Sizing up the Gulf's Dead Zone through Geostatistical Modeling

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Overview:

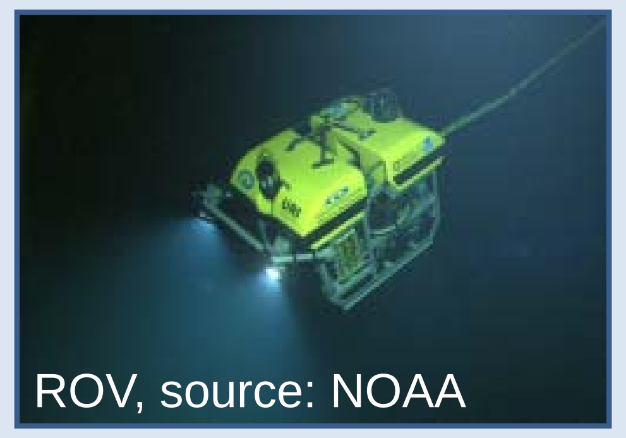
Many coastal ecosystems are subject to an environmental condition known as hypoxia, defined by dissolved oxygen levels too low for the support of healthy aquatic life. A particularly severe example of this problem is the hypoxic zone that forms each summer on the Louisiana coastal shelf. Comprehensive surveys of the coastal shelf are performed each summer by the Louisiana Universities Marine Consortium (LUMCON) [1]. These "shelfwide" cruises are used to assess the severity of hypoxia and to estimate the overall areal extent of the hypoxic zone. The primary objective of this study is to improve our knowledge of the hypoxic extents by:

- Development of a kriging methodology capable of estimating both **hypoxic area and volume**.
- Determination of the **uncertainty** associated with each estimate
- Improvement of model through the inclusion of **spatial and bathymetric trends** (universal kriging, UK).

R/V Pelican, source: LUMCON

A secondary objective is to provide a means for evaluating alternate sampling strategies by:

- Determination of hypoxic extents based on **different subsets of available data**, and assessing the impact on estimation uncertainty.
- Determination of hypoxic extents based on dissolved oxygen **measurements that do not reach sea floor** (e.g. ROV), and assessing impact on estimation uncertainty.



ROV, source: NOAA

Methodology:

In this study, we model the thickness of the hypoxic layer using universal kriging (UK). Sites that are not hypoxic (bottom DO > 2 mg L^{-1}) are assigned effective negative thicknesses based on the degree to which they exceed the hypoxic threshold. Deterministic trends are included using depth and geographic coordinates as covariates; and the stochastic component is modeled using an exponential variogram/covariance function, allowing for anisotropy. Note that if the deterministic component is omitted, then we are left with an ordinary kriging (OK) model. Similarly, if the spatially correlated component is omitted, then we are left with a multiple linear regression model. Estimates of hypoxic area and volume (and their uncertainties) are determined through creating an ensemble of conditional realizations which sample from the stochastic portion of the model, e.g. [2].

UK Formulation:

$$F = X\beta + \eta + \epsilon$$

Response Variable

Deterministic Trends

Spatially Correlated Stochasticity

Uncorrelated Stochasticity

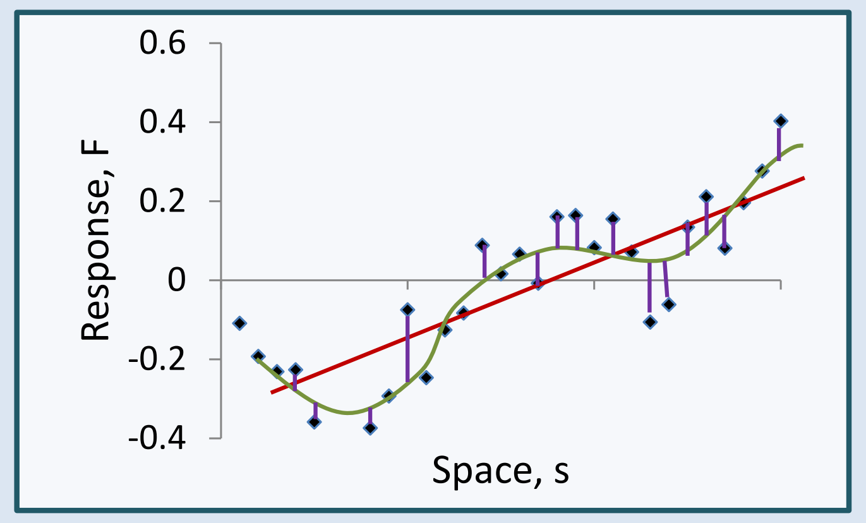


Figure 1: Illustration of UK model components for a simple, example dataset (colors corresponding to equation on left)

Hypoxic extents determined using complete shelfwide cruise data:

Estimates of hypoxic thickness, area, and volume were developed for a ten-year period (1998-2007). Figure 2 shows UK results for 1998 and 2007, two years with very different spatial patterns in hypoxia. Area and volume results are summarized for the entire study period in Figure 3. As shown, there is a great deal of interannual variability in the size of the hypoxic zone. Compared to the UK results, OK results (not shown) have greater uncertainty and tend to over-estimate the hypoxic extents because results are not constrained by the deterministic trends.

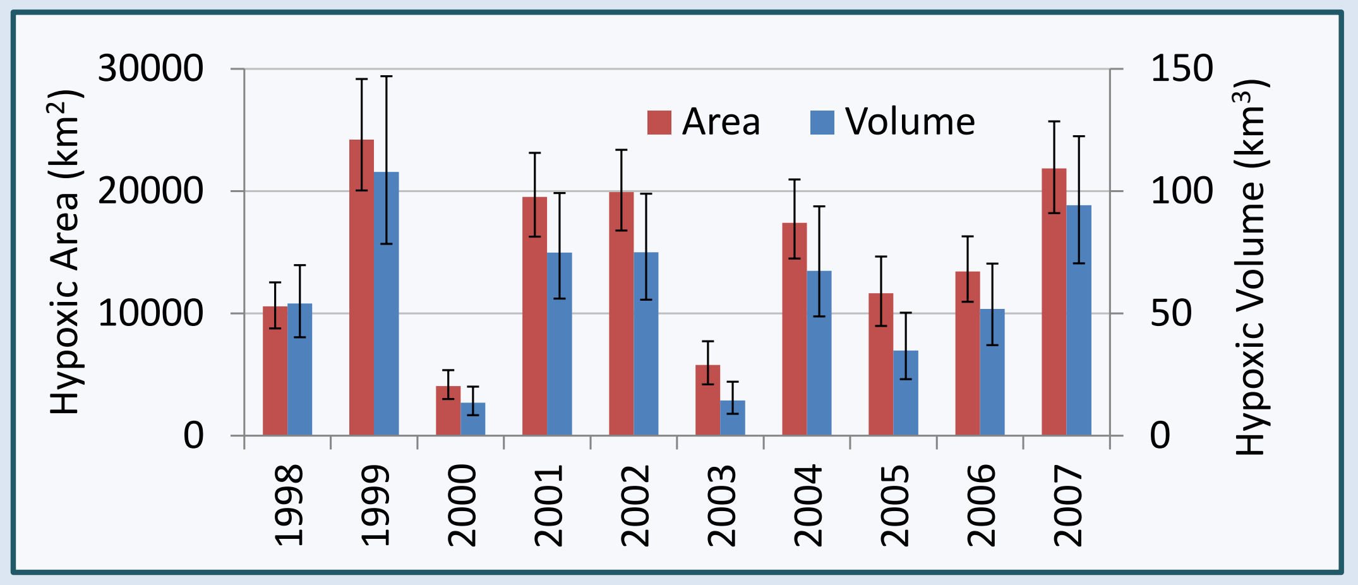


Figure 3: UK Area and Vol. results with 95% CI

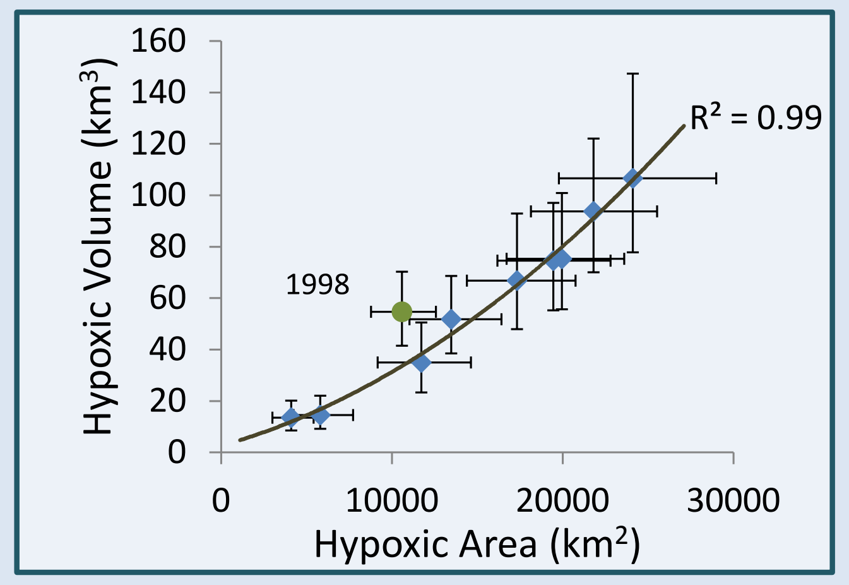


Fig. 4: Volume vs. Area w/95% CI

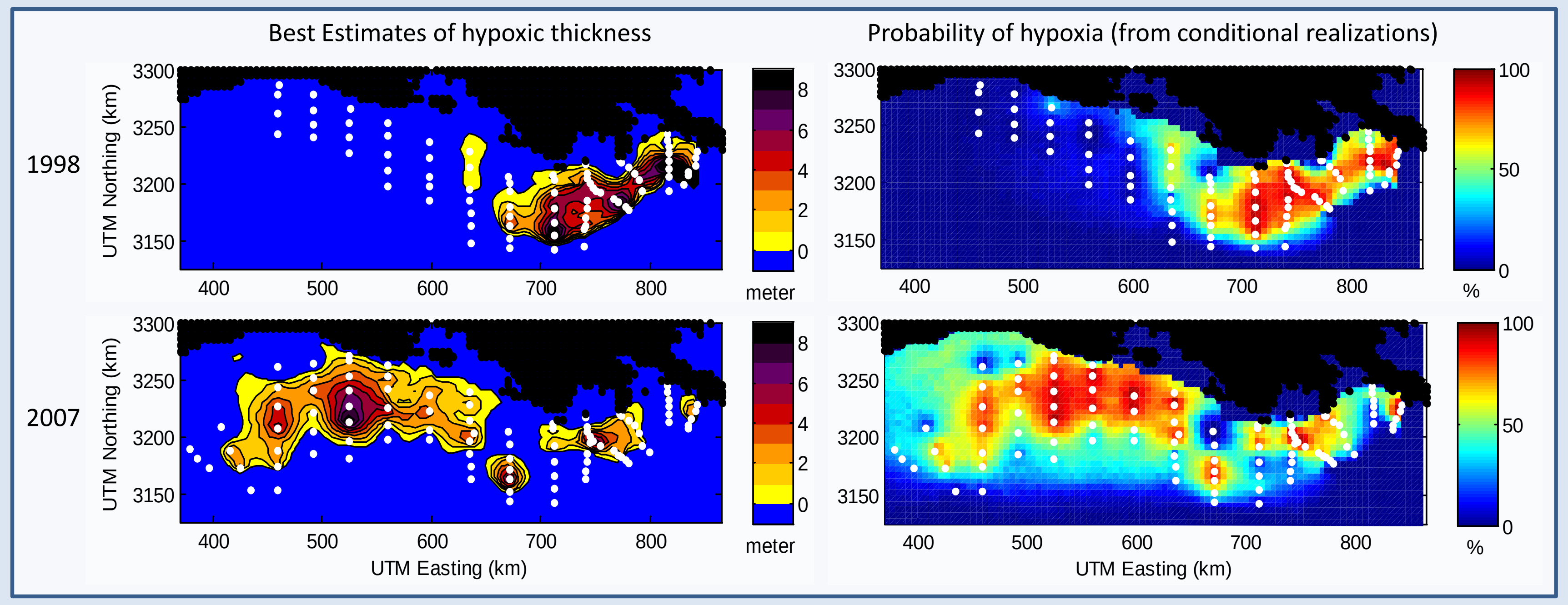


Figure 2: Example UK results for 1998 and 2007

There appears to be a non-linear relationship between hypoxic volume and area (Figure 4). This implies that as the hypoxic area increases, so to does the average hypoxic thickness, resulting in an increasingly stressed aquatic environment. In 1998, which appears to be an outlier year, hypoxia was "piled up" on the eastern end of the study area (see Figure 2, upper left). This was due to unusually strong eastward currents [1], which resulted in a similar pattern of hypoxia in 2009 [3].

Results for alternate sampling scenarios:

Several alternate sampling scenarios were considered in this study (Table 1). All of these scenarios represent a reduction in sampling effort when compared to the complete LUMCON shelfwide cruises (Scenario "A"). The "T" scenarios include only certain sampling transects, while the "S" scenarios include only a fraction of sites along the transects. As an example, Figure 5 shows the sites included in scenarios S33 and T4 for 2004. The "O" scenarios use all of the available sites, but are based on the hypoxic thicknesses that exist above a given offset from the sea floor (thus representing sampling instruments that do not reach the bottom of the water column).

Table 1: Alternate sampling scenarios

Type	Scenario	Description	sites used
All data	A	all samples	100%
Transect thinning	T6	keep A,C,D,F,H,J transects	50.1%
	T4	keep A,C,F,H transects	34.9%
	T2	keep C & F transects	19.8%
Sample thinning	S50	keep every 2nd sample	50%
	S33	keep every 3rd sample	33%
	S20	keep every 5th sample	20%
Bottom offset	O1	remove data for bottom 1m	100%
	O2	remove data for bottom 2m	100%
	O3	remove data for bottom 3m	100%

As fewer data are used, estimates of the hypoxic extents become less certain. This is illustrated in Figure 6, which presents the mean relative standard error (RSE) for each sampling scenario. Note that the "T" scenarios result in greater uncertainty than the "S" scenarios, though they use comparable numbers of sites (see Table 1).

As uncertainty increases, it becomes more difficult to identify year-to-year changes in the size of the hypoxic zone. This effect can be quantified by calculating the percent of year-to-year pairings that are significantly different (90% level) for each scenario. For example, scenario A results in 76% of the year-to-year pairings of hypoxic area being significantly different, while scenario T2 results in only 42% being significantly different.

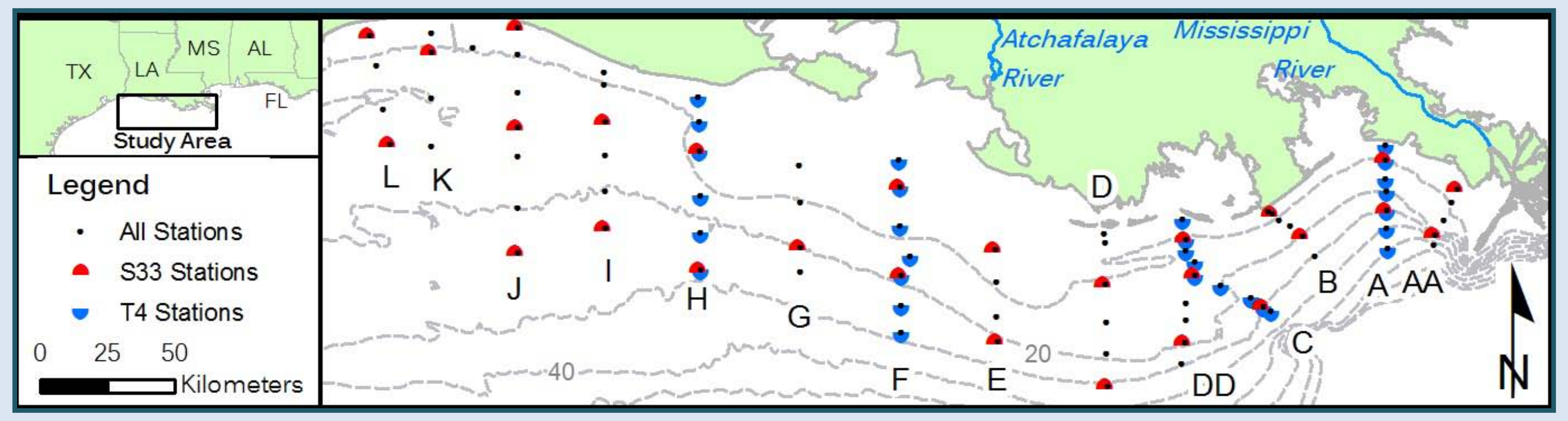


Figure 5: S33 and T4 alternate sampling scenarios, 2004

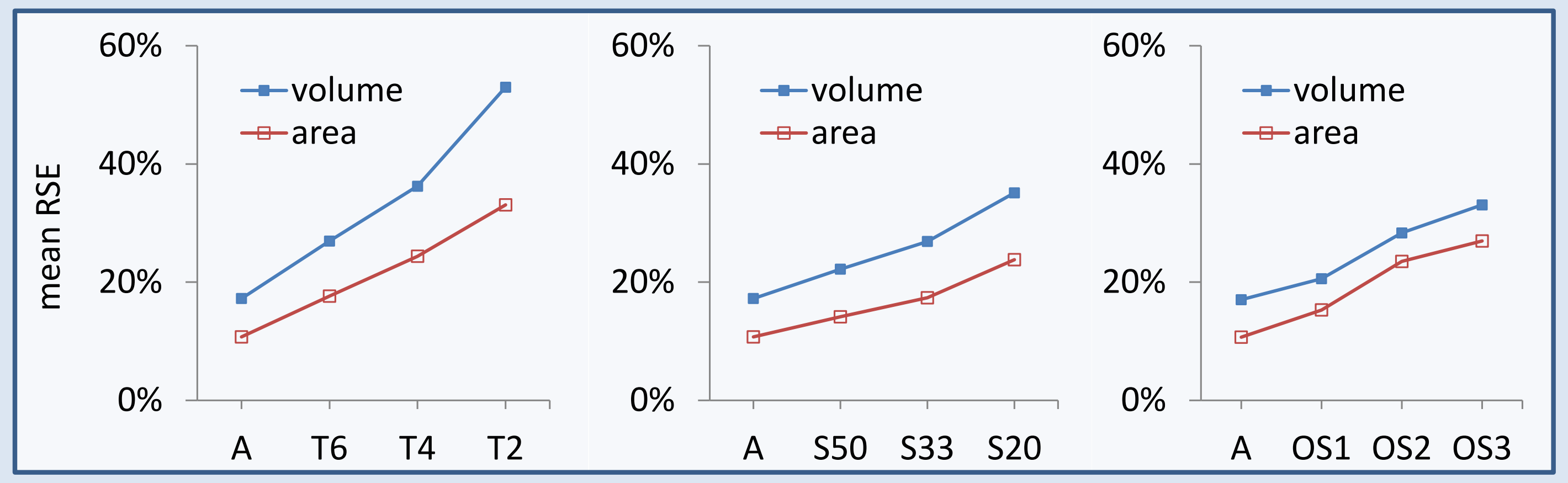


Figure 6: Mean uncertainty (RSE) for different sampling scenarios

Summary:

- Geostatistical modeling provides an effective means of estimating the hypoxic area and volume along with the associated uncertainty.
- Inclusion of deterministic trends (UK) substantially reduces the uncertainty in the model-estimated extents.
- Using this approach and the existing shelfwide cruise data, we can develop fairly precise estimates of hypoxic area and volume with mean RSE's of 11% and 17%, respectively.
- Using this approach, we can evaluate alternative sampling strategies based on their resulting uncertainties.
- From a modeling perspective, the existing transect sampling pattern is suboptimal for estimating hypoxic extents because monitoring sites are too dense in the N-S direction relative to the E-W direction.
- The relationship between hypoxic area and volume appears to be non-linear because hypoxic thickness typically increases with area.

Works cited:

[1] Rabalais, N.N., et al., Hypoxia in the northern Gulf of Mexico: Does the science support the plan to reduce, mitigate, and control hypoxia? *Estuaries and Coasts*, 2007.

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[3] Turner, R.E., et al., Predicting summer hypoxia in the northern Gulf of Mexico: Redux. *Marine Pollution Bulletin*, 2012.

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RESULTS SHOWN ARE PRELIMINARY AND SUBJECT TO CHANGE