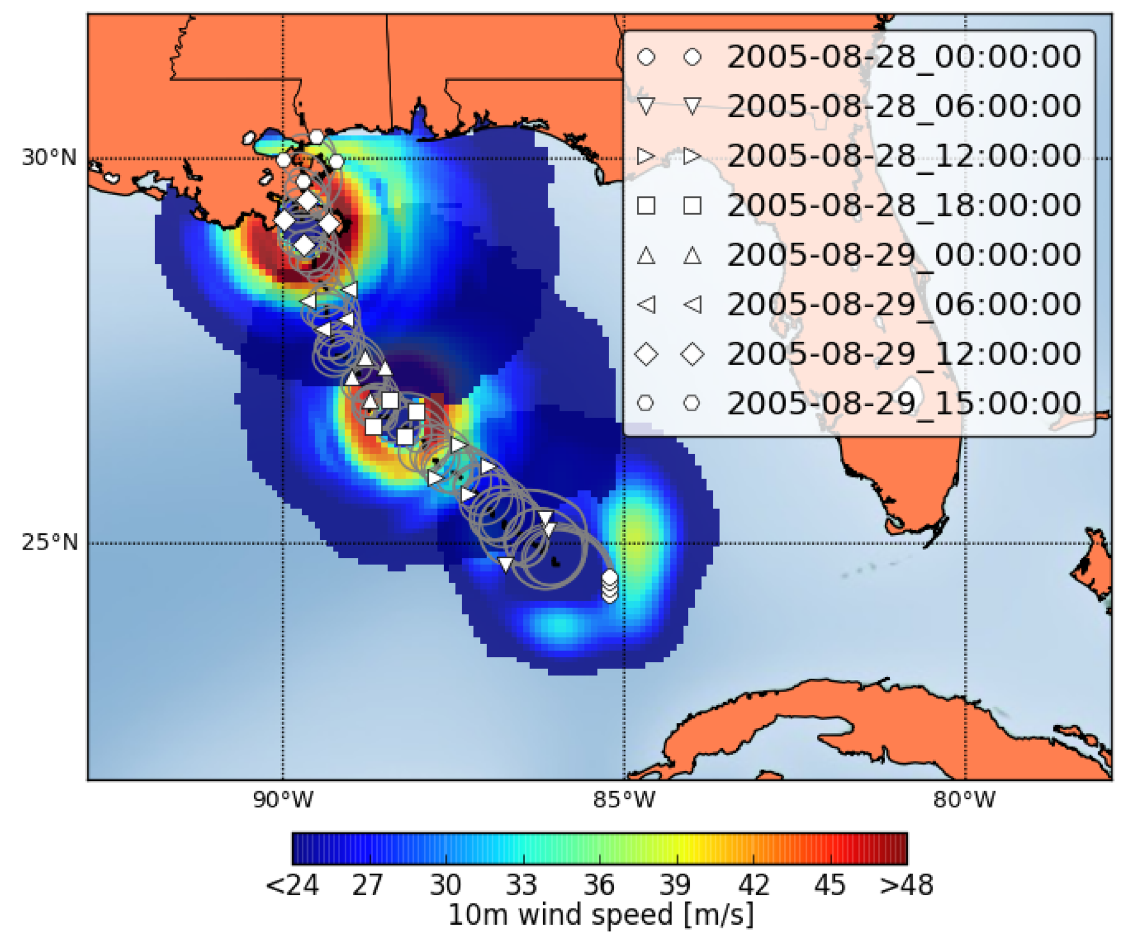
Results



Maneuvering of eight balloons within a simulation of a hurricane. TOP-LEFT: a cluster of four balloons is released from sea level, and another cluster of four balloons is released from an altitude of 20km. TOP-RIGHT: after less than four hours, the target configuration is obtained. BOTTOM-LEFT: leveraging the flowfield, one of the groups of four balloons is directed out to a larger target radius. BOTTOM-RIGHT: the balloons are returned to their initial configuration. The gray surface represents the time-evolving manifold of zero radial velocity.



Simulation of controlled balloon trajectories TOP: balloons trajectories in the $x-y$ and $r-z$ plane for the first 1.25 hours after deployment. BOTTOM: radial (with respect to the moving hurricane center) and vertical position, azimuthal separation, and vertical control velocity.



Tracks (in gray) of a group of four balloons within a WRF simulation of hurricane Katrina from 0000 UTC 28 August 2005 to 1500 UTC 29 August 2005. White symbols mark the location of the balloons every 6 hours. In color: 10m velocity field every 18 hours.