Flash before the Storm: Predicting Hurricane Intensification using LANL Lightning Data

1st Year Review, July 18, 2008

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LA-UR-08-3119

Overview

- Our project is a **new** LDRD project that began last October.
- Our FY08 budget is ≈ 950K; about 12 people including 2 postdocs and 2 students.
- The goal of our project is too improve hurricane intensity forecasts via:
  - New RF array measurements of hurricane lightning.
  - New cloud physics modeling of cloud electrification.
  - New data assimilation scheme to ingest lightning observations, and thereby, improve hurricane forecast accuracy.
- For today's review, focus on our **new Gulf RF array**, and the **hurricane modeling and science** that validates continued LDRD support of this project.
- Leave data assimilation for discussion period.

Criteria for Successful Project Review

General criteria for assessing a 1st year LDRD/DR:

1. **Relevance**. Relation to strategic directions of the Laboratory? Does PI have a transition plan, mapping out future for the project?
2. **Performance**. Good progress against its first year milestones? Appropriate team, collaborators, and facilities?
3. **Quality**. Are the initial S&T results of high quality? Are project participants publishing in the archival literature and conferences?

Specific criteria for this 1st year LDRD/DR:

1. Demonstrate refined hypotheses and specific plans for testing these hypotheses with regard to (i) incorporation of electrification into the model, and (ii) non-linear processes that drive larger spatial scale behavior within the eyewall.
2. Demonstrate 3-D geolocation of lightning through a preliminary deployment of the sensor array. While full deployment and demonstration is not feasible by the time of the review, demonstrate that the 3-D spatial resolution of the sensor array is sufficient to resolve convection in the eyewall.

Outline

- Project motivation, framework and goals.
- New Gulf RF Lighting Array:
  - What is new and unique?
  - Where is it? Who are our collaborators?
  - What are the challenges?
  - Excellent progress that's been made.
- New Hurricane Modeling Studies:
  - First-ever detailed hurricane studies with cloud electrification.
  - Discovery: idealized hurricane simulations show a sudden burst of lighting activity due to convective forcing.
  - Realistic simulations of hurricane Guillermo.
- Publications
- Summary

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Science & Technology Framework

In three years, we will achieve success in two broad **Science & Technology Grand Challenges** that are the foundation of this project:

- Perform the first-ever real-time 3D mapping of **convective events in the hurricane eyewall** using lightning as a proxy, and enabled by the **world's first dual VLF-VHF lightning mapping array** deployed in the Gulf of Mexico.
- Demonstrate that rapid **hurricane intensification**, the sudden *large-scale* transition and reorganization of a vastly multiscale system, can be **accurately forecast** using a novel model that **assimilates real-time knowledge** of critical *small-scale* processes.

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Metric of Success

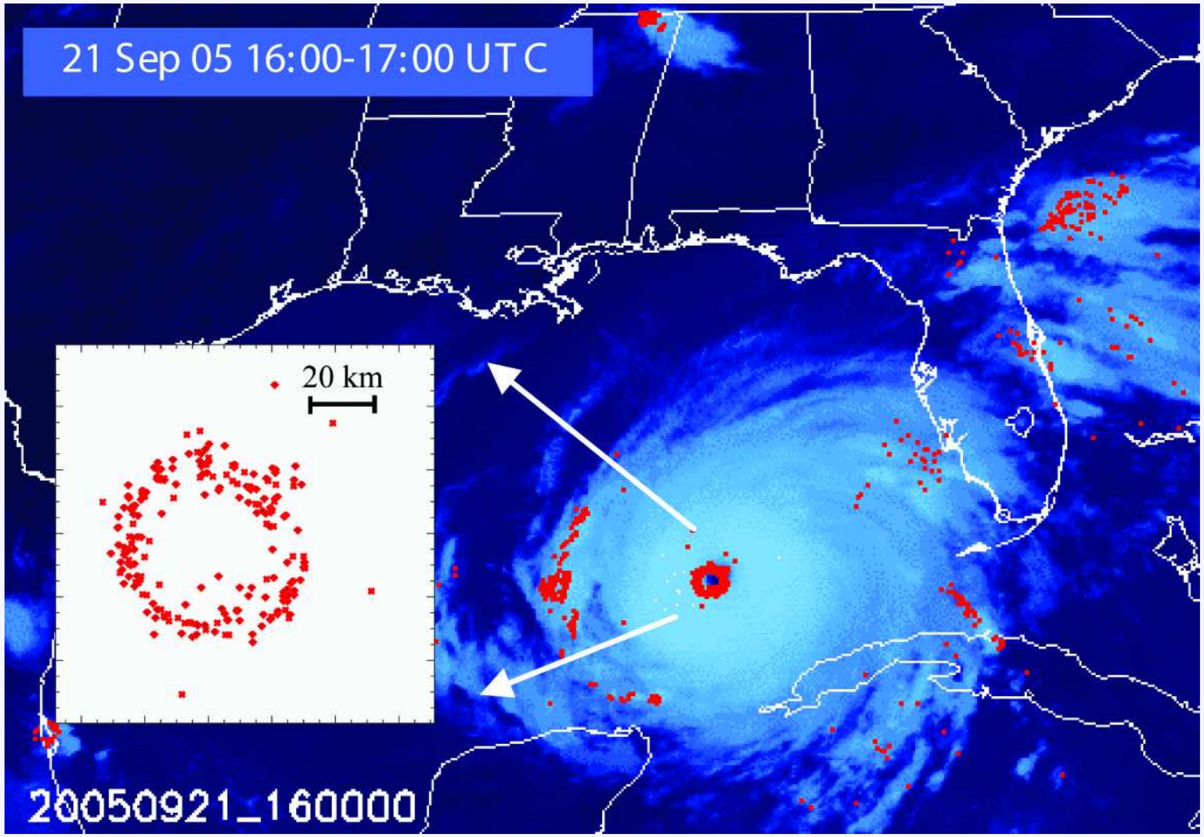
Our metric of success is a national standard established by NOAA's Hurricane Intensity Research Working Group:

> . . . achieve a *10 knot improvement in 48-hour intensity forecasts* of hurricane-strength storms in *5 years* by the application of
> 1. *advanced numerical models*,
> 2. *novel methods of data assimilation*, and
> 3. *improved observations*
>
> through a focused applied research and development program.

We have the proven observational technology and scientific expertise to achieve this national goal in **only 3 years**.

Improved Observations

Lightning activity from Hurricane Rita.



- Motivates need for new 3D "total lightning mapping" array.
- What is the charge structure of hot towers in the eyewall?
- How is lightning activity influenced by intensification?

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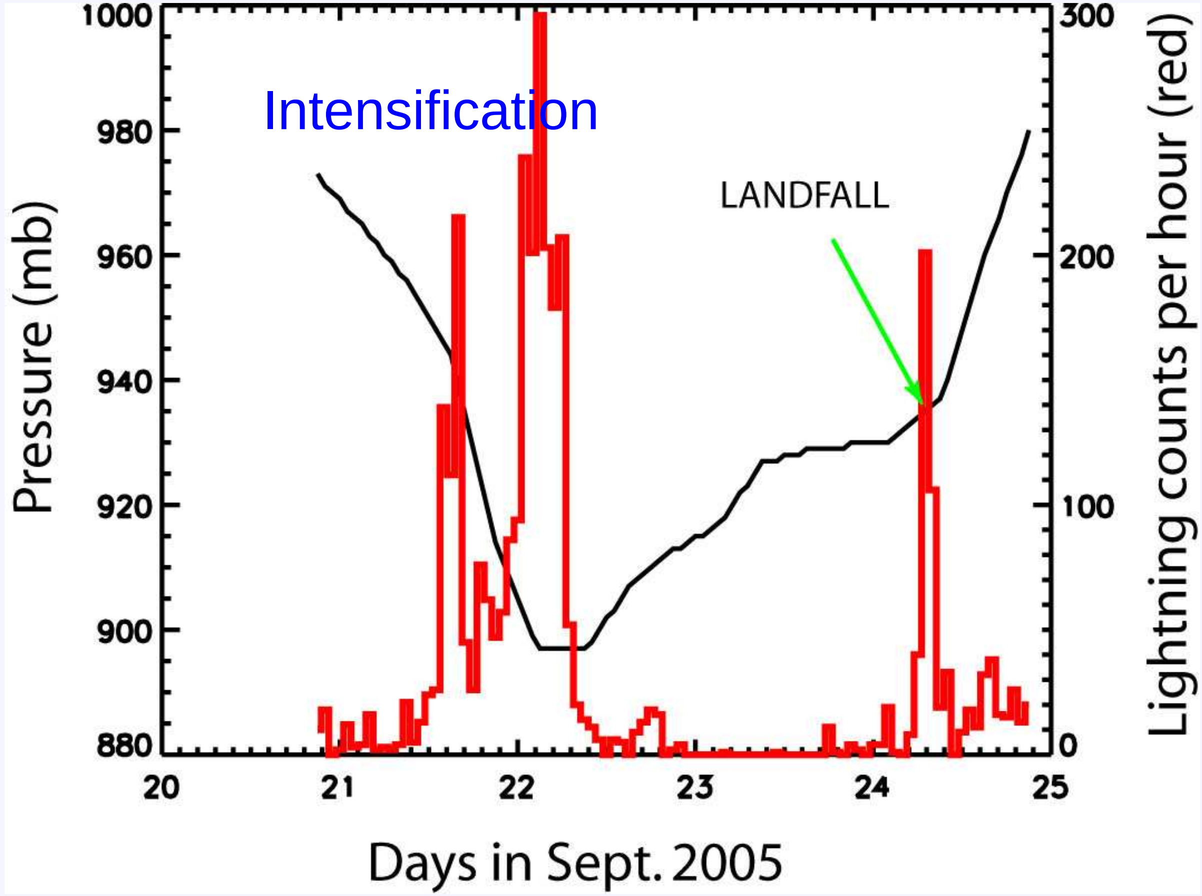
Improved Observations (II)



- Hurricane Rita's intensification is coincident with onset of lightning activity.
- Eye pressure is calculated a-posteriori from a reanalysis.

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Context for a New Lightning Array in Gulf

Two paradigms for lightning detection and geolocation:

VLF Detection: Record RF radiation in 10-20 KHz band.

- Long-range (2000+ km) detection, and 2000+ km array baselines.
- NLDN (used by NWS) only detects cloud-to-ground (CG).
- LANL technology records sferic (EMP pulse); detects both intra-cloud and CG lightning.
- NLDN data has no vertical resolution; LANL system may provide some height info via ionospheric modeling.

VHF Detection: Record RF radiation in 1-70 MHz band.

- Very accurate (100 m) height retrieval.
- Signal is attenuated over land.
- Line-of-sight detection; short 50 km baselines.
- Technology pioneered by NM Tech, for periodic campaigns.

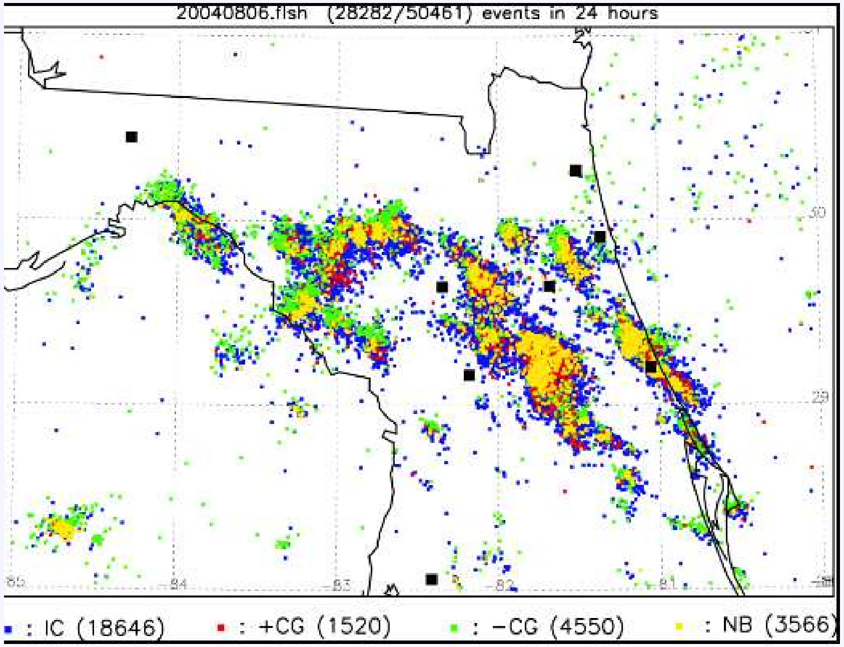
A New Dual VLF-VHF Lightning Observing System

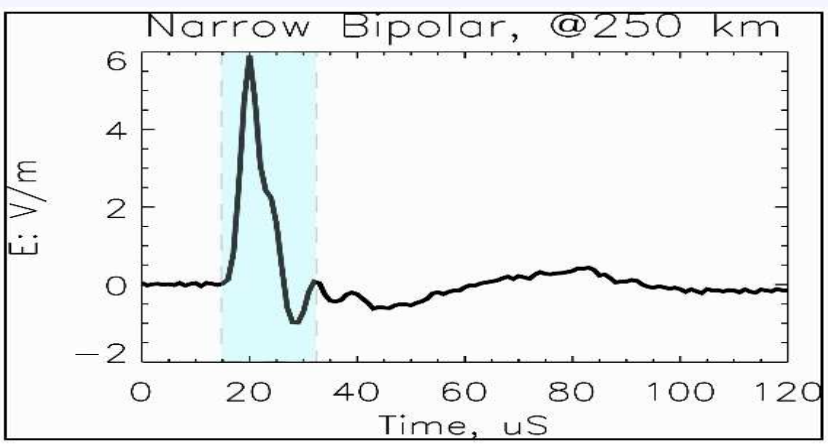
We are developing the first-ever
dual VLF-VHF lightning observing system
in the Gulf of Mexico, that exploits:

- Low VHF attenuation over sea water.
- Longer 150 km baselines for long-range (500 km) VHF detection.
- LANL capability to detect both CG and IC lighting.

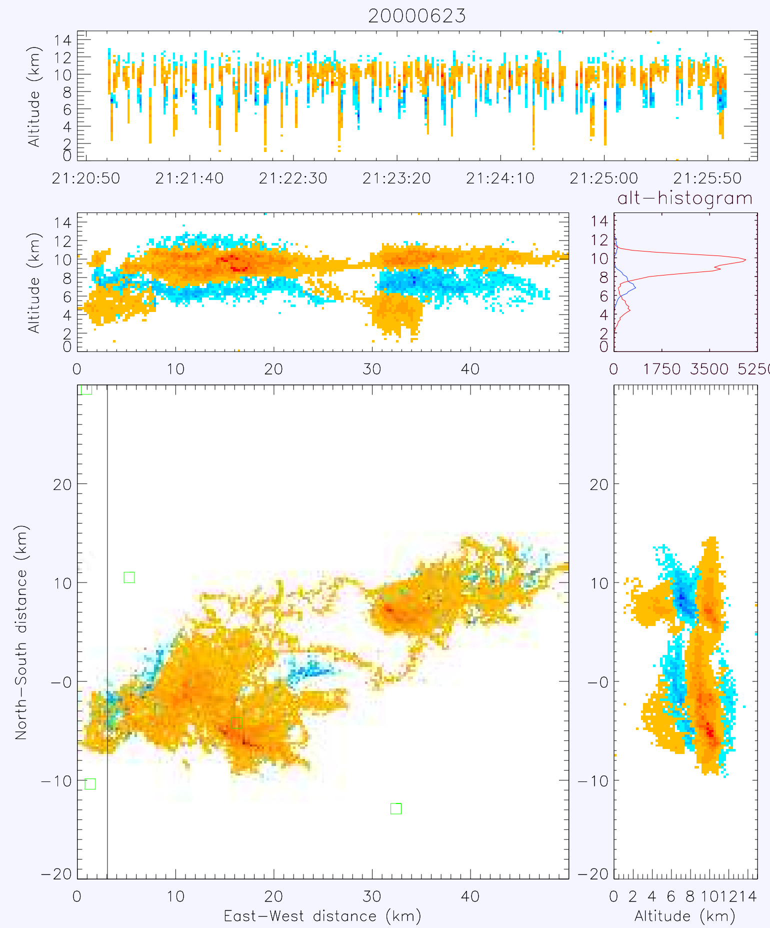
A New Dual VHF-VLF Lightning Observing System (II)

LASA VLF





VHF (from NM Tech LMA system)



Charge transfer can be calculated from new dual VHF–VLF.

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Our New Gulf RF Lightning Array

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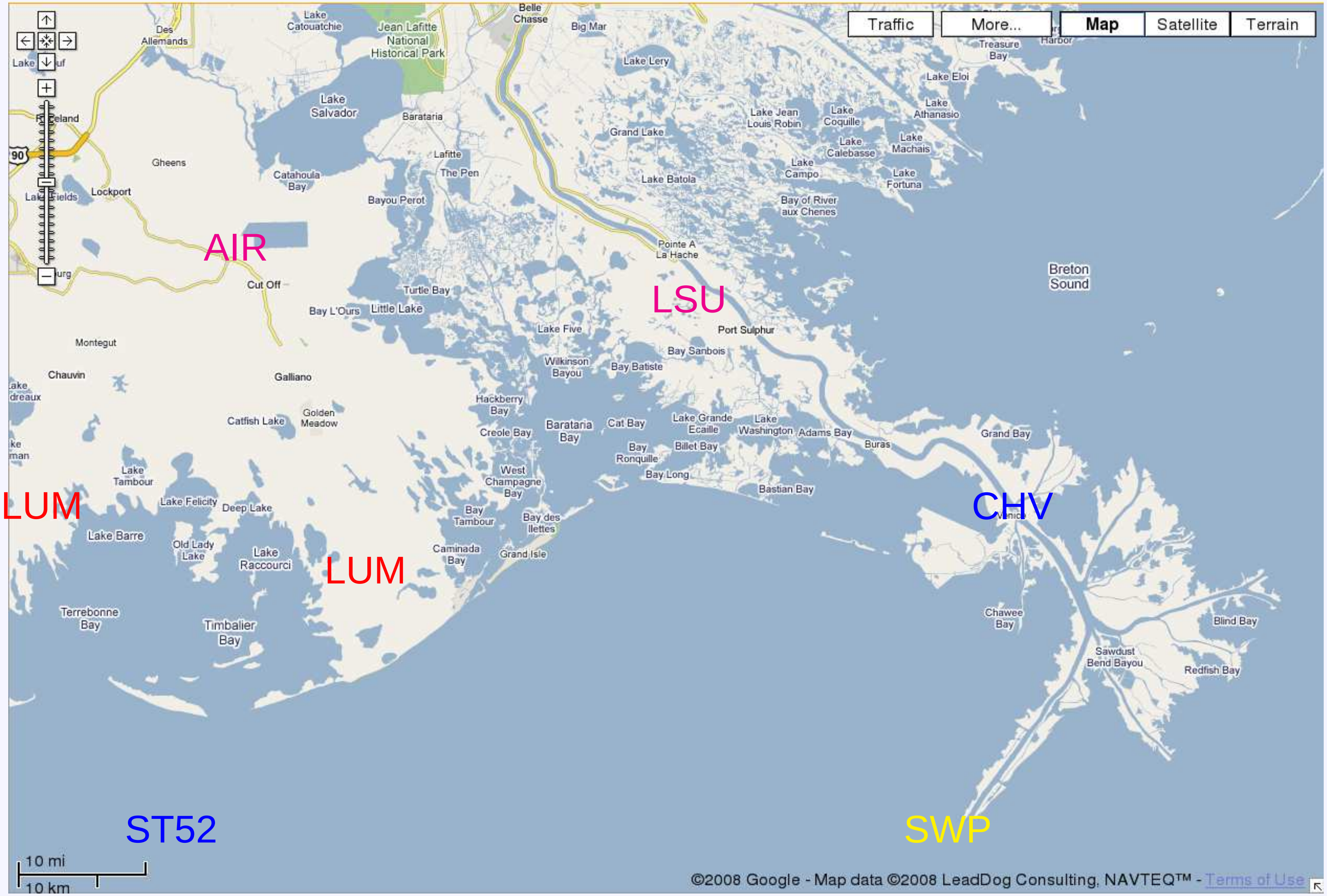
Sensor Array–New Orleans Area



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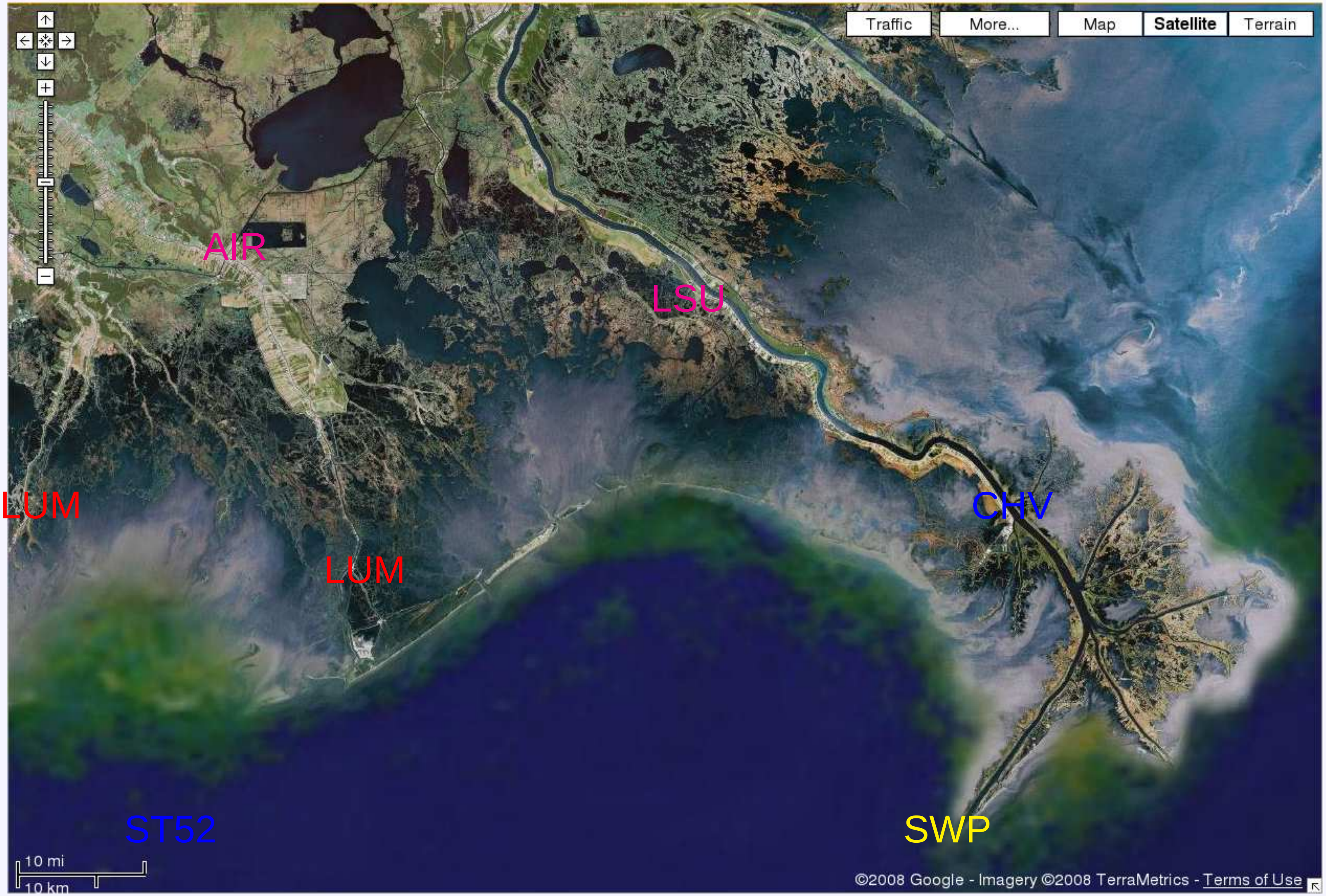
Sensor Array–New Orleans Area



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Why Hurricanes? Why Gulf of Mexico?

We are all aware of the enormous human tragedy inflicted by hurricanes Katrina and Rita.

But, these hurricanes also exposed the vulnerability of our energy security to hurricane disaster.

- Gulf of Mexico provides **29% of domestic oil supply** and **19% of domestic gas production**.
- Katrina, alone, destroyed **46 platforms** and **four jack-up rigs**.
- She inflicted severe damage on 37,000-ton, billion-dollar Shell Mars platform—**most prolific in Gulf** producing 148,000 barrels/day and designed for 140-mph winds/70 ft waves.
- Given current energy crisis, a hurricane in the Gulf this summer would have **dire consequences** for US economy and energy security.

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Our University–Chevron–LANL Partnership

LUMCON: Louisiana Universities Marine Consortium.
- (1) Headquarters,
- (2) Fourchon.

Nicholls University:
- Roof of the library.

River Pilot Association:
- Base at tip of Mississippi.

Chevron:
- (1) Venice on-shore base,
- (2) Oil platform ST-52.

LSU:
- Agricultural area.

Fourchon Port Authorities:
- Airport.

Challenges of Building a Real-Time VHF Array in New Orleans

Firstly, this task is **much more difficult**, than one might first suggest.

1. New sensor technology; requires new design and testing.
2. Rely on generosity of host.
3. Background VHF noise. Challenging in Mississippi delta with development along narrow bayous.
4. Internet access. Lightning sensors have high data rates (256–512 kbps). DSL service is often not available. SWP and oil platform are challenging. Satellite internet is “download” oriented & unreliable in severe weather.
5. Legal hurdles. LANL will not indemnify universities or corporations.

Summary of Progress to Date

9 months into the project, our progress has been excellent.

- We have designed and tested the world's first dual VLF-VHF lightning sensor.

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- We have deployed 5 sensors on site (3 pending legal agreement).
- We have internet access in place at 5 sites (3 contracts pending).

Site	Sensor	Test	Deployed	Internet	Data
LUMCON1	✔	✔	✔	✔	✔
LUMCON2	✔	✔	✔	✔	✔
SWP	✔	✔	✔	✔	✘
Airport	✔	✔	✔	✔	✘
LSU	✔	✔	✔	✘	✘
Nicholls	✔	✔	✘	✔	✘
Chevron	✔	✔	✘	✘	✘
Platform	✔	✔	✘	✘	✘

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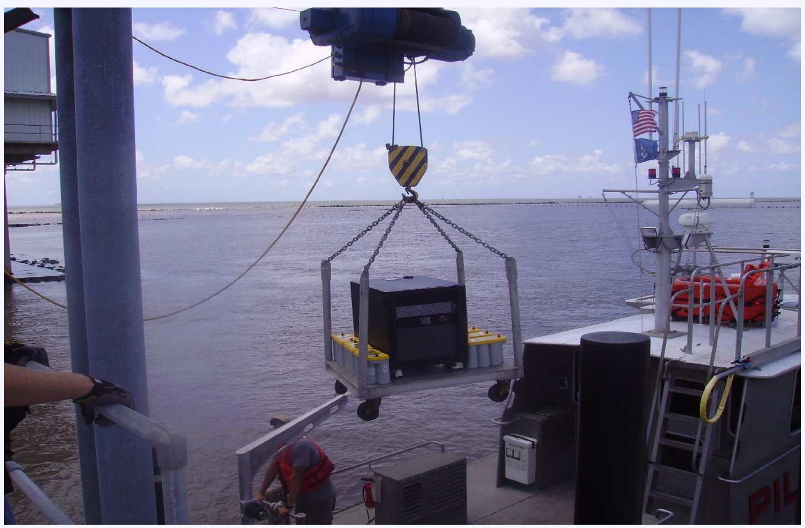
Challenge #1: New Sensor


Sensor unit consists of computer server, pull-out monitor, GPS unit, log amplifier, filters and UPS.

Challenge #1: New Sensor

Antenna is a 1m Rohde & Schwarz monopole with 10 khz–80 Mhz bandwidth.

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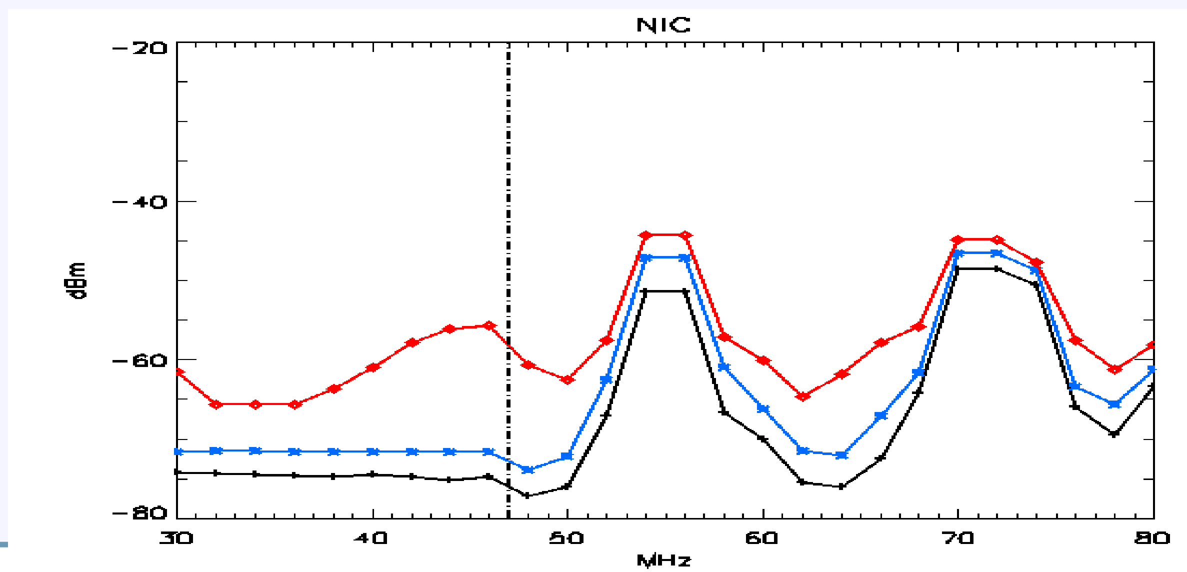
Challenge #2: Background Noise, Nicholls

Nicholls University

VHF Spectrum showing Channel 2 & 4



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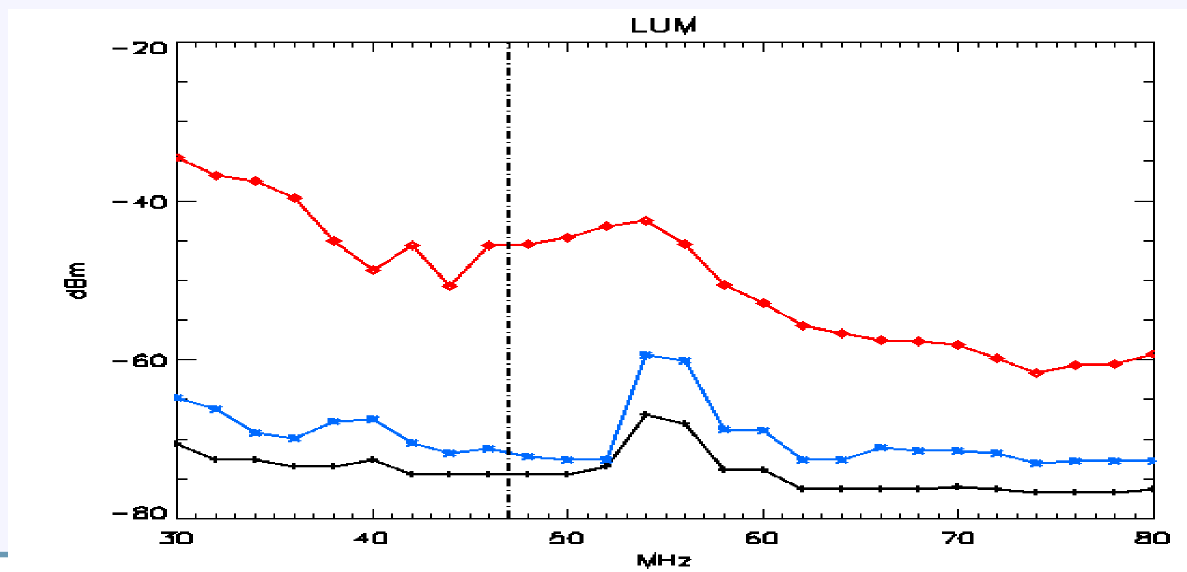
Background Noise, LUMCON Headquarters

View from LUMCON

VHF Spectrum: Channel 2 & Equipment Noise



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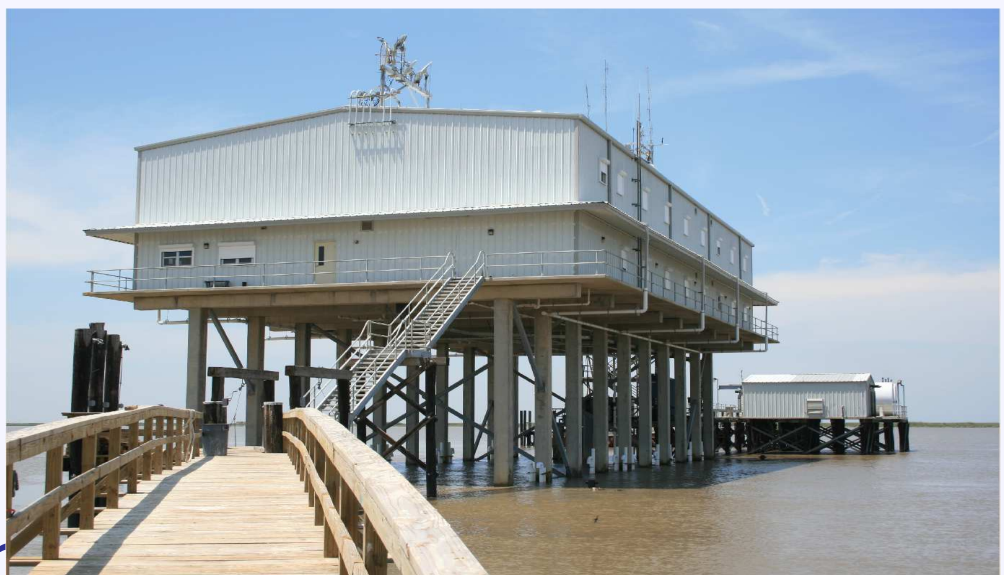
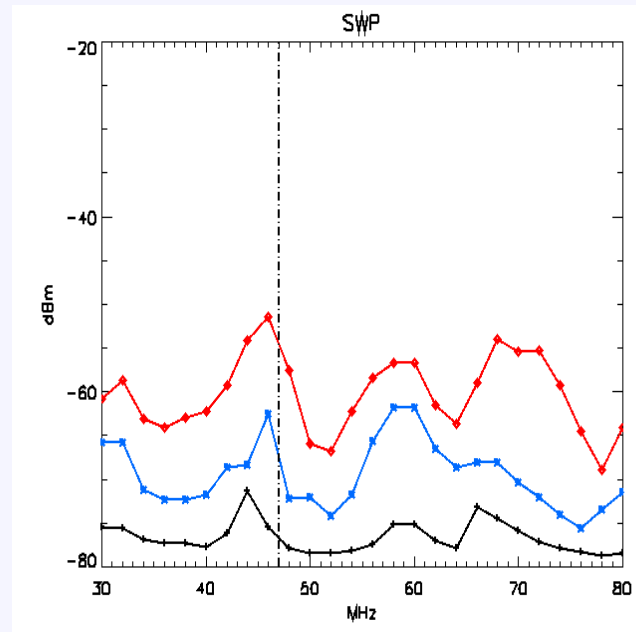
Background Noise, River Pilots at Southwest Pass

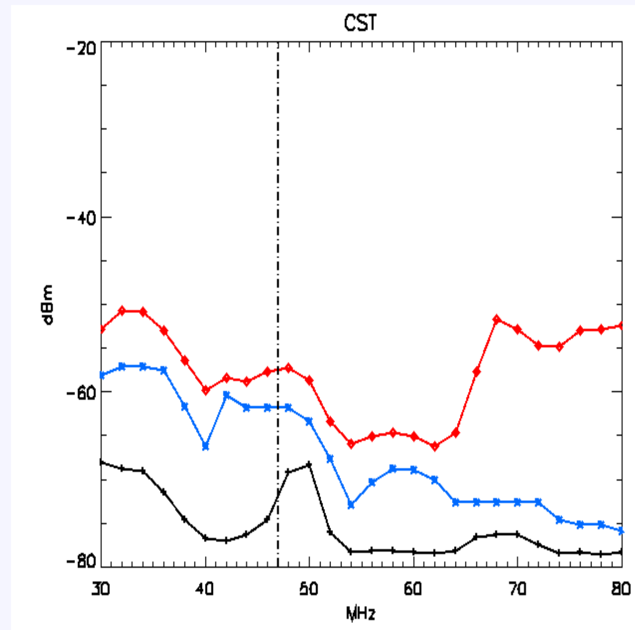


Channel 3 is Clear



Background Noise, Oil Platform ST-52

Channel 3 is Clear



Challenge #3: Internet Access

- Internet access is a primary challenge for our array due to high sensor data rates (256–512 kbps).
- Satellite internet appears promising, but (i) download oriented, (ii) fair-access policy throttles data, (iii) unreliable in severe weather.
- Stratos SGI operates an expensive microwave network in Gulf.

Site	Internet	Cost	Installation	Data
LUMCON1	DSL	–	✔	✔
LUMCON2	Cable	–	✔	✔
SWP	Stratos MW	$250/month	✔	✘
Airport	DSL	$150/month	✔	✘
LSU	T-1	–	✘	✘
Nicholls	T-1	–	✔	✘
Chevron	T-1	$700/month	✘	✘
Platform	Stratos MW	$800/month	✘	✘

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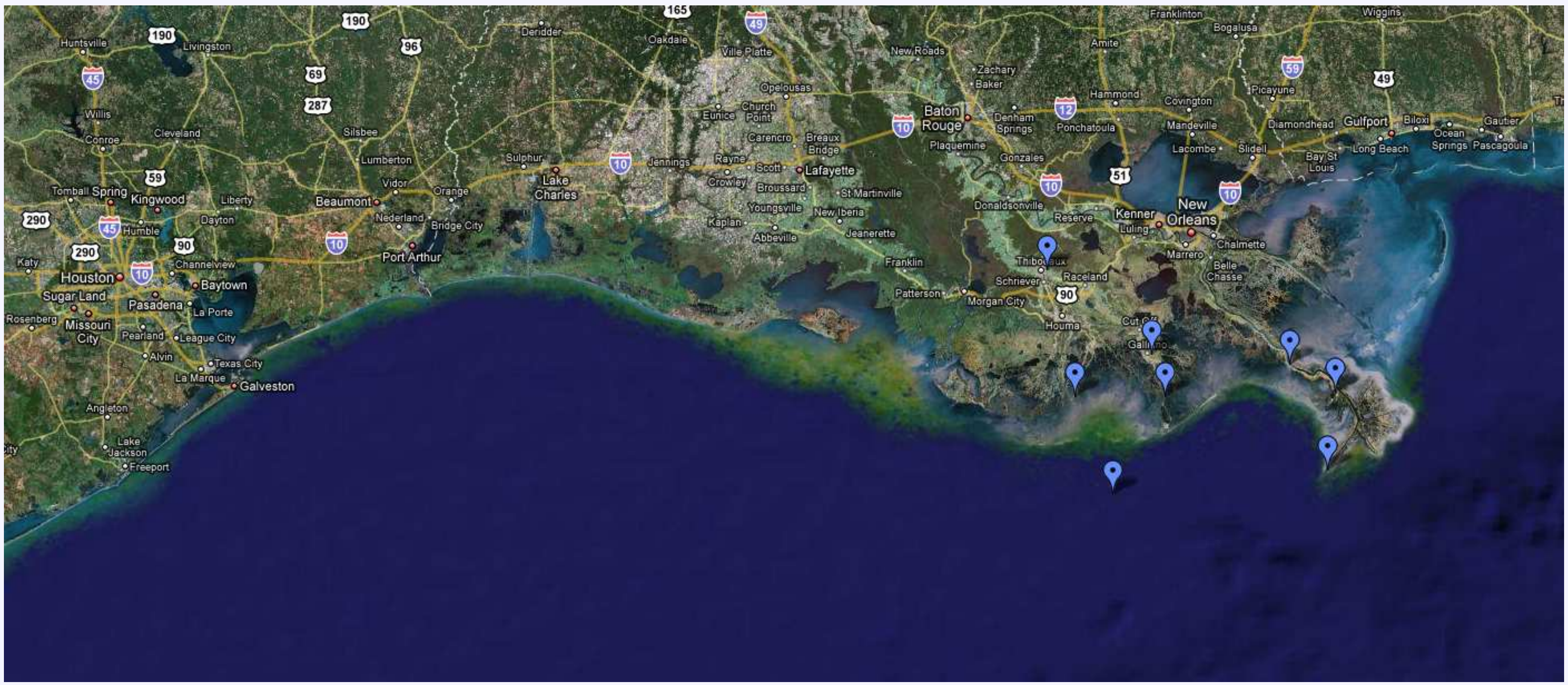
Relevance to National Hurricane Program?

Top hurricane threatened areas:

1. New Orleans, Louisiana
2. Lake Okeechobee, Florida
3. Florida Keys
4. Coastal Mississippi
5. Miami/Ft. Lauderdale, Florida
6. Galveston/Houston, Texas



We are building infrastructure and capability for real-time high-frequency observations, e.g. atmospheric profiling

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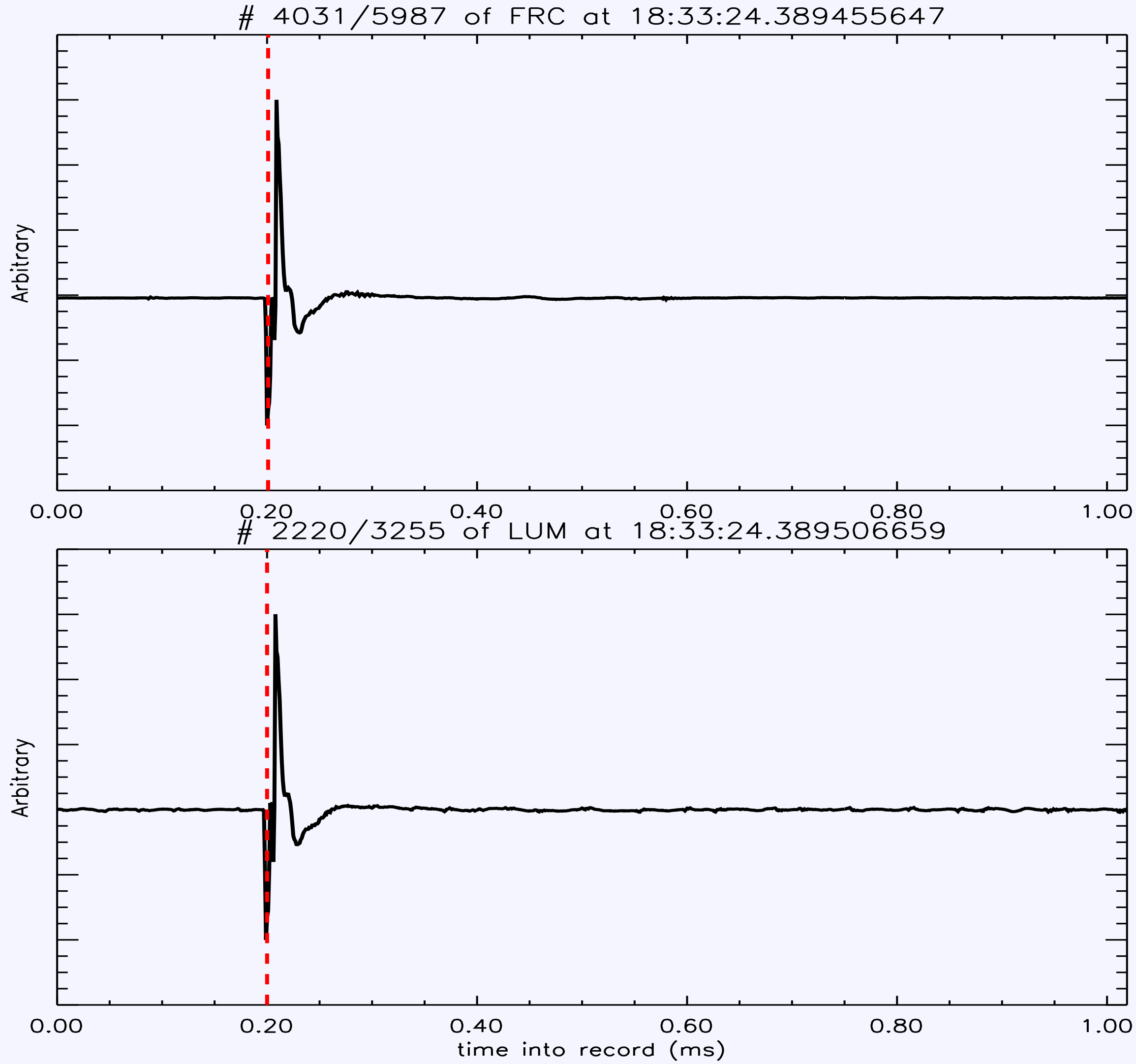
Challenge #4: Legal Agreements

- Most frustrating and disappointing aspect of this project: slow, tedious progress on legal agreements.
- Basic problem is one of indemnity. LANL provides insurance for workers and liability insurance for their actions. But LANL will not indemnify a corporation or university.
- Both Chevron and Nicholls State University wanted LANL to indemnify them for damages caused by our sensor. Both are considering weaker indemnification language.

Secondary issues:

- Very difficult to get full attention of LANL/Chevron legal council; no $$$ involved.
- Negotiations started with a “space-lease agreement”, evolved into MOU via PCM office; requires Director’s signature.

Preliminary VLF Array Data



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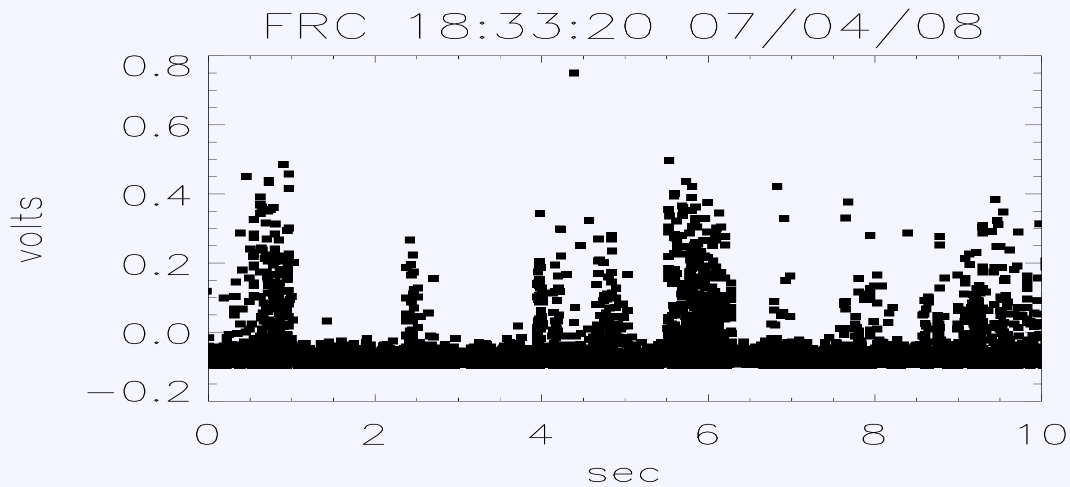
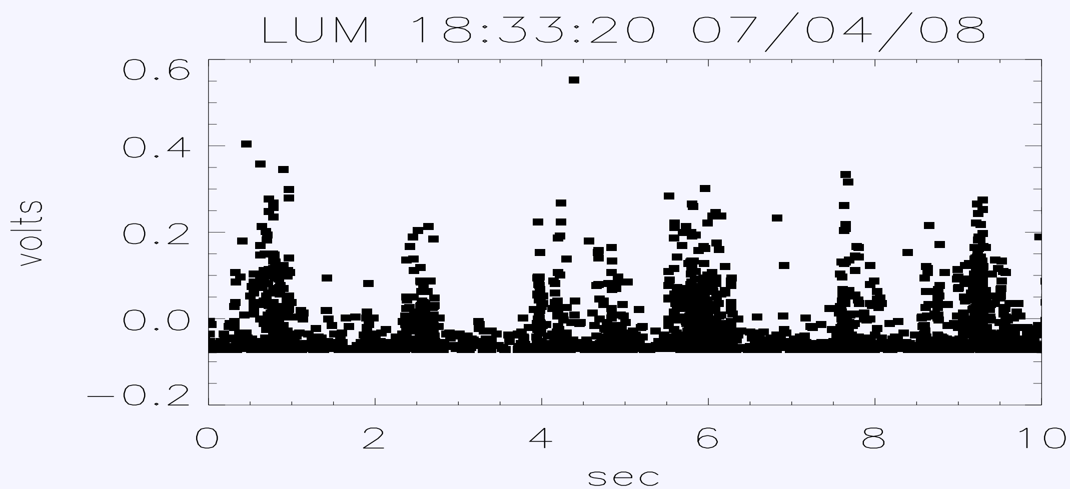
Preliminary VHF Array Data





Accuracy from laboratory VHF pulse tests:

$\Delta x = (100\ ns) \times (3 \times 10^8\ m/s) = 33\ m$; Accuracy in field depends on # sensors, background noise etc.

Keeping up with the Jones'. . .

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Lightning Modeling and Hurricane Intensification

Lightning, Cloud Physics and Hurricane Intensification

- Hypothesis that lightning detection can forecast hurricane intensification is not new (Molinari et al. 1994, 1999).
- Various groups studying lightning/microphysics & hurricanes, e.g. Observational Studies:
    - Deierling & Latham (NCAR), Petersen & Christian (Alabama), demonstrated strong correlation (>0.9) between lightning flash rate and ice/precipitation masses and fluxes in thunderstorms.
    - Businger (Hawaii) studying hurricane lightning.
    - Future NPOESS VIIRS for on-orbit lightning monitoring (NRL).

  Modeling Studies:
    - McFarquhar, Heymsfield, Dudhia, Halverson etc., impact of cloud microphysics on hurricane forecasts.
    - Oklahoma group (Mansell, MacGorman etc.): leads the field in lightning modeling and data assimilation.

Lightning, Cloud Physics and Hurricane Intensification

The central objectives of this project:

- Build and deploy the world's first dual VLF-VHF lightning array in the New Orleans area.
- Perform the first-ever systematic study and validation of hurricane simulation and forecasting with cloud electrification and lightning prediction.
- Develop a new data assimilation scheme to ingest dual VLF-VHF lightning observations, and thereby, improve hurricane forecast accuracy.

Our first-year achievements wrt understanding the relationship between eyewall lightning, convection and hurricane intensification prediction are aligned with these goals.

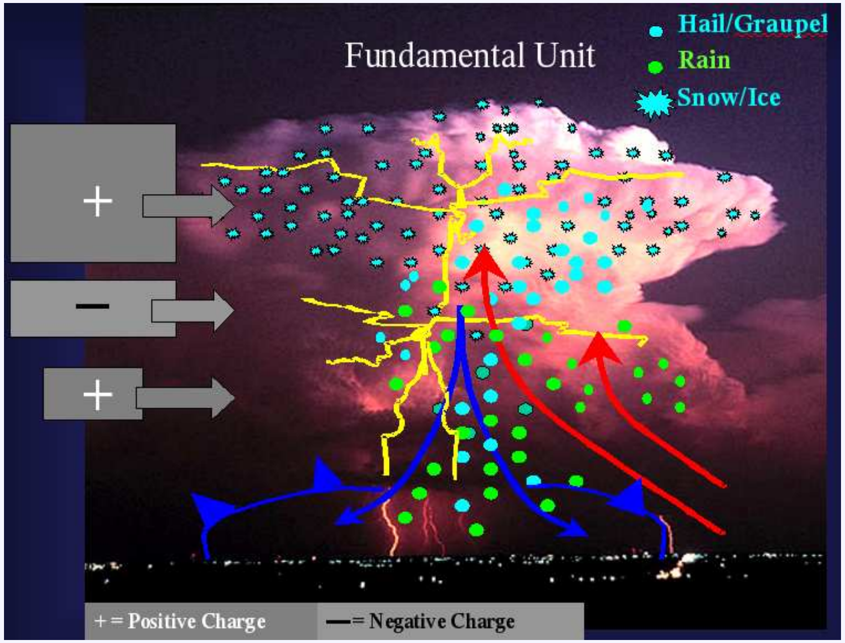
Lightning & Intensification: 1st Year Achievements

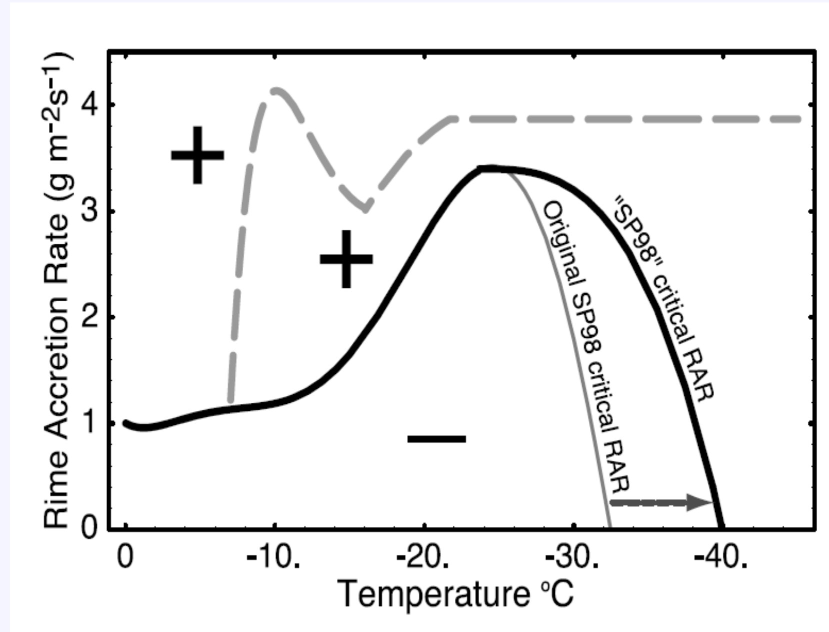
- Developed a unique hurricane forecast model with
  - Cloud electrification and lightning prediction.
  - Differential (smooth) numerics with greatly reduced time errors.
  - Option to use a particle-based (Lagrangian) cloud model which overcomes bin limitations.
- Performed the first-ever detailed hurricane simulations with lightning prediction.
- Demonstrated the first modeling validation that intense eyewall convection that produces **rapid** intensification generates significant eyewall lightning.
- Preliminary results indicate the causal mechanisms involved.

Unique LANL Hurricane Model

- Excluding the discharge model, the entire model is differentiable and can be readily linked to data assimilation approaches.
- Time errors are two orders of magnitude smaller than found within current hurricane models. . . described in a MWR paper currently under review.
- Particle-based (Lagrangian) cloud model is at least ten times faster than a bin model and can be used to quickly understand basic cloud processes within a hurricane. . . described in a paper accepted to JGR.
- Includes the option to transport the momentum, energy, and mass of sea spray.
- Five hydrometeor classes (droplet, rain, ice, snow, graupel); prognostic equations for mass, number density and charge.

Cloud Electrification Module





- Based on Oklahoma group’s work (Mansell et al., 2005).
- Fundamental microphysical quantity for non-inductive charge transfer is rime accretion rate (RAR)
  $RAR = E_{g,l}\rho_{liquid}V_{graupel}$.
- Critical RAR curve determines sign of charging.
- Discharge occurs when electric field reaches critical level.

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Idealized Hurricane Simulations

Goal of this simulations is to answer the following questions:

- What happens when a cloud electrification module is used to predict lightning under server hurricane conditions?
- Does our new hurricane model predict eyewall lightning?
- Is the simulated eyewall lighting associated with intensification?
- What causal mechanisms are suggested?

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Idealized Hurricane Setup

- A Gaussian in time and space water vapor source function is used to spin up an idealized hurricane.
- The source function triggers cyclogenesis.
- A near-stationary state is achieved with homogeneous boundary conditions.
- The electrification module predicts hydrometeor charge; discharge occurs when electric field reaches critical level.
- Simulations utilize variable horizontal (2 km near eye) and vertical resolution (10 m near the ground).
- 200x200x71 grid cells were utilized.

The steady-state idealized hurricane model does not produce lightning.

Idealized Rapid Intensification Study

- At 12 h, additional water vapor via Gaussian function is added in right quadrant.
- Three simulations, employing varying magnitudes of the forcing function, are compared.
- Water vapor $\longrightarrow$ latent heat release $\longrightarrow$ intense vertical convection $\longrightarrow$ axisymmetrization $\longrightarrow$ intensification.

Hurricanes intensification is found to be roughly proportional to the amount of water vapor added.

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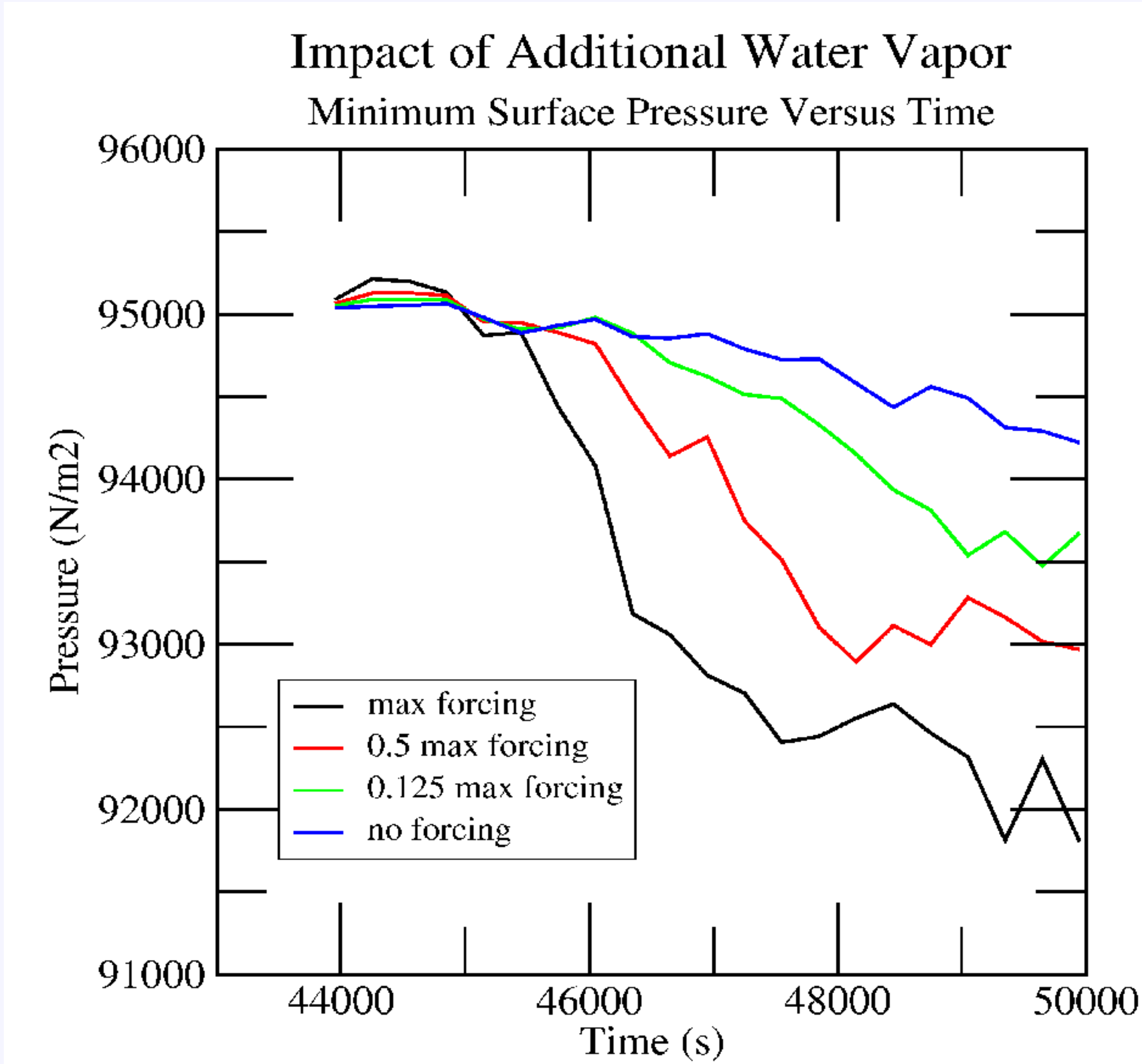
Pressure change due to forcing



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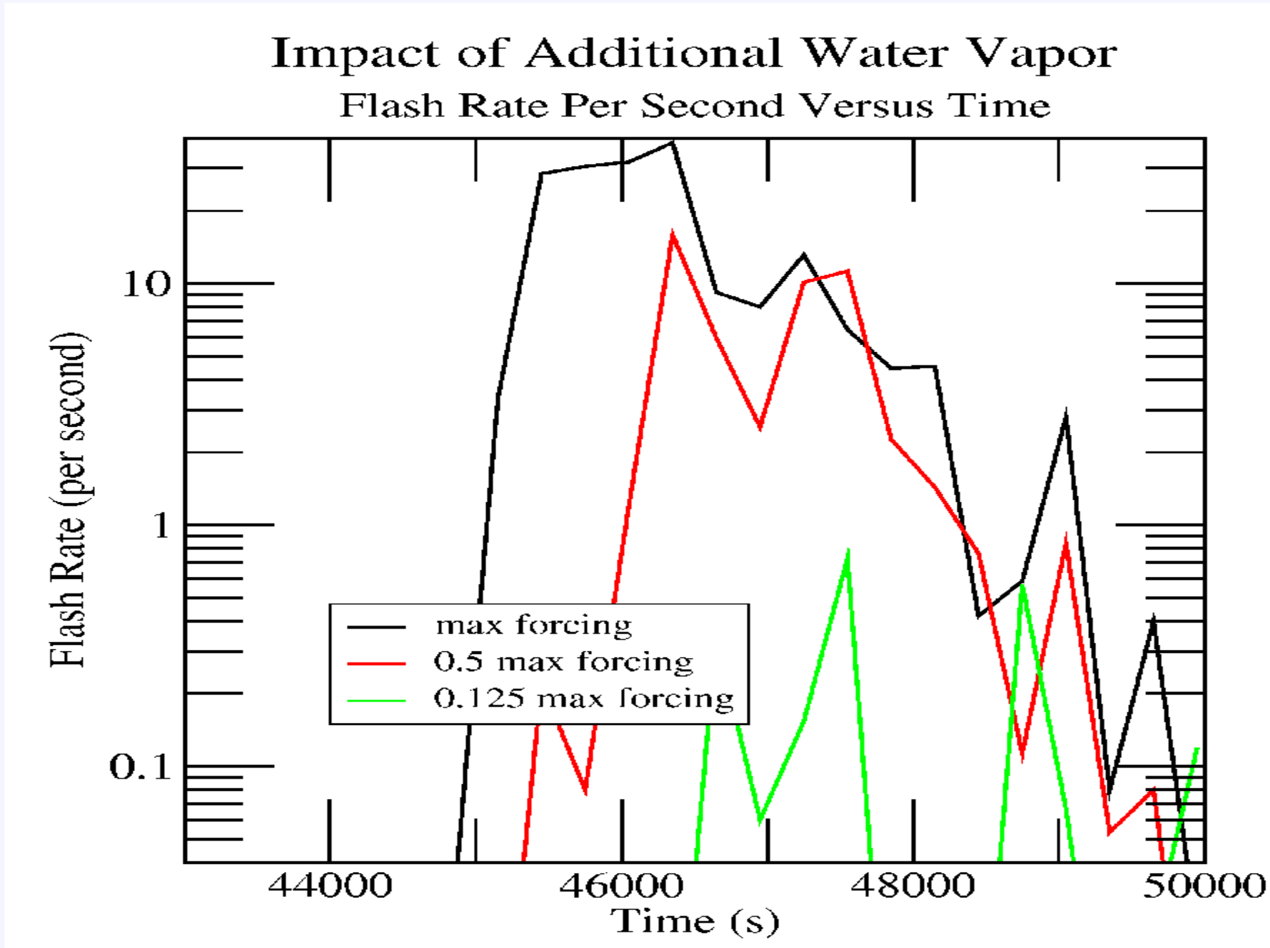
Discovery: Sudden burst of Lightning Activity



Burst of lightning activity over one hour period. Nonlinear relationship between forcing and lightning activity, suggestive of a threshold behavior.

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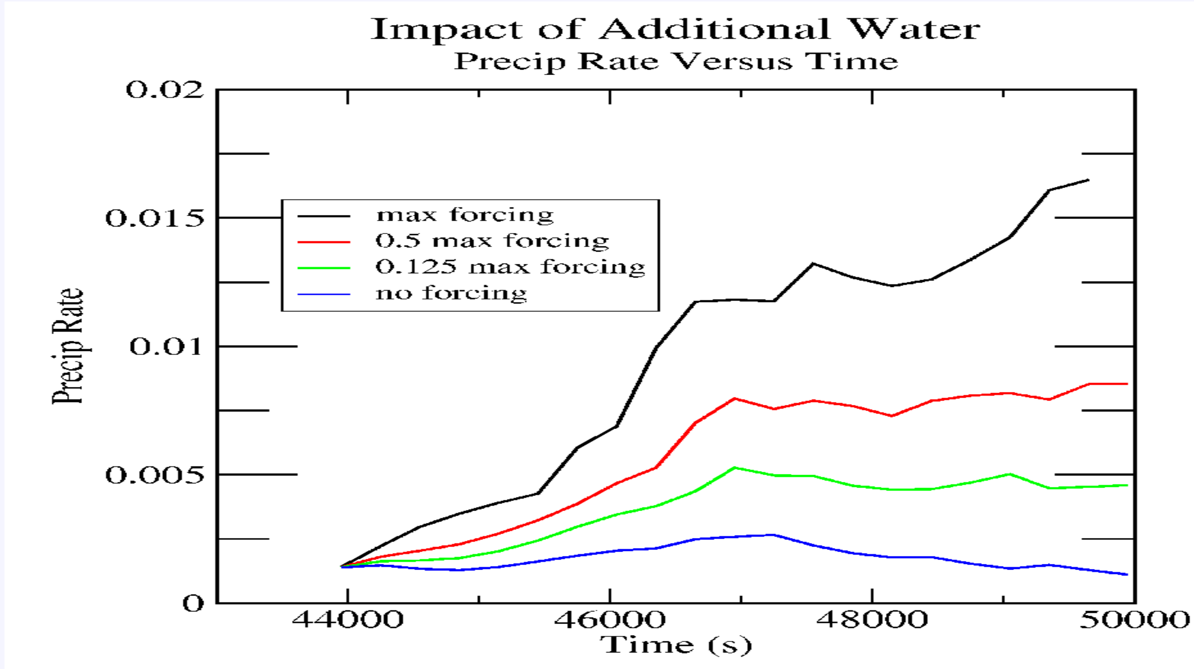
Discovery: Sudden burst of Lightning Activity



Preliminary hypothesis for burst of lighting activity:

- Initial forcing produces supercooled liquid water.
- Large water density increases RAR and charging: $RAR = E_{g,l}\rho_{liquid}V_{graupel}$
- Cloud glaciates and supercooled water decreases.
- No charging when $RAR < 0.1\ \mathrm{gm}^{-2}\mathrm{s}^{-1}$.

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Idealized Hurricane: Movie

Run Animation:

- Spin-up
  - Blue = Rain
  - Yellow = Graupel
- Forcing = maximum
  - Blue = Rain
  - Yellow = Lightning

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Hurricane Guillermo Simulations

- Hurricane Guillermo (1997) formed in Eastern Pacific, rapidly intensifying Aug 2-3rd.
- High spatial resolution dual-Doppler dataset collected during NOAA campaign.
- Eyewall exhibited quasi-persistent wavenumber-1 pattern, and alternated between open and closed periods.
- Period of maximum intensification coincided with most intense convective events.

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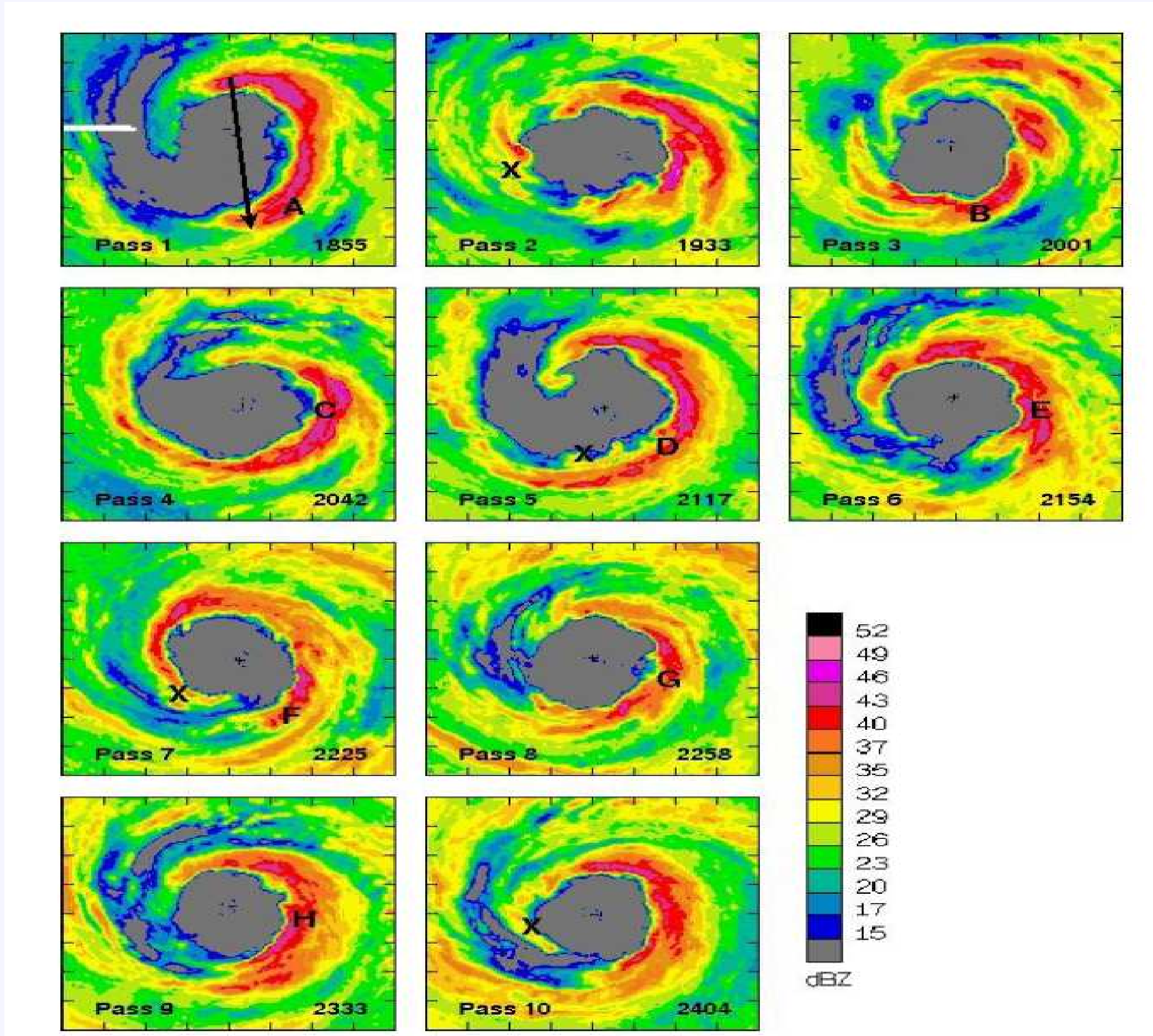
Hurricane Guillermo Structure



Maximum reflectivity in left-of-shear semicircle; maximum ascent in downshear-left quadrant. C-E is maximum intensification.

Why study Guillermo?

- Exhibits both axisymmetric and asymmetric modes of intensification.
- Different physical mechanisms of intensification can (potentially) co-exist in simulations.
  - Axisymmetrization of PV anomalies (transport by VRWs).
  - Momentum and entropy mixing between eye and eyewall.
  - Axisymmetric projection strengthens; Asymmetric projection weakens.
- Dual-Doppler radar provides heating profiles; identify outflow and convergence regions.

> Realistic simulation of Guillermo provide an excellent framework to test relationship between lightning and different candidate mechanisms of intensification, e.g. axisymmetric vs asymmetric modes and transport.

Setup for Guillermo Simulations

- Same domain as idealized simulations.
- ECMWF data was used to initialize all fields.
- Condensational heating derived from dual-Doppler radar measurements was used to spin up the hurricane.
- Preliminary results indicate complex wavenumber-1 structure and dynamics.
- We are currently using the radar data to validate our microphysical parameterizations; next-step is to run model with electrification.

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Hurricane Guillermo: Movie

Run Animation:

- Zoom of Eyewall
  - Green = 25 dbz
  - Yellow = 30 dbz
  - Red = 35 dbz

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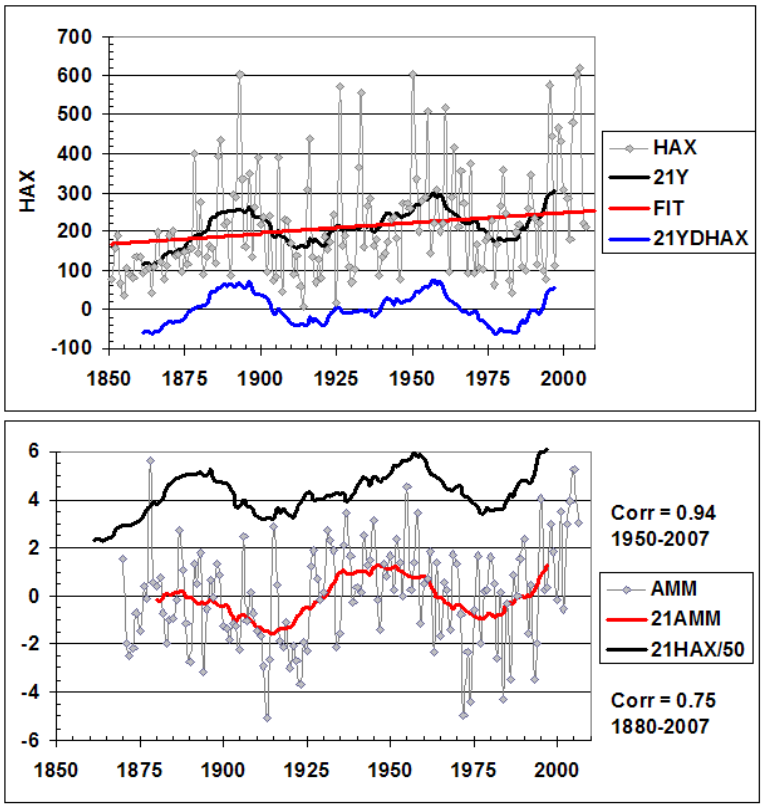
Publications

Chylek and Lesins, “Multi-decadal variability of Atlantic hurricane activity: 1851-2007”, in review, JGR, 2008.



Hurricane Activity Index (Simplified version of the ACE - Accumulated Cyclone Energy)

- Oscillating character Related to Atlantic Multidecadal Mode (AMM)

- Linear increase Related to global warming and improved observations

High level of hurricane activity till 2015-2020.

Find quasi-periodic behavior with a period of 60 years superimposed upon a linearly increasing background; correlated with AMM.

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Other Publications

- Reisner and Jeffery, “A smooth cloud model”, in review, MWR, 2008.
- Kao and Ide, “A reduced Extended Kalman Filter method of data assimilation and parameter optimization”, in review, JCP, 2008.
- Five conference presentations (AGU, AMS, ICCP etc).
- Two invited presentations (NHC, LANL).

Relevance

1. **Relevance**. Does the PI have a transition plan, mapping out a future for the project?

Our target program for sustained funding is the emerging **National Hurricane Research Program**, potentially $320M/year new funding. A key objective of the program is to provide real-time guidance to research aircraft using

- Data collected **in real-time** from new instruments in the Gulf; Shell and **Chevron oil platforms** are specifically targeted.
- Improved hurricane forecast models.
- New data assimilation schemes that will rapidly ingest the real-time data.

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Summary

1. **Relevance**. Our new hurricane lighting project is a timely, high-profile effort that will help protect coastal areas and energy infrastructure in the Gulf, and is well-positioned for long-term support. Our project is aligned with the national hurricane research agenda and combines three essential tasks: (i) new sensors & observations (ii) improved modeling and simulation, (iii) new data assimilation techniques, leading to improved forecast accuracy.
2. **Performance**. We have made excellent progress building and deploying the world's first dual VLF-VHF lighting array in the Gulf. We have performed the first-ever in-depth modeling study of the relationship between hurricane intensification and eyewall lightning using a new LANL hurricane model with cloud electrification. We have discovered that our modeling framework predicts a burst of lighting activity triggered by a threshold level of vertical convection and mitigated by cloud glaciation; this confirms our original hypotheses.
3. **Quality**. We are already publishing in influential journals, and are well positioned to make significant contributions to hurricane dynamics, cloud microphysics and atmospheric electricity in following years.

The Power of Kalman Filtering

We use an **Extended Kalman Filter** (EKF) to assimilate LASA lightning data into the LANL hurricane forecast model.

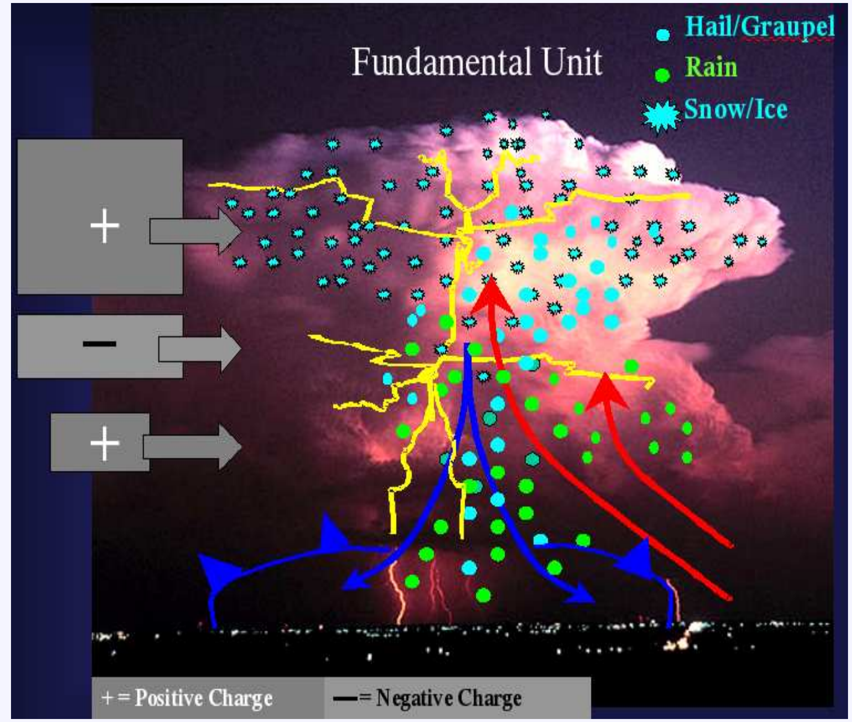
$$\begin{aligned} \boldsymbol{X}_{opt} &= \text{Optimal Prediction } \textbf{with Data Assimilation} \\ \boldsymbol{X}_{pred} &= \text{Model Forecast} \\ \boldsymbol{Y}_{obs} &= \text{Lightning Observations} \\ \boldsymbol{\mathcal{H}}(\boldsymbol{X}_{opt}) &= \text{Model Predicted Lightning} \end{aligned}$$

EKF allows observation of non-state-variables $\boldsymbol{Y}_{obs}$ to influence optimal state-variables $\boldsymbol{X}_{opt}$ via minimization of a global cost function J.

$$\begin{aligned} J &= \frac{1}{2}\left[\boldsymbol{X}_{pred} - \boldsymbol{X}_{opt}\right]^T \left[\boldsymbol{X}_{pred} - \boldsymbol{X}_{opt}\right] / \text{Model\_Err\_Covar}(X_i, X_j) \\ &+ \frac{1}{2}\left[\boldsymbol{Y}_{obs} - \boldsymbol{\mathcal{H}}(\boldsymbol{X}_{opt})\right]^T \left[\boldsymbol{Y}_{obs} - \boldsymbol{\mathcal{H}}(\boldsymbol{X}_{opt})\right] / \text{Obs\_Err\_Covar}(Y_i, Y_j) \end{aligned}$$

Lightning Data Assimilation

$$\overline{w'T'} > 0$$
$$\overline{\rho'_{ice} w'} > 0$$
$$\overline{\rho'_{rain} w'} < 0$$
$$\overline{\text{(charge)} w'} (top) > 0$$
$$\overline{\text{(charge)} w'} (bottom) < 0$$
$$\overline{\text{(flash rate)} \rho_{graupel}} > 0$$
$$\overline{\text{(flash rate)} w'} > 0$$



$$J = \frac{1}{2}\left[\boldsymbol{X}_{pred} - \boldsymbol{X}_{opt}\right]^T \left[\boldsymbol{X}_{pred} - \boldsymbol{X}_{opt}\right] / \text{Model\_Err\_Covar}(X_i, X_j)$$
$$+\frac{1}{2}\left[\boldsymbol{Y}_{obs} - \boldsymbol{\mathcal{H}}(\boldsymbol{X}_{opt})\right]^T \left[\boldsymbol{Y}_{obs} - \boldsymbol{\mathcal{H}}(\boldsymbol{X}_{opt})\right] / \text{Obs\_Err\_Covar}(Y_i, Y_j)$$