The Promise of Long-Range Lightning Detection in Better Understanding, Nowcasting, and Forecasting of Maritime Storms

Collaborators in the Development of the Pacific Lightning Detection Network (PacNet)

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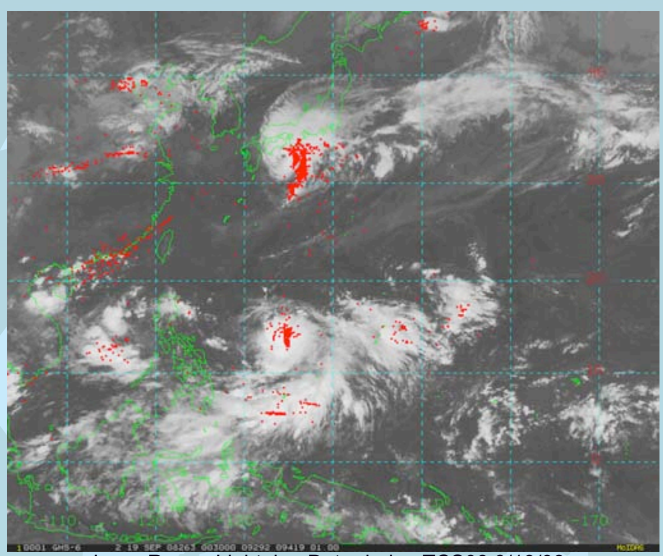
- Dr. Tiziana Cherubini, UH
- This research is supported by ONR, NASA, and Vaisala



Long-Range Lightning Data during TCS08 9/19/08

MET at UH

VAISALA

DEPARTMENT OF THE NAVY ONR Science & Technology

NASA

Outline

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III. Relationships Between Lightning, Precipitation, and Hydrometeor Characteristics[2]

IV. Nowcasting Applications for Data Streams[3]

V. An Operational Lightning Data Assimilation System at UH[4]

References

1. Pessi, A. T. et al., 2008: J. Atmos. and Ocean. Tech., 26, 145–166.
2. Pessi, A. T., and S. Businger, 2009: J. Appl. Meteor., 48, 833–848.
3. Squires, K. and S. Businger, 2008: Mon. Wea. Rev., 136, 1706–172.
4. Pessi, A. T., and S. Businger, 2009: Mon. Wea. Rev., In press.

I. Background

Types of Lightning Discharge
Cloud-to-ground (CG) Flash

- Negative CG flashes usually produce 3-4 “return strokes”, high-current impulses accompanied by a strong light emission.
- In the center flash, 3 strokes were resolved in time by panning the camera.

Cloud-to-Cloud Flashes

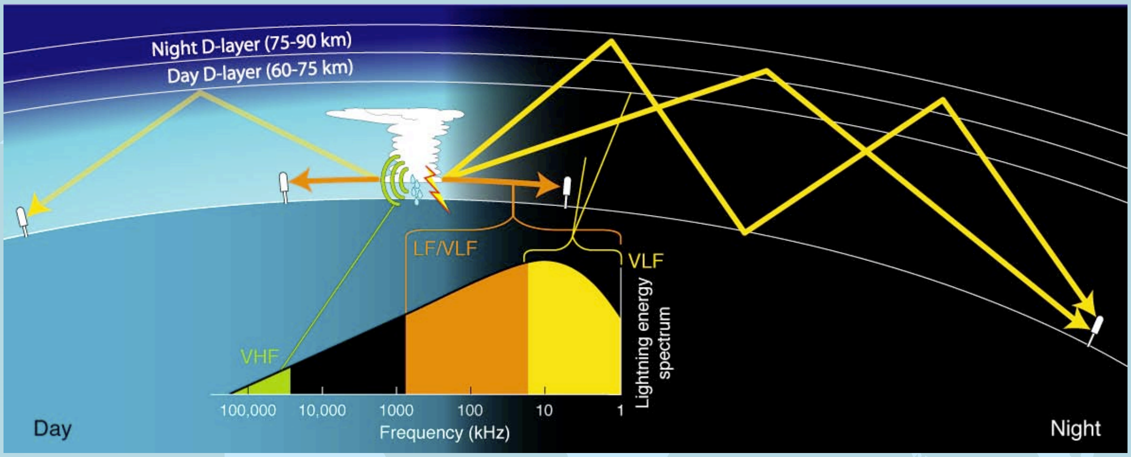
- Intracloud (IC) and cloud-to-cloud flashes do not have return strokes.
- These are the majority of discharges, typically comprising 60-80% in non severe storms and up to 99-100% in some severe storms.
- Long-range lightning sensors detect only a small fraction of IC flashes (<5%).

Long-Range Lightning Detection Networks

- Can detect flash rate, location, peak current, polarity of stroke
- Can *continuously* monitor convective storms over wide ocean areas.
- Represent a real-time data stream - suitable for nowcasting and operational data assimilation.

✓ To realize the full potential of the new data streams, the performance of PacNet must be well known (calibrated).

Background: VLF Signal Propagation



- The wave energy produced by cloud-to-ground (CG) discharges peaks in the very low frequency (VLF) regions of the spectrum (3-30 kHz). *Sferics* can propagate effectively in the earth-ionosphere waveguide for thousands of kilometers.
- VLF signals attenuate less during the night because the gradient in electron density with height increases (ionosphere is more sharply defined at night).
- VLF signals attenuate significantly less over the ocean than over land because of higher electrical conductivity of salt water.

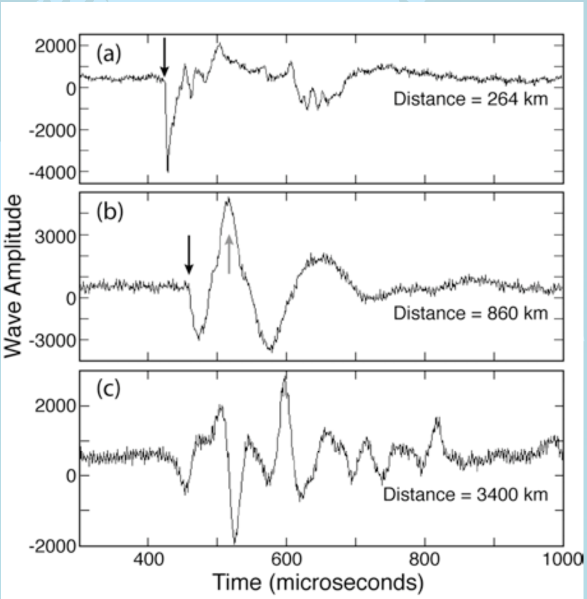
VLF Signal Waveforms

a) 264 km - ground wave

b) 860 km - ground wave followed by a single-hop ionospheric reflection of opposite polarity.

c) 3400 km - multiple ionospheric components.

Note that the flash changes electric field polarity at each reflection.



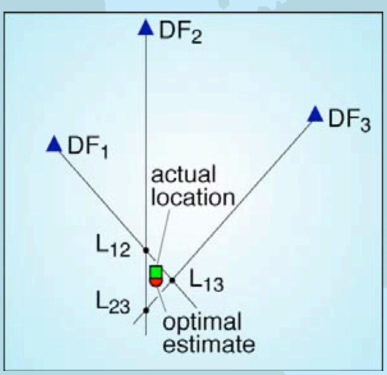
II. Lightning Detection Network Performance

Traditionally two indicators are used to measure the performance of a lightning detection network:

- Location accuracy (LA): Location error (km) from the actual flash location
- Detection efficiency (DE): $DE(x,y,t) = \dfrac{\#\ \text{of flashes detected}}{\text{actual}\ \#\ \text{of flashes}} * 100\%$

Lightning Location Methods

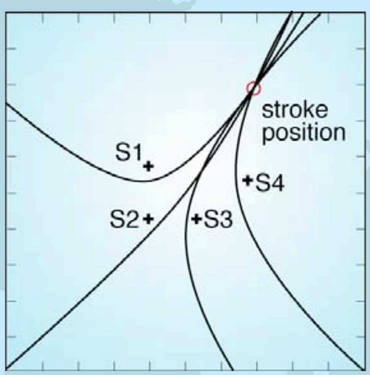
DIRECTION FINDING



3 sensor solutions

Individual locations L12, L13, and L23 are triangulated locations for pairs of sensors.
The optimal estimate is produced by using the direction information from all reporting sensors.

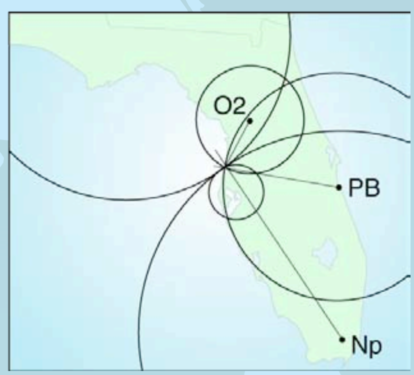
TIME OF ARRIVAL



4 sensor solutions

The location is based on the intersection of hyperbolas produced by arrival-time-differences between pairs of sensors.

COMBINED DF+TOA



2 sensor solutions

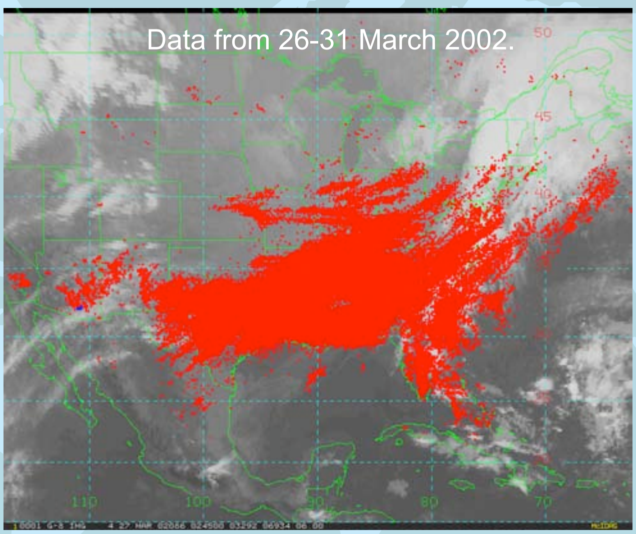
Combined MDF + TOA technology Location with Least-squared Error Combination of Arrival-time and Angle.

Detection Efficiency

DE* depends on *DE = (number of flashes detected/actual number of flashes) x 100

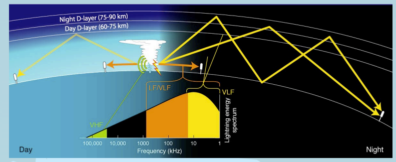
- signal attenuation – distance between the lightning and sensors
- strength of the lightning discharge – peak current
- nature of the waveguide – surface conductivity and diurnal cycle in electron density gradients
- specifics of the hardware

NLDN VHF Data used for Calibration

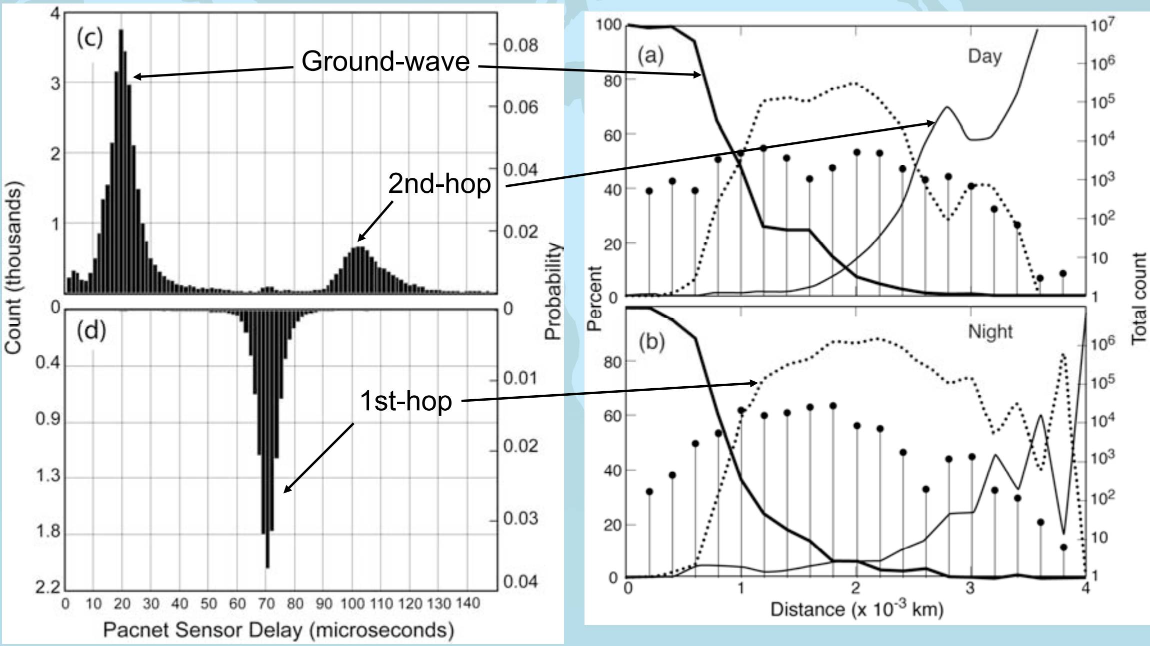


Because no high-quality lightning data are available over the Pacific Ocean, lightning data detected by the National Lightning Detection Network (NLDN) over the U.S. were time-correlated with data from a PacNet test sensor located in Tucson, Arizona to calibrate the sensor and to develop the DE and LA models.

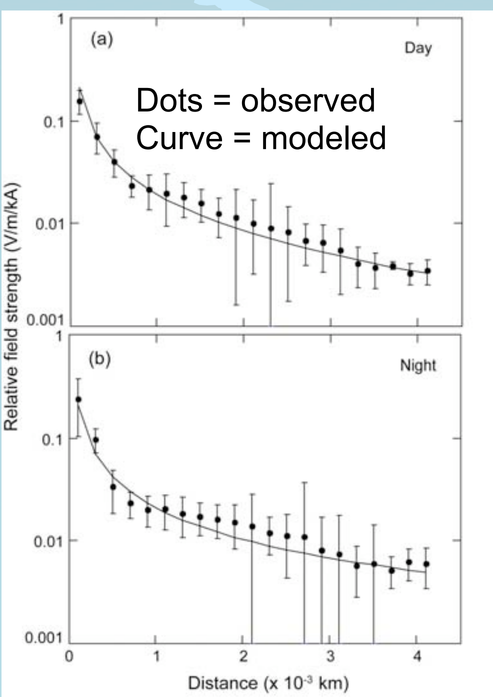
Propagation Types



Clear separation in the signal delay allows propagation types to be distinguished.



Signal Attenuation



Exponential loss with distance sets a lower bound on the space constants for day and night, due to the involvement of land, as opposed to salt water, in the propagation path to the Tucson test sensor.

Attenuation function :

$$A = \frac{\alpha_f}{R}\sqrt{\left(\frac{\theta}{\sin(\theta)}\right)}\exp\left(-\frac{R}{\lambda_f}\right)$$

α : scaling constant

λ : e-folding distance (space constant)

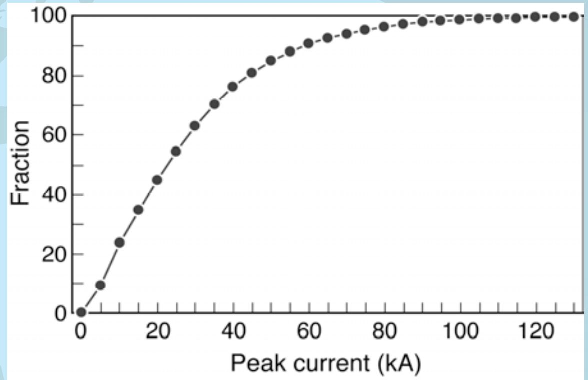
R : distance to lightning

θ : R/ R_e

R_e : radius of the earth

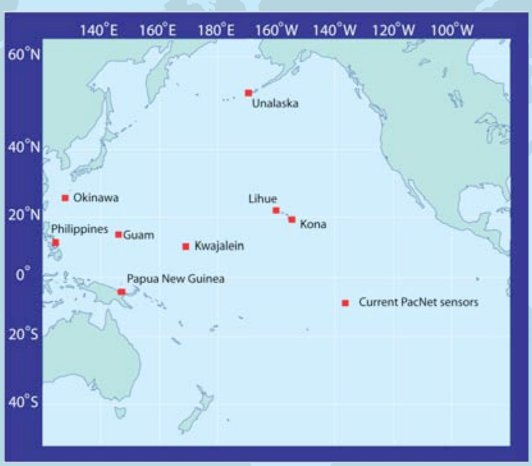
DE Model Calibration for Ocean Condition

- Observe the reference peak current distribution using PREPA CG data striking the sea near Puerto Rico.*
- Use this distribution in the DE model adjusting the day and night space constants to produce the observed DE in Puerto Rico.



★ Puerto Rico Electric Power Authority (PREPA) local lightning detection network was used, which has DE of >90% and LA of ~0.5 km.

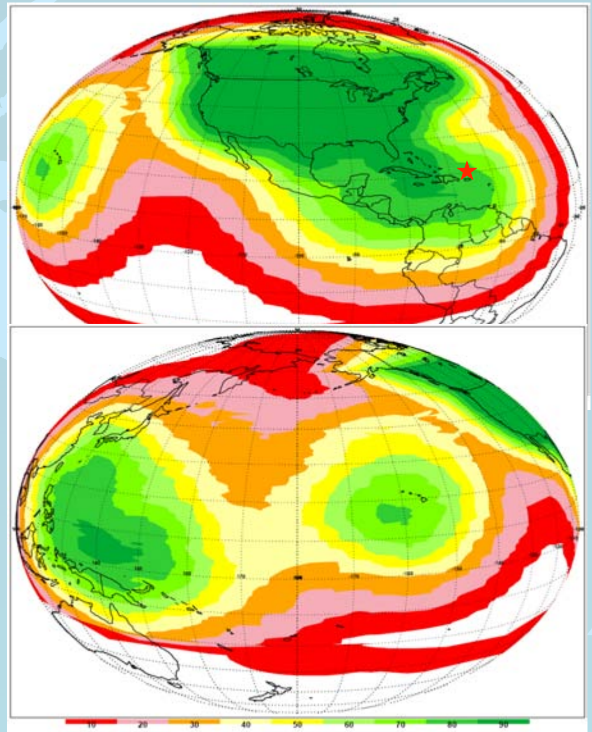
PacNet Sensor Sites



Dr. Pessi in Dutch Harbor, AK installing a Vaisala detector that utilizes an innovative combined time-of-arrival (TOA) and direction finding (DF) method. The gain has been set to a high level and the bandwidth has been adjusted to have greatest sensitivity in the VLF band to receive weak, ionospherically reflected sferics.

DE Model Calibration for Ocean Condition

- Use the observed peak current distribution in the DE model adjusting the day and night space constants to reproduce the observed DE in Puerto Rico.★
- Employ the resulting space constants and peak current distribution in the PacNet configuration.



Comparison of Observed DE (LIS vs PacNet data) and Modeled DE:

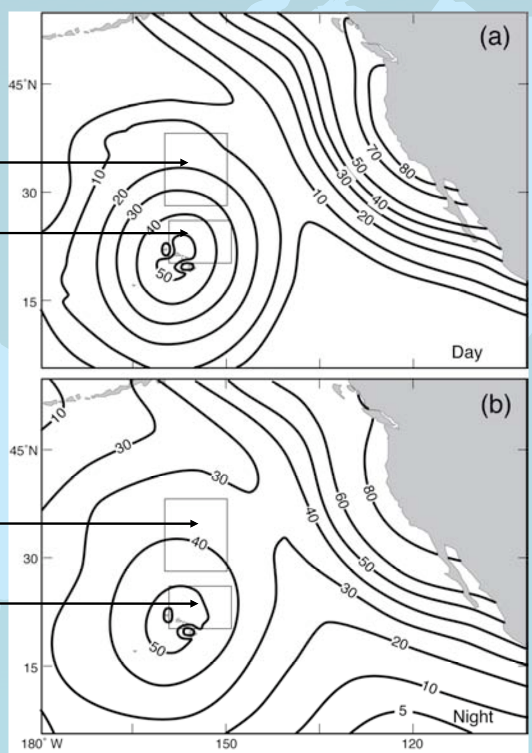
Observed

~19%

~42%

~44%

~61%



Modeled DE Day

Modeled DE Night

III. Relationships Between Lightning, Precipitation, and Hydrometeor Characteristics over the North Pacific Ocean*

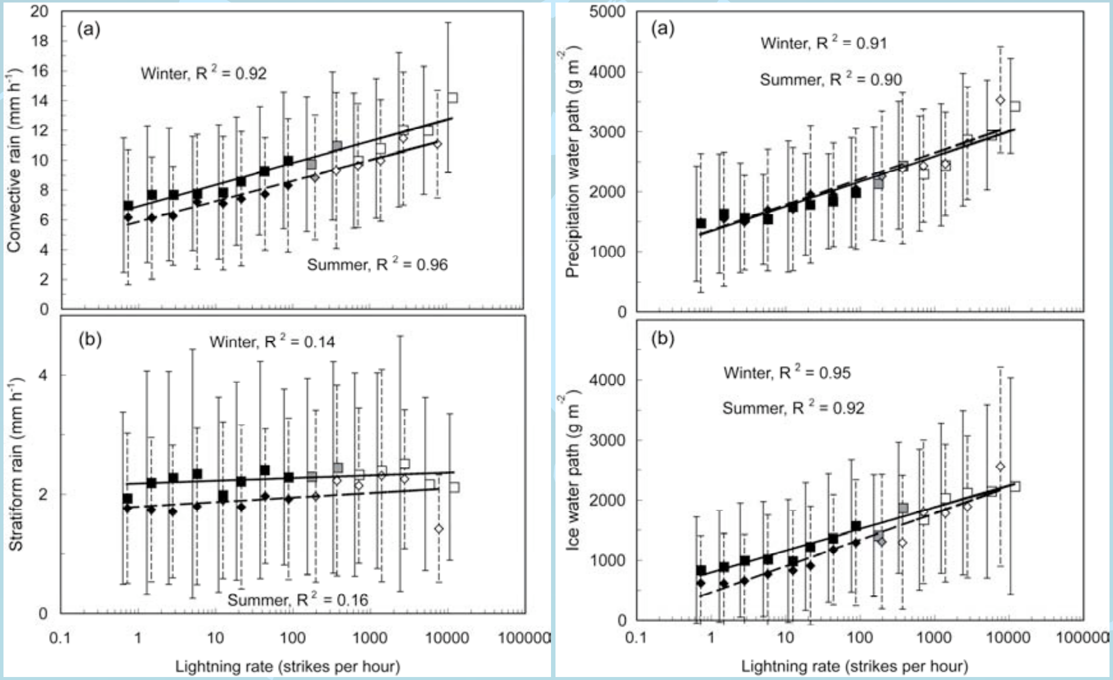
*Pessi, A. and S. Businger, 2008: *J. Appl. Meteor.* **48**, 833–848.

Data and Methods

- Data from over 2000 TRMM overpasses during a 3 year period (February 2004 - February 2007).
- Lightning data from PacNet (quality controlled) and TRMM's Lightning Imaging Sensor.
- Precipitation and hydrometeor data from TRMM's Precipitation Radar (2A25 v6) and Microwave Imager (2A12 v6).
- Domain divided into 0.5° x 0.5° grid cells.
- PacNet lightning strikes counted ±15 min from satellite overpass time.
- DE model applied to PacNet data to quantify the lightning rates.
- Data divided to winter (October-April) and summer (June-September) storms.

Convective rain

Precipitation water path



Stratiform rain

Ice water path

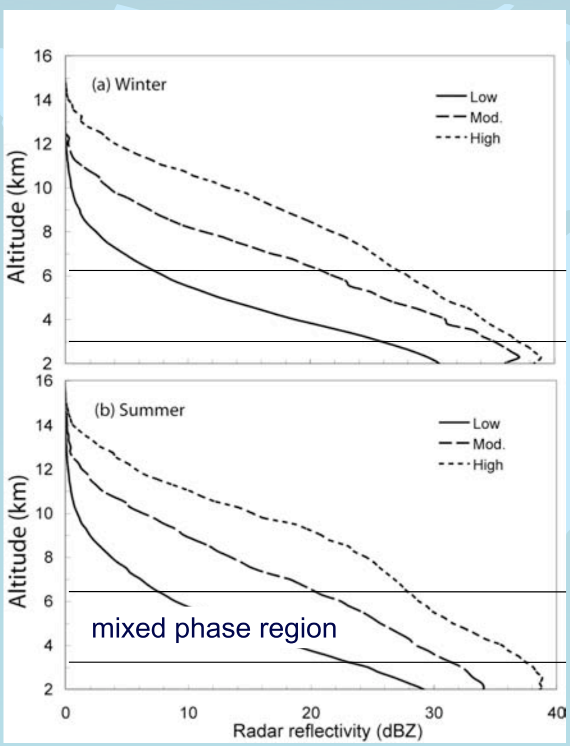
Lightning vs. Radar Reflectivity

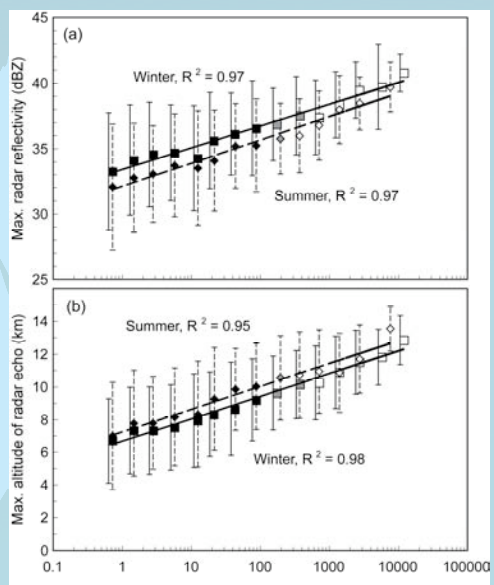
-20°C

0°C

-20°C

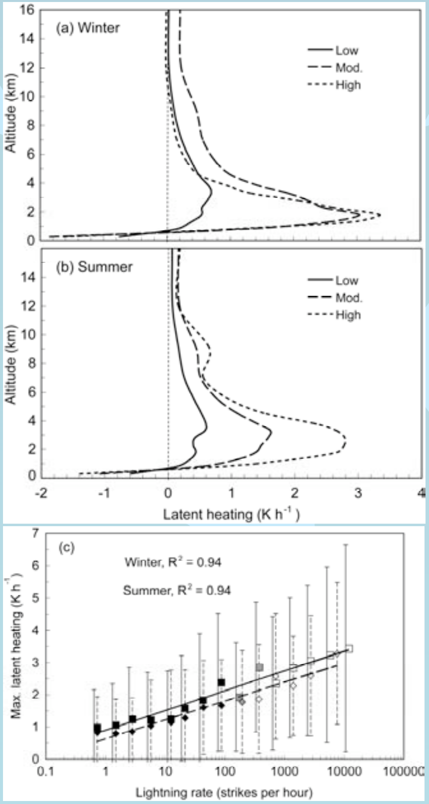
0°C



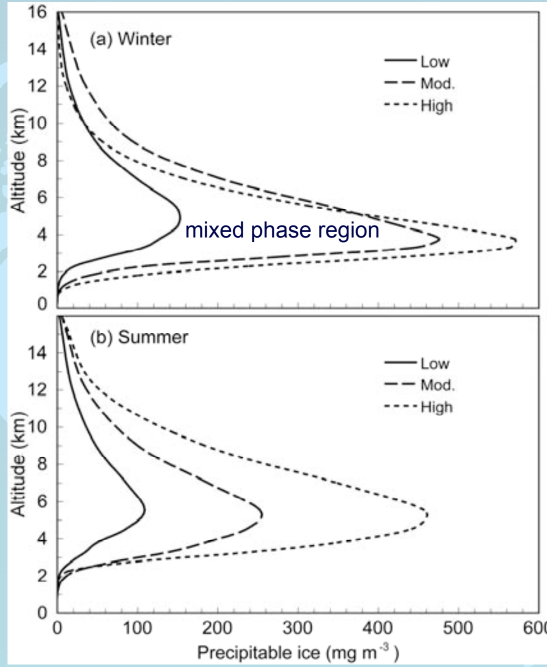


Black symbols PacNet data
White symbols LIS data
Grey symbols combined PacNet/LIS

Latent heat

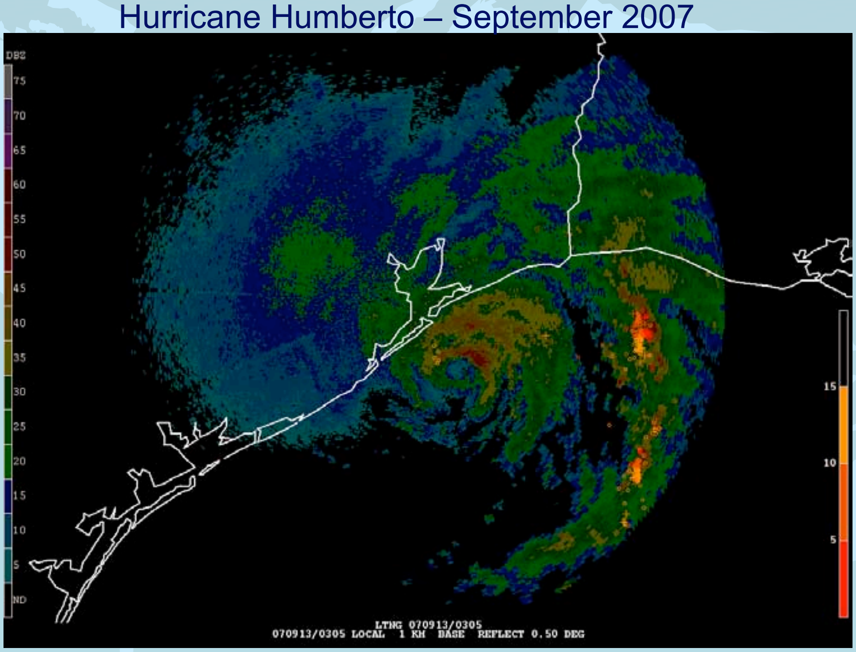


Precipitable ice



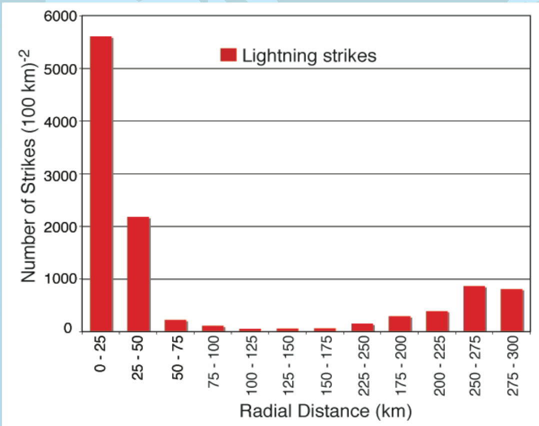
3. Applications – Nowcasting*

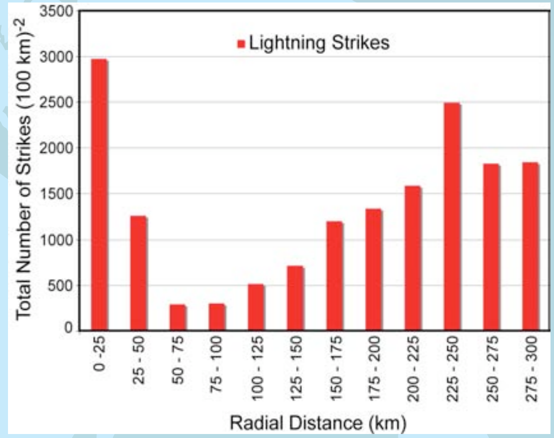
Hurricane Humberto – September 2007



*Squires and Businger, MWR 2007:
The Morphology of Eyewall Lightning Outbreaks in Two Category Five Hurricanes

Radial Distribution of Lightning Strike Density

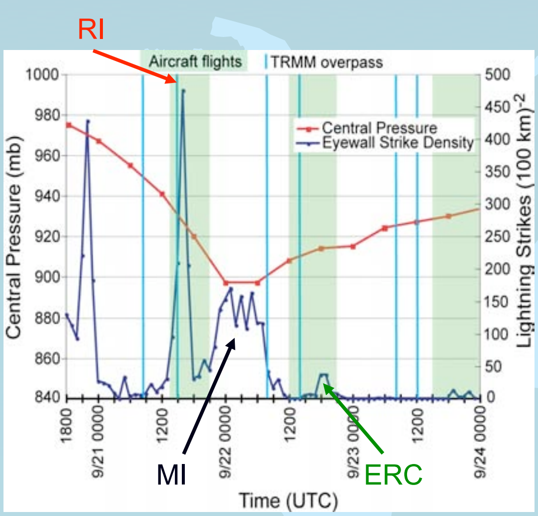




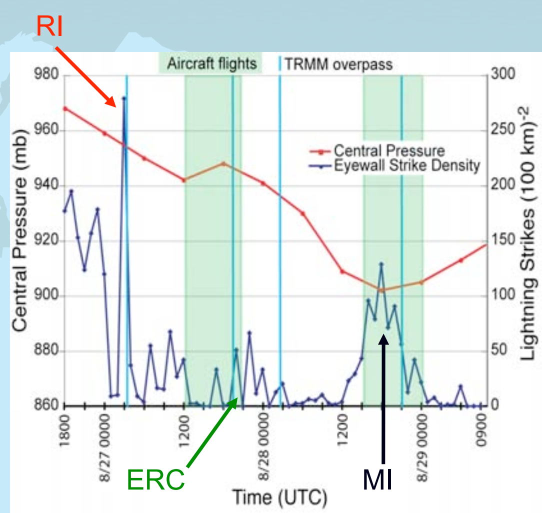
Hurricane Rita (1800 UTC 20 Sept. - 0900UTC 23 Sept.)

Hurricane Katrina (1800 UTC 27 Aug. - 0900 UTC 29 Aug.)

Types of Eyewall Lightning Outbreaks



Hurricane Rita



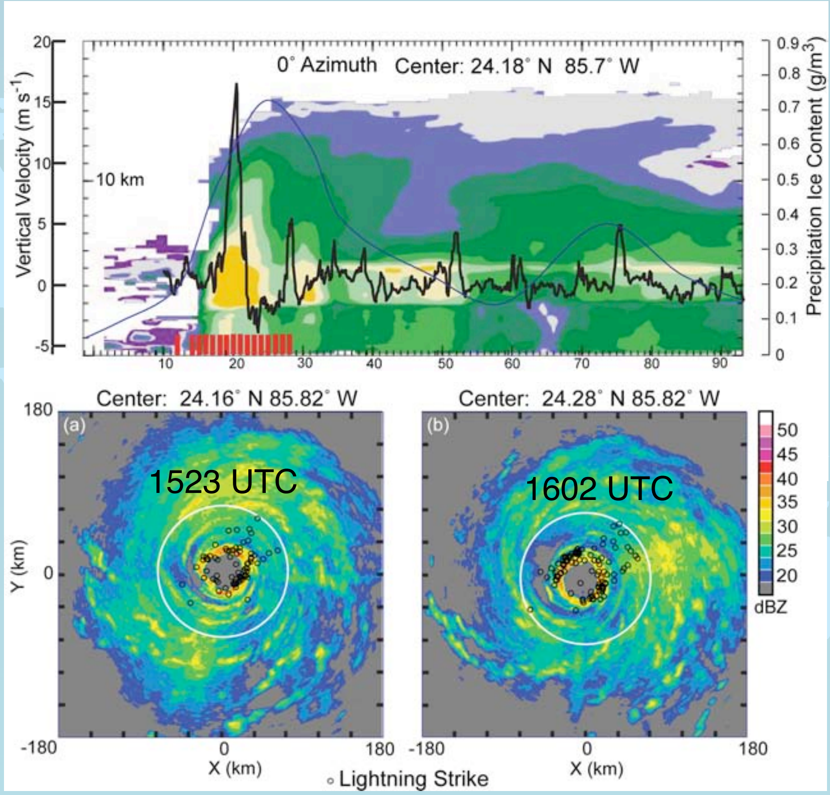
Hurricane Katrina

Rapid Intensification (RI)

Eyewall Replacement Cycle (ERC)

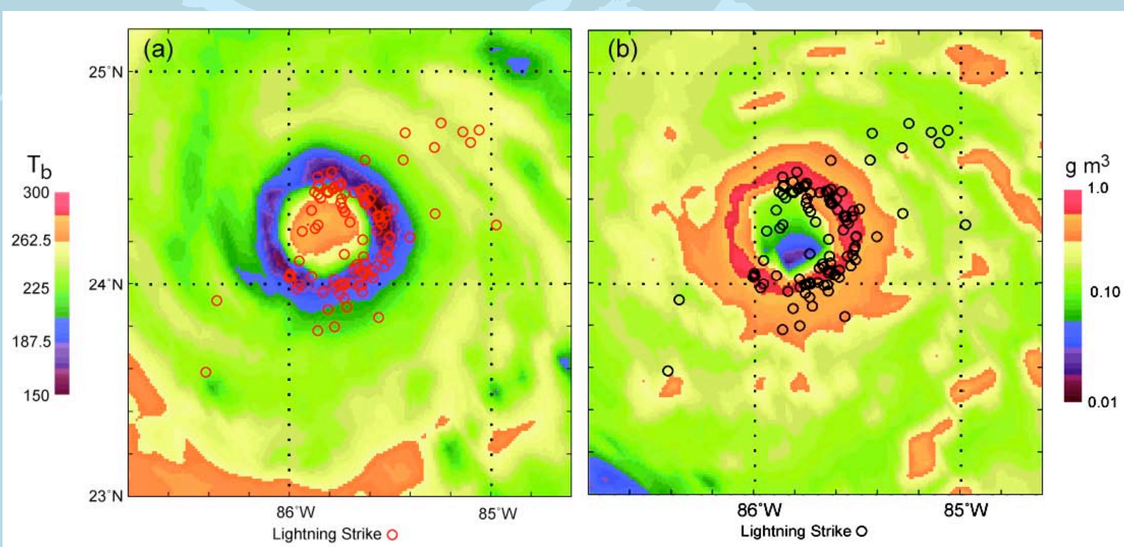
Maximum Intensity (MI)

Rapid Intensification Eyewall Outbreak: Hurricane Rita



Aircraft radar on 21 Sept. overlaid with 20 min of lightning data

Rapid Intensification Eyewall Outbreak: Hurricane Rita



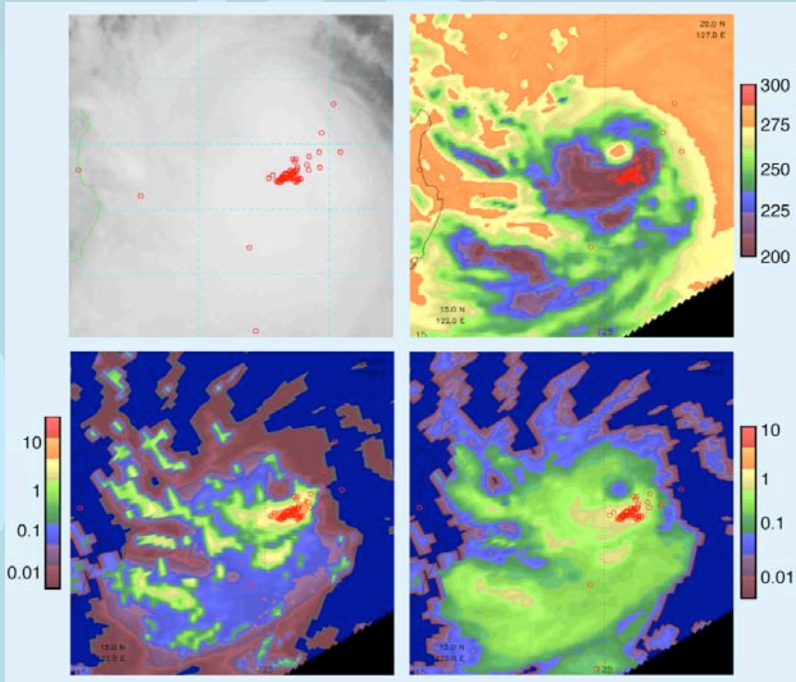
85 GHz T_b

8-10 km PIC

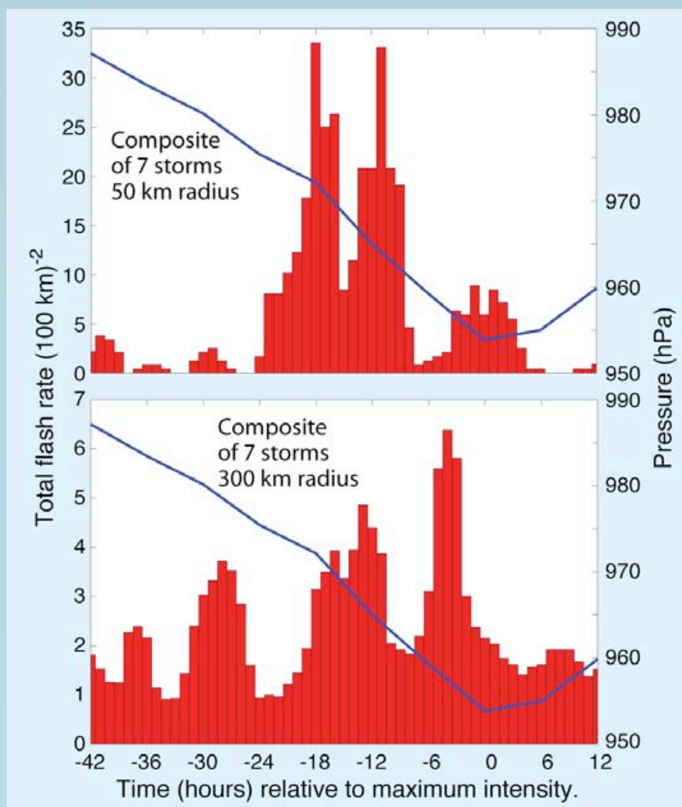
TRMM data at 1540 UTC 21 Sept. overlaid with 20 min of lightning data

Lightning in Typhoon Nuri

Overlay of lightning strikes (red) and TRMM satellite data

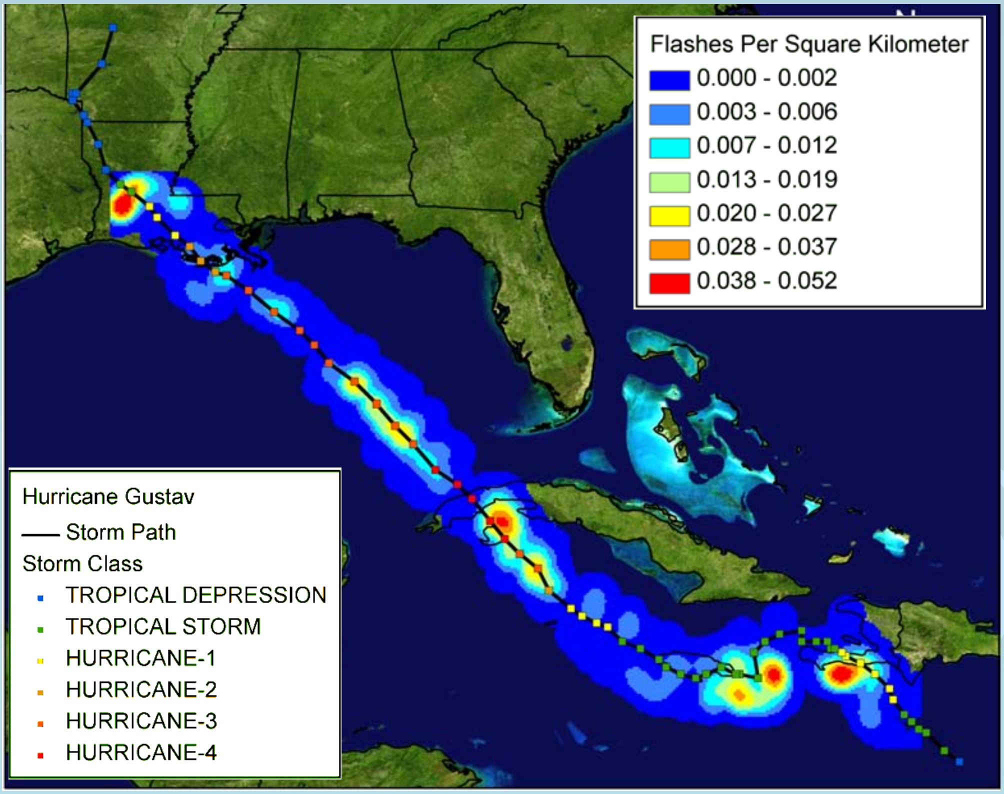


Composite Radial Distribution of Lightning in 7 Named Typhoons

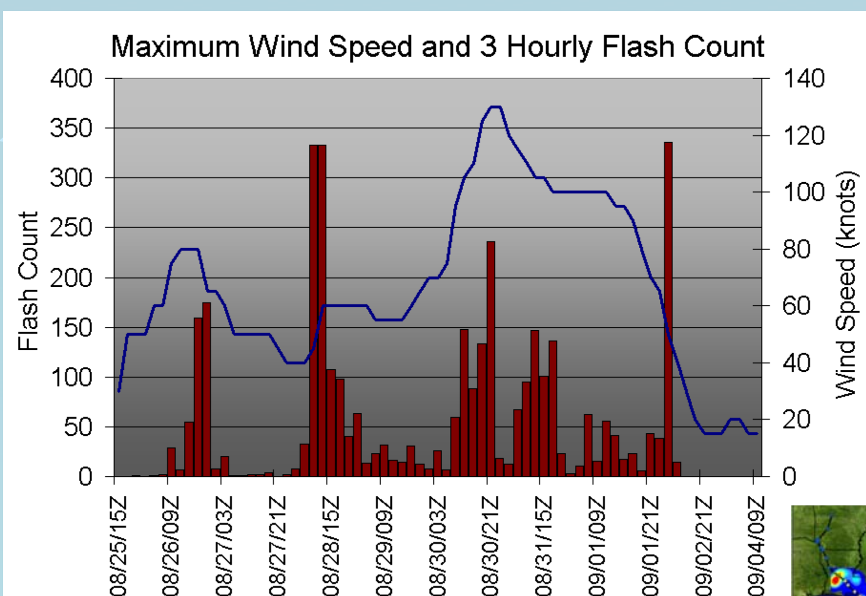


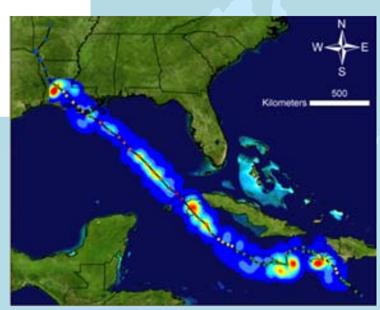
Composite central pressure and CG lightning strikes within 50 km (300 km bottom) of the storm centers for all seven tropical cyclones in TSC08.

Density of Flashes in Hurricane Gustav

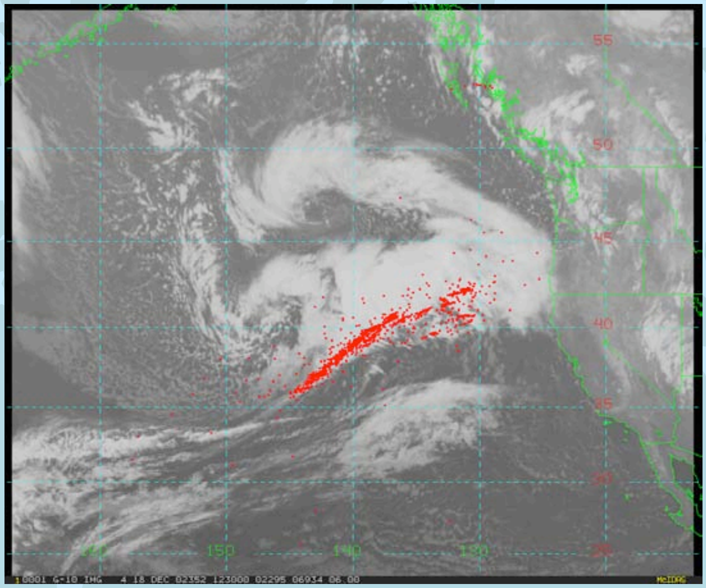


Gustav Time Series





4. Applications – Operational Lightning Data Assimilation System at the University of Hawaii



Northeast Pacific Storm 18-20 December 2002

Pessi, A. and S. Businger, 2009: *Monthly Weather Review*. In Press.

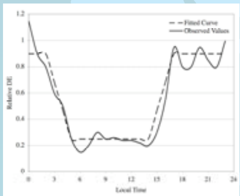
Lightning Data Assimilation into NWP Models

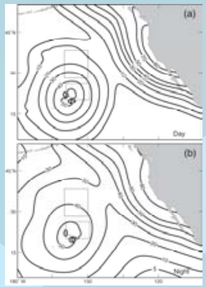
- Previous lightning data assimilation work:
  - Alexander et al. 1999; Chang et al. 2001; (latent heating)
  - Papadopoulos et al. 2005; (moisture profiles)
  - Mansell et al. 2006; (BL moisture and updraft speed)
  - Weygandt et al. 2006; (hydrometeor fields)
- What is new in this study?
  - Long-range lightning data over the open ocean.
  - Lightning rates quantified using the detection efficiency model.
  - Experiment design has been made operational for real-time forecasts.

Latent Heating Assimilation Method

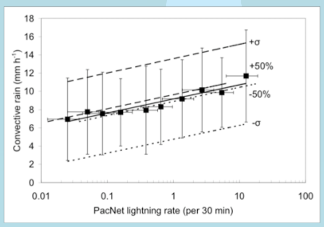
Create an input file before the model run starts

1. Apply DE model to quantify the lightning rates (lat, lon, LT at each flash location).





2. Convert the lightning rates to rainfall rates over the whole domain and each timestep using the relationship formula.



Assimilation method

- The method was programmed to WRF's Kain-Fritsch convective parameterization scheme.
- The method uses Newtonian relaxation (nudging) technique to adjust the model's vertical latent heating profiles according to 'observed' rainfall rates.
- Adjustment is done in the model's convective temperature tendency equations.
- The method is a 4DDA-type assimilation method, where nudging occurs during the forecast run.

Latent Heating Assimilation Method

Is there lightning in the grid cell?

No → No action. No lightning ≠ no rain

Yes → Is model producing rain?

- No → Search adjacent model grid points for similar rain rates as observed. Use modeled latent heating profile from matching grid point. Saturate levels where dT/dt > 0.
- Yes → Scale latent heating rates:

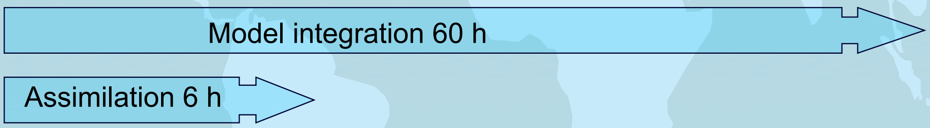
$$c = \frac{R_o - R_m}{R_m}$$

$$\Delta T_i = (1 + c)\Delta T_i^{\text{model}}$$

c = scaling coefficient
R_o = 'observed' rainfall (derived from lightning)
R_m = modeled rainfall

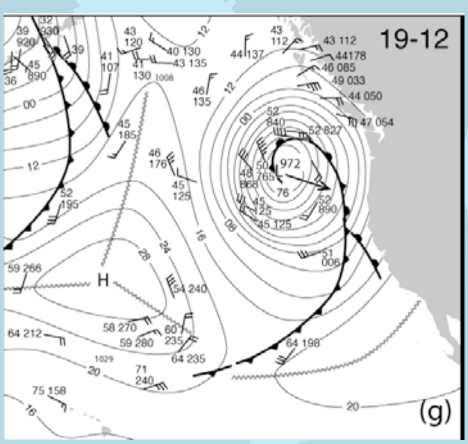
Operational System Design

- WRF model in Linux cluster
- Model initialized with LAPS (Local Analysis and Prediction System)
- Boundary conditions from GFS every 6 hours
- Horizontal resolution 15 km, 40 vertical levels, currently no nesting
- Model time step 64 s

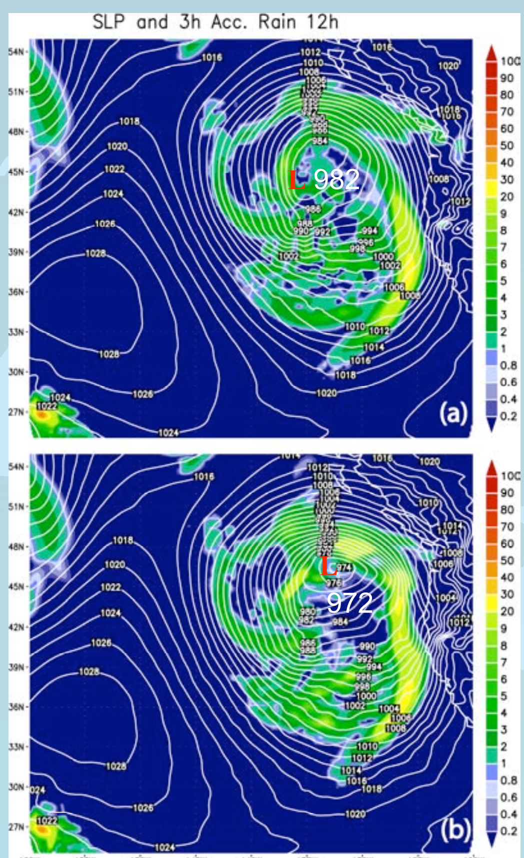


- Kain-Fritsch convective parameterization scheme
- Horizontal radius of influence 0.125°
- Time window of influence ±15 min
- Vertical latent heating profiles adjusted every timestep

12-Hour Forecast of Sea-Level Pressure and 3-h Rainfall



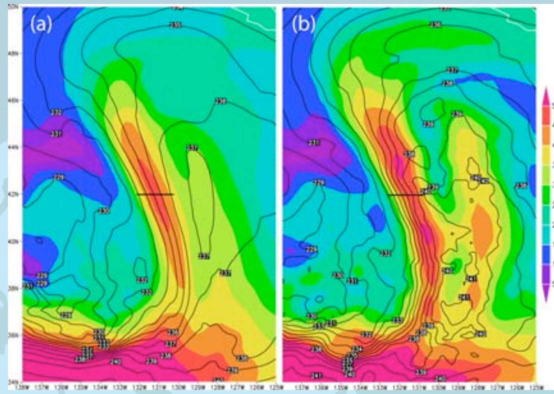
Surface analysis
Valid 1200 UTC
19 December 2002



Control

Lightning Assimilation

Advection of High Theta-e Air into the Storm Center



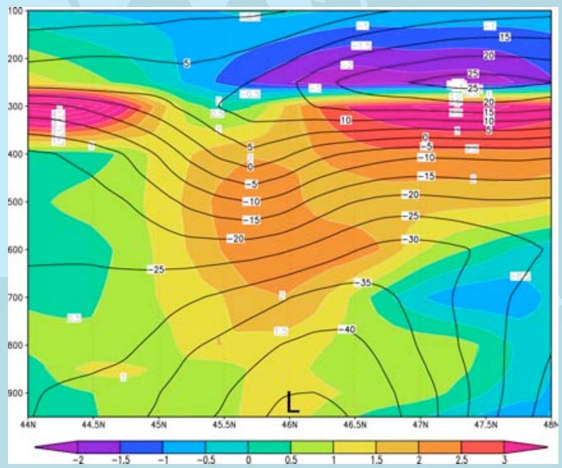
Upper figure:

(a) CTRL, (b) LDA

Wind speed at 400 hPa (m/s, shaded)

Temperature at 400 hPa (K, contours)

Latent heating, as indicated by the high lightning rates, increased temperature and ∇T across the front. This resulted in increased along-front winds, consistent with thermal wind balance.



Lower figure:

Difference between LDA and CTRL in:

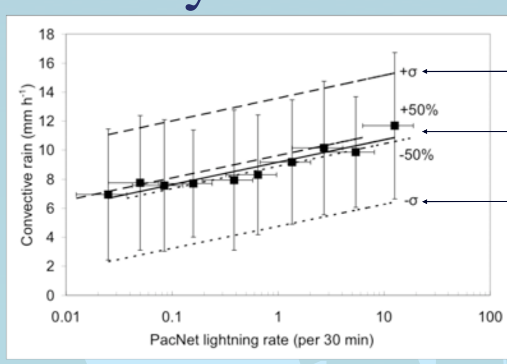
Virtual temperature (K, shaded)

Geopotential height (m, contours)

Enhanced advection of warm air over the storm center dropped the surface pressure hydrostatically.

Sensitivity Studies

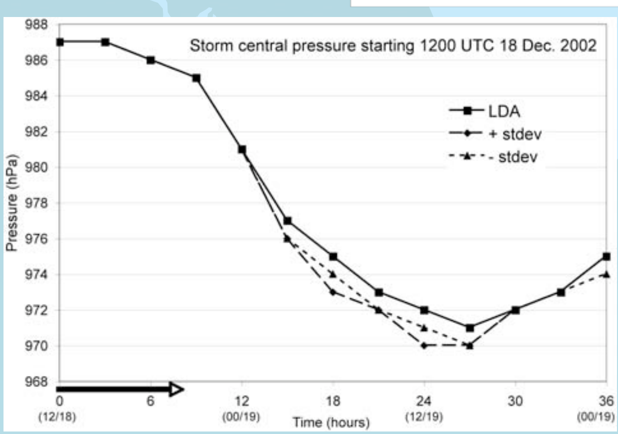
How do the errors in lightning rates and/or DE model, and lightning-rainfall relationship affect the model results?



+stdev LDA

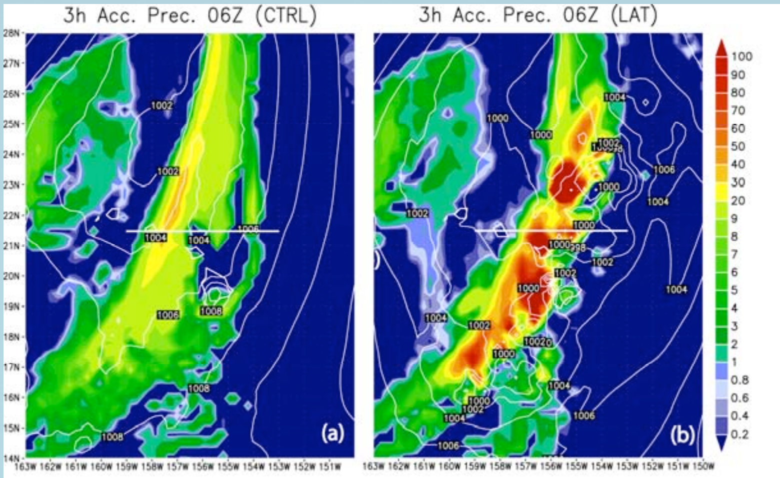
standard LDA

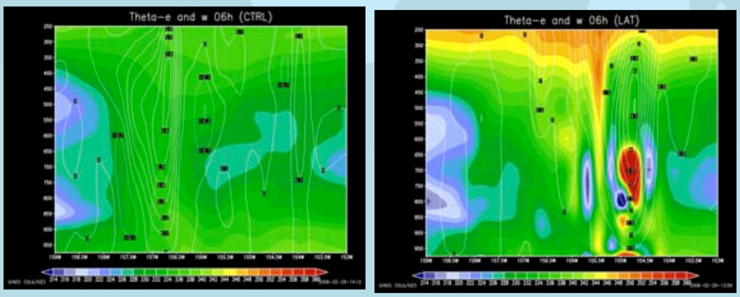
-stdev LDA

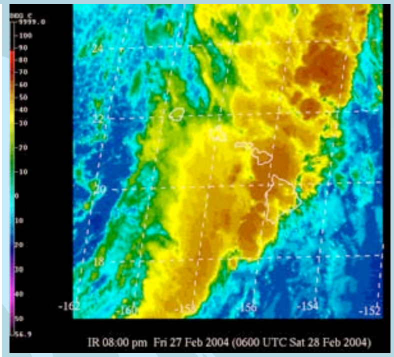


Model insensitive to assimilated rainfall rates and very insensitive to errors in lightning rates.

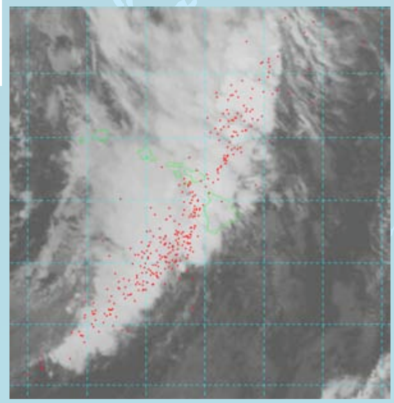
06 UTC 28 February 2004



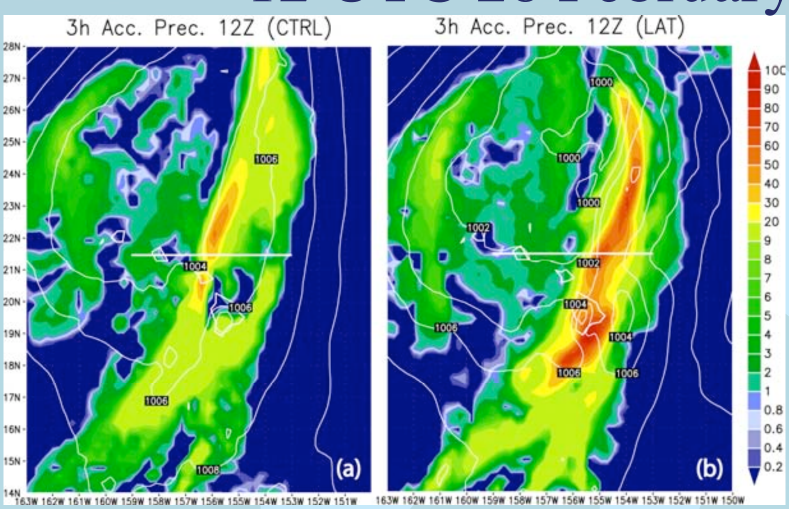


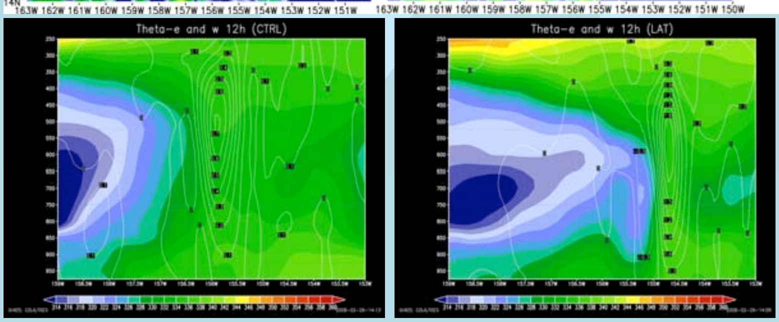


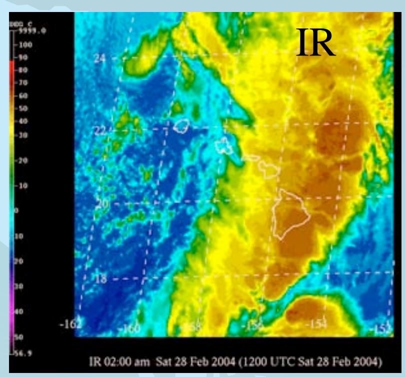
Satellite IR



12 UTC 28 February 2004







Vaisala's Expanding Lightning Network

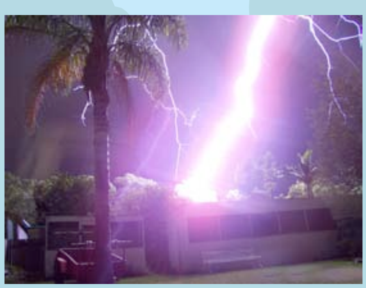
- Two results from our PacNet research have facilitated a breakthrough in long-range lightning detection performance.

1. Documentation of the slow signal attenuation over water and increased sensor sensitivity results in greater network range.
2. Improved signal processing that ingests the whole wave form allows separation of ground wave from 1st and 2nd ionospheric hops, greatly reducing location errors.

- These innovations are being implemented by Vaisala in a new network that promises have global reach.

Summary

- Advent of GPS and microprocessors opened the door for long-range lightning detection.
- Performance of Long Range Lightning Detection Networks must be known for quantitative applications of the data.
- Calibration of PacNet showed that the space constant over water is larger than previously estimated (>10,000 km) and that the whole wave form must be processed for optimal network performance.
- Relationships between lightning rate and convective precipitation rate are robust over the Pacific, leading to nowcasting and data assimilation.
- PacNet data assimilated operationally in Hawaii in WRF to improve regional ocean forecasts.



Future Work

- Development of nowcasting tools and visualization techniques are in their infancy.
- Current assimilation approach adjusts the latent heating profile in the cumulus parameterization in areas experiencing lightning. Other proxies to be investigated include water vapor profiles, CAPE, surface fluxes, etc.
- Future assimilation methods will adjust the explicit cumulus dynamics in higher resolution simulations.
- Continuous nature of data stream is ideal for 4D-VAR.

Community Lightning Model – Research / Program*

Basic research	Observation/validation	Operational products
Numerical methods	Map in-situ electric field	Improved global/mesoscale prediction
Data assimilation	Medium long-range lightning detection	Probabilistic lightning forecasting
Case studies: - cyclogenesis - cyclone intensification	High temporal/spatial resolution optical imaging	Initialization of tropical cyclones and maritime cyclogenesis
Microphysics	Mixed phase microphysics structure	Fire weather, lightning caused
Electrification/discharge parameterizations: varying complexity	Parameterization validation	Aircraft routing, refueling Maritime/fleet safety

✴ Ideas developed at a recent "Workshop on use of novel lightning data and advanced modeling approaches to predict maritime cyclogenesis," held in Monterey, CA March 24-26, 2009.

Questions?

Thank you!