Assimilation of Long-Range Lightning Data over the Pacific

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LONG-TERM GOALS

A Pacific Lightning Detection Network (PacNet) has recently been constructed with support from ONR and NASA. PacNet consists of five hybrid receivers, two sited in Hawaii, one in the Marshall Islands, one in the Aleutian Islands, and one to be installed on Christmas Island (Fig. 1). Together the PacNet sensors continuously monitor sferics over the central Pacific Ocean and adjacent land areas. The long term goals of this project are to continue development of PacNet and to support operational utilization of the data stream at NRL for (i) nowcasting convective activity, (ii) convective rainfall analyses over the Pacific, and (iii) to improve marine prediction of cyclogenesis and squall-line motion through sferics data assimilation in COAMP and NOGAPS. Technology transfer to NRL will be accomplished in close collaboration with NRL scientists, with data processing and analysis support from Vaisala and NASA scientists.

OBJECTIVES

The scientific and technical objectives of the Pacnet project are to collect long-range lightning data over the central and north Pacific Ocean, refine the relationship between lightning and rainfall rates and work toward implementation of operational assimilation of lightning derived products into numerical models.

APPROACH

Diabatic heating sources, especially latent heat release in deep convective clouds play an important role in storm development and dynamics. Lack of observations over the Pacific Ocean can lead to inadequate initialization of the numerical models and large errors in storm central pressure and rainfall forecasts. Specifying diabatic heating sources in the early hours of the forecast can improve the model's performance. Data from Pacific Lightning Detection Network (PacNet) are used to identify the areas and intensities of convective activity and latent heat release in storms over the Pacific Ocean.

Our hypothesis is that in cases of cyclogenesis in marine air masses, including subtropical cyclogenesis, the relationship between rainfall and lightning rates will be relatively robust because the aerosol and cloud microphysical environment is more uniform. Results of our comparison of the lightning rate measured by PacNet and convective rainfall obtained from Aqua's and TRMM's microwave sensors for a variety of storm systems over the central north Pacific indicate that the ratio of lightning to rainfall rate shows a relatively stable relationship over the Pacific Ocean. This suggests

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that lightning data over the Pacific can be assimilated into numerical models as a proxy for latent heat release in deep convective clouds.

Personnel and their tasks for the Project

At UH, Professor Steven Businger, the PI, is working with Antti Pessi, PhD. Student, on the data assimilation. Kirt Squires, MS student is working on lightning in tropical cyclones. Duilia Mora, undergraduate student, is looking at climatology and distribution issues as a senior thesis topic.

Ken Cummins at Vaisala and Dennis Boccippio at NASA are collaborating with UH in using satellite and PacNet data to calibrate the network. Ken is also working with Antti Pessi to develop a detection efficiency model for PacNet.

At the Navy Research Lab in Monterey, Dr. Allen Zhao and Dr. Melina Peng will undertake data assimilation studies. Dr. Joe Turk will investigate nowcasting applications of the lightning data stream over the Pacific.

WORK COMPLETED

Previously lightning data from PacNet were assimilated into MM5 by two methods. The first method capitalizes on a lightning-rainfall-moisture profile relationship. The method involves a Four-Dimensional Data Assimilation (FDDA) of lightning data into MM5. The model predicted vertical moisture profiles are nudged towards moisture values inferred from lightning data.

The second method capitalizes on the relationship of lightning rate and latent heating profiles. This method involves modifying the Kain-Fritch convective parameterization scheme in the MM5 code, and a lightning data input file is constructed. The method scales model's vertical latent heating profiles at each gridpoint and model level, depending on the ratio between model predicted rainfall and rainfall derived from the lightning data. Scaling is done only if the observed rainrate, derived from lightning, is greater than model predicted rainrate. As reported in our last annual report, both methods significantly improved the location and strength of the storms studied (Pessi et al. 2005).

Work completed since the last annual report

Significant progress has been made on five fronts during the past year.

i) A site for our fifth lightning detector has finally been identified. Palmyra Atoll is located ~1500 km south of Kauai and is a US territory (see map in Fig. 1). A growing research presence on the Atoll has afforded regularly scheduled flights and barge trips. In addition it has allowed for installation of broadband Internet with a satellite uplink. Thus, two logistical issues are resolved, and the fact that the Atoll is under US jurisdiction means there are no political issues to face. Installation of the fifth sensor is scheduled for spring 2007 and will significantly improve the geometry to the south of Hawaii.

ii) Calibration and empirical analysis of the detection efficiency of PacNet has proceeded and a detection efficiency model has been constructed and implemented at UH (Fig. 2). This is a significant milestone because it makes possible the use of the PacNet data in quantitative applications such as numerical weather prediction (NWP).

iii) The relationship between lightning rates and rainfall rates has been refined with reference to the DE model for the central North Pacific Ocean, with improvements in the statistics. The resulting log-linear relationship (Fig. 3a) is fundamental to the application of the PacNet data stream in NWP. In addition, the relationship between the lightning rate and the precipitable ice product from TRMM has been investigated and a very similar log-linear relationship has been uncovered (Fig. 3b). A goal for the coming year is to explore how this new relationship and additional information on the vertical distribution of ice can be exploited in NWP (Fig. 4).

iv) A climatological study was undertaken of the distribution of lightning strikes and its relationship to storm track, rainfall and aerosol distributions observed by TRMM and Aqua. Patterns seen in the data sets show striking similarities, suggesting that distributions of lightning, rainfall, and large aerosols share a common cause in midlatitude storms (Fig. 5).

v) Data collected by the National Long-Range Lightning Detection Network (LLDN), along with TRMM and reconnaissance aircraft data, were used to analyze the morphology of lightning outbreaks in the eyewalls of hurricanes Rita (2005) and Katrina (2005). The LLDN network is one of few observing systems, outside geostationary satellite-based instruments, that provide continuous real-time data throughout a synoptic-scale coverage area over the open ocean (Fig. 6). Conclusions of this research are provided in the results section below. Only figures from Rita are included here for the sake of brevity.

RESULTS

The eyewalls of hurricanes Rita and Katrina are shown to have extraordinary lightning flash densities when compared to historical storms (Fig. 7). LLDN detected lightning strikes in hurricanes Rita and Katrina were closely collocated with areas of intense convection, as determined by aircraft radar reflectivity data. Therefore, by using the lightning data as a proxy for convective intensity, it may be possible to continuously monitor the convective evolution within hurricane eyewalls through close examination of the evolution of the LLRD lightning data.

Both storms' eyewalls contained their greatest hourly flash density during a period of rapid intensification (Fig. 8). These outbreaks were similar in duration and magnitude; however, they had very different spatial distributions. Rita's eyewall lightning was symmetric (Figs. 9 and 11), whereas, Katrina's eyewall lightning showed an asymmetric distribution. During Katrina's shorter lightning outbreak it was only a category 1 hurricane, with more limited vertical shear of the horizontal winds. Eyewall replacement cycles in each storm produced a series of short-lived (< 1 h), localized lightning outbreaks. These lightning outbreaks were nearly stationary with respect to the storm center and were associated with convective cells in the dissipating inner eyewall.

The lightning flash density displayed a consistent relationship with TRMM Precipitation Ice Concentration (PIC) product (e.g., Figs. 10 and 11). Large lightning flash rates were nearly always associated with large PIC. Conversely, large PIC within layer 12 does not guarantee the presence of large flash density, presumably owing to the fact that ice can have an extended residence time in the upper troposphere. The collocation of lightning strikes and high PIC was clearest in the TRMM layer 12 (8 – 10 km) PIC, however the relationship was present for all levels provided by the TRMM 2A12 algorithm (e.g., Fig. 11).

One of the most intriguing results is that Hurricanes Rita and Katrina both contained a long-lived eyewall outbreak directly centered on the time which maximum intensity was reached (Fig. 8). The elevated flash densities lasted for 9 to 10 h centered on the time of maximum intensity for each storm. During this period the eye for each storm had contracted and reached a minimum diameter. The eyewalls were also steep, with enhanced convection surrounding most of the eye.

Maxima in eyewall flash density were collocated with maxima in flight-level reflectivity (e.g., Figs. 9 and 10). However, flash density maxima and radar reflectivity maxima are not always collocated with minima in brightness temperatures and high PIC. Observed spatial displacement between the location of lightning and PIC maxima can be attributed to vertical shear of the horizontal winds over the area of convection. It was observed that PIC maxima are located upwind of convective cores that rotate cyclonically around the storm center, and downwind of convective cores that are stationary relative to the storm center.

IMPACT/APPLICATIONS

Long-range lightning data can be used to aid the real time examination of active convective areas within the eyewall of TCs. As a result of the masking effects of high cloud blow-off, it is often difficult to track the motion of individual convective areas within the eyewall region. Using continuous lightning data overlaid onto these infrared satellite images would allow for much better tracking of any area of active eyewall convection, which is producing cloud to ground lightning. For a convective system to produce the flash rates that were recorded in both Rita and Katrina, a modest amount of CAPE within the eyewall environment is necessary. The eyewall lightning within these two storms was also maintained for many consecutive hours, sometimes for more than a day. Therefore, the results of this limited study suggest that for some extended periods of time, appreciable values of CAPE are present within the eyewall of some mature hurricanes. The better understanding of the structure and evolution of the eyewall convection while the TC is still over the open ocean, could lead to more accurate intensity forecasts.

Progress has been made during the past year in quantifying the detection efficiency of PacNet, an important step toward operational application of the lightning data stream. With the establishment of a fifth detector at Palmyra and continued calibration of PacNet, the quality of the data stream will continue to improve in support of our primary goal. The primary goal of the project is to assimilate the lightning data employing COAMPS[1] and 3-D variational data assimilation. Initial tests of two methods of data assimilation conducted at UH to investigate the impact of convective latent heating on forecasts of storm evolution are very promising. The early success of the methods holds promise for application in a variety of settings, including tropical cyclones.

In an operational forecast system, latent heat assimilation has some advantages over moisture profile assimilation (Table 1). Construction of the moisture profiles requires prior knowledge of the temperature, whereas latent heating scaling technique is independent of environmental temperature, making this approach more robust.

[1] COAMPS – Coupled Ocean/Atmospheric Mesoscale Prediction System. http://128.160.23.41/Products/modeling/coamps

RELATED PROJECTS

NASA MSFC, in collaboration with Vaisala Thunderstorm Group and UH, has completed a validation the data using LIS on TRMM. Vaisala Thunderstorm Group has conducted a The results of their work will have important implications for attaining our goals of operational data assimilation since the NASA results will provide a calibration of the PacNet network.

European VLF-Detector Network: The European Community has been actively developing a VLF lightning detection network in Europe. Contact has been made with one of the principals (Chris Kidd at the U of Birmingham, C.Kidd@bham.ac.uk) in that effort to facilitate synergy and scientific exchange.

Table 1. Comparison of Lightning Data Assimilation Methods. Latent heating vs. FDDA

Latent Heating	FDDA
Lightning observations mapped to rainfall	Lightning observations mapped to rainfall-moisture profile
Modification of model equations and physics	No model modification – only input files
Model stability and physical issues: Assimilation to conv., non-conv. or combined?	FDDA relatively stable. Only a few adjustable parameters in a configuration file
Lots of tuning options by modifying model	Less tuning options by modifying configuration file
Improved storm central pressure forecast	Improved storm central pressure forecast

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Pessi, A., S. Businger, T. Cherubini, 2006. Comparison of two Methods for Assimilation of Lightning Data into NWP Models. Preprints, 1st International Lightning Meteorology Conference, Tucson, Arizona, 26-27 April 2006.

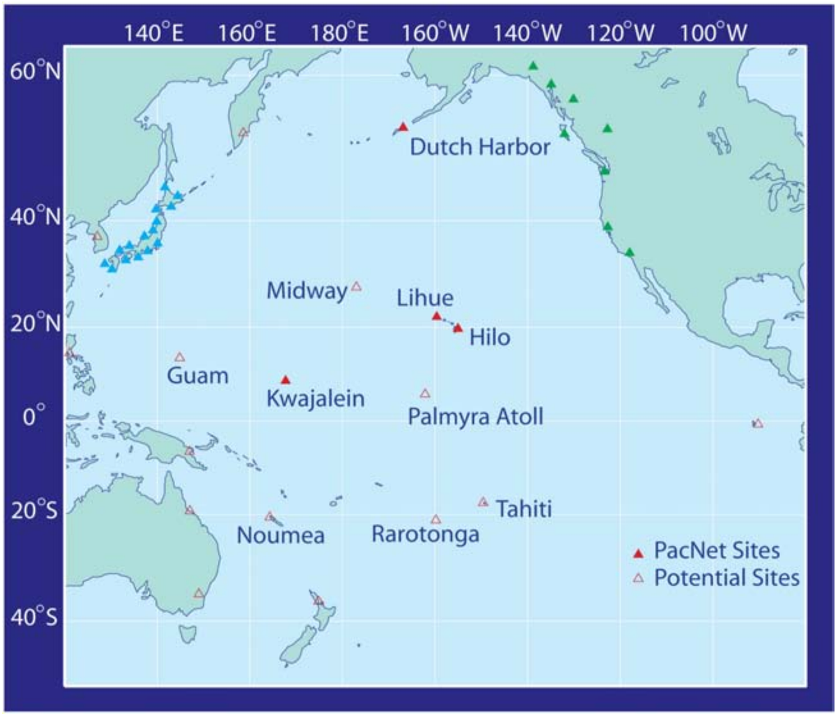


Fig. 1 PacNet's current and potential future sites for lightning detectors in the central Pacific. A fifth lightning detector is scheduled to be installed at Palmyra Atoll in spring 2007 enhancing the network geometry to the south of Hawaii. Data from detectors located in Japan and along the west coast of the U.S. are used in the processing stream received at the Vaisala Thunderstorm Unit to complement the PacNet data.

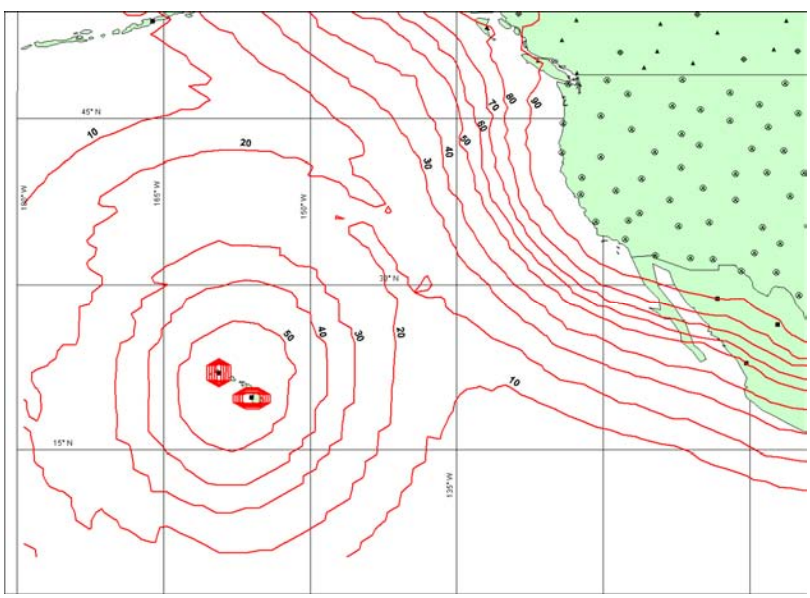
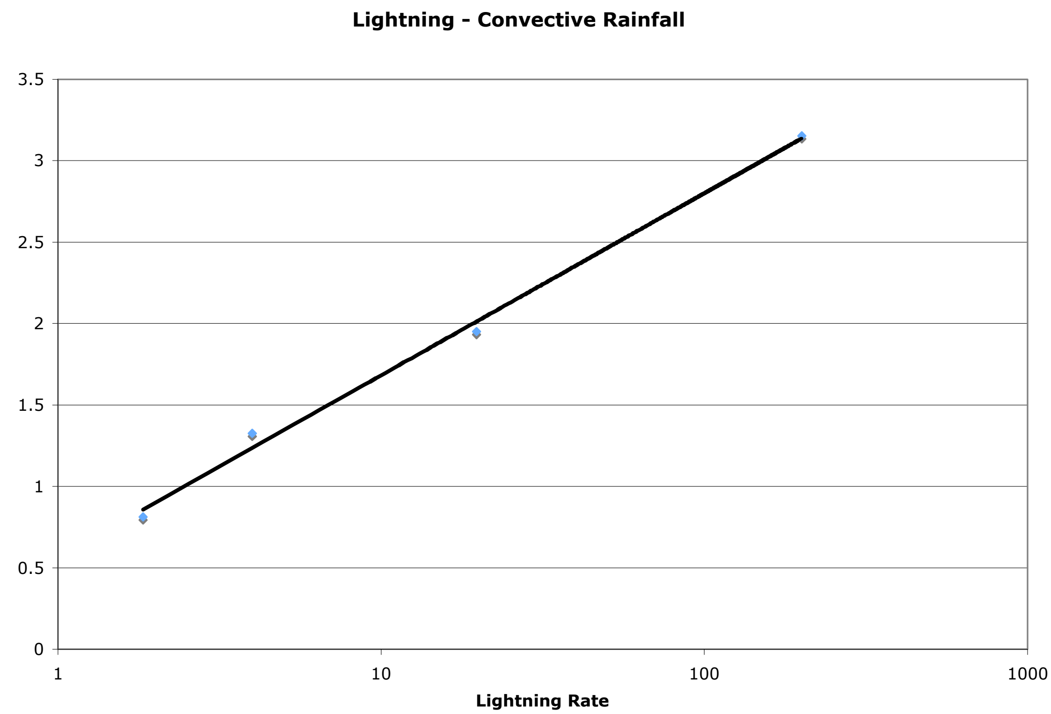


Fig. 2 Modeled detection efficiency (%) over the central north Pacific at night. Tight contouring near Lihue and Kona sensors reflects the fact that the DE falls to zero just behind the sensors.



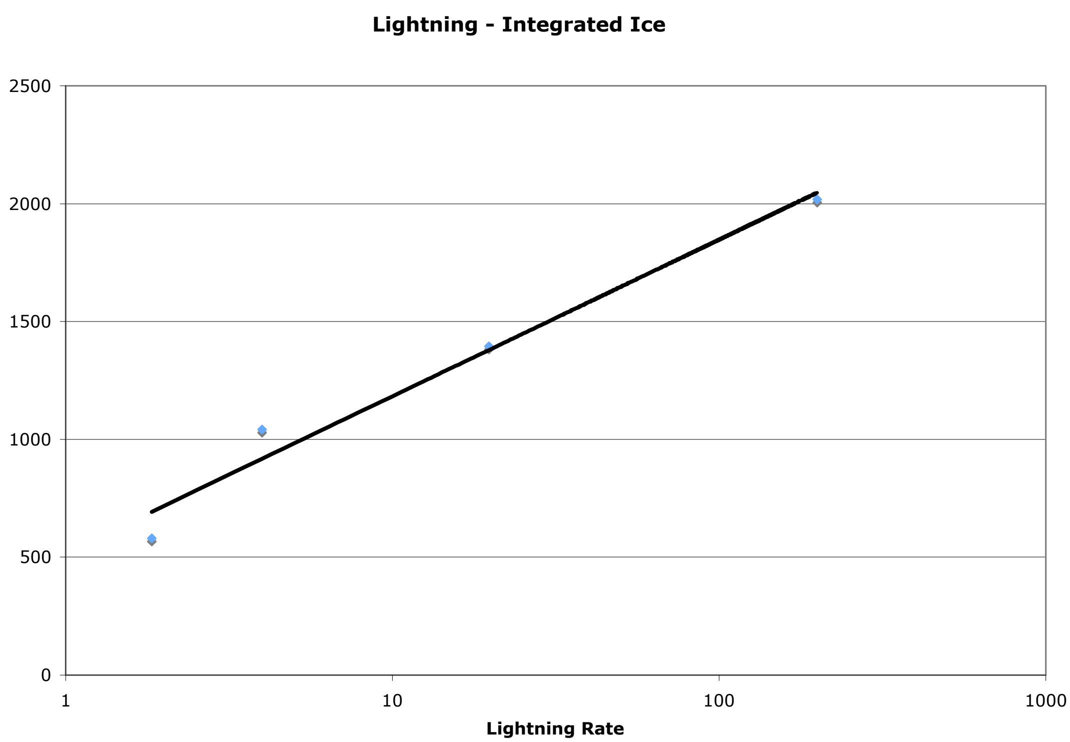


Fig. 3 a) Lightning data from PacNet and convective precipitation, and b) vertically integrated precipitable ice both derived from TMI data. The four data points correspond to the average lightning rates in the four categories shown in Fig. 4.

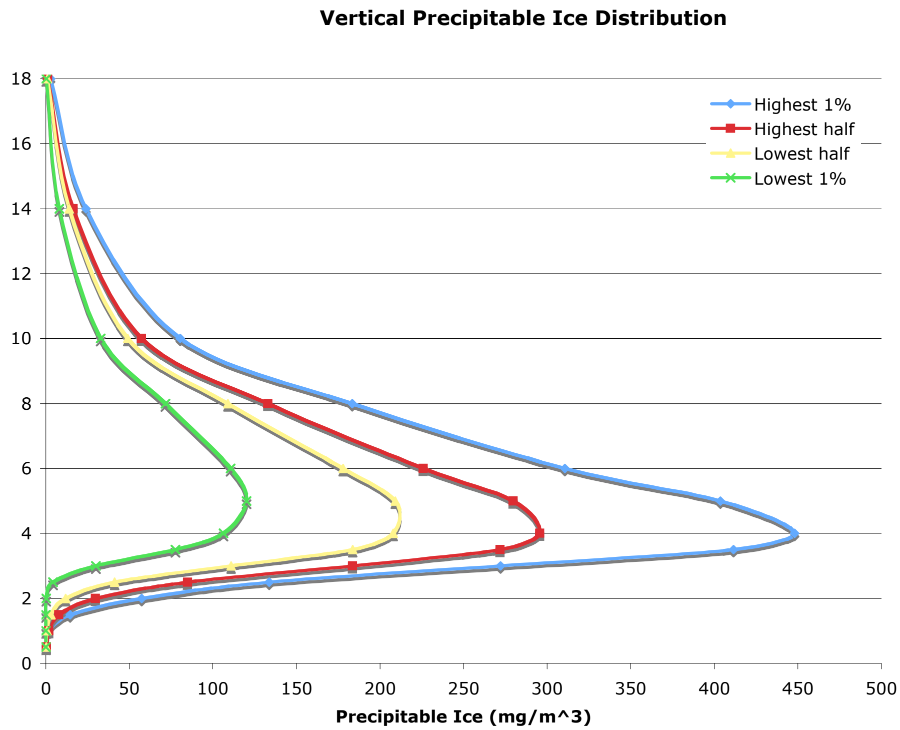


Fig. 4 Precipitable ice distribution from TMI data as a function of height. Color-coded curves correspond to four different lightning rate categories with blue being the highest and green the lowest percentile in lightning rates. Red and yellow are the highest and lowest half excluding the first and last percentiles. Lightning rates used in this analysis have been DE corrected.

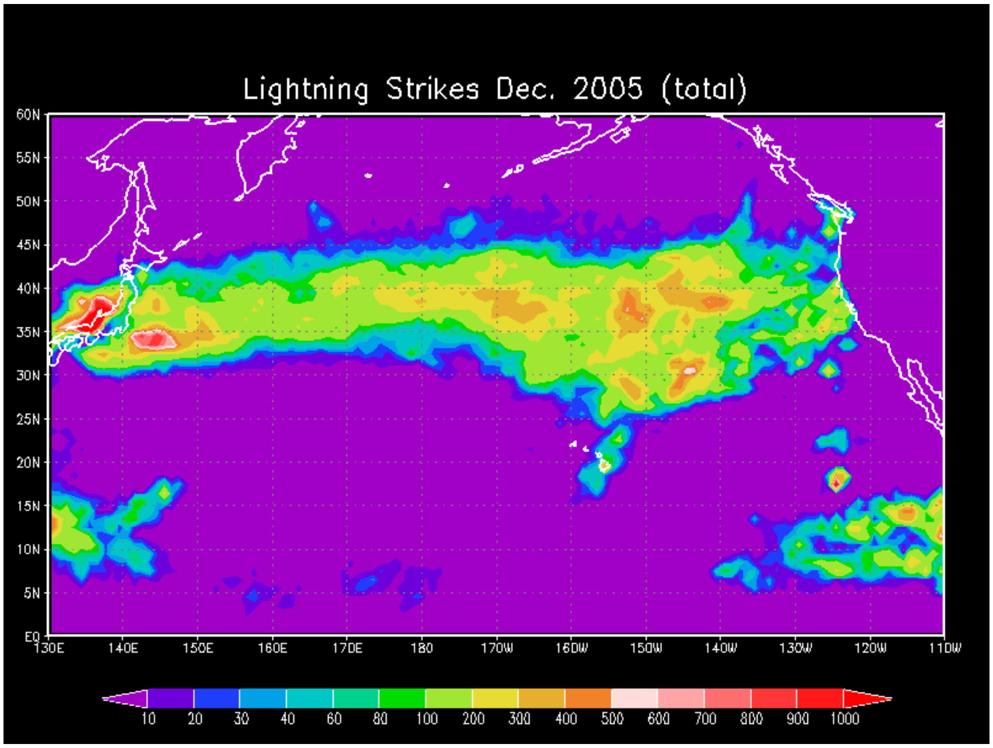


Fig. 5a Total number of lightning strikes (no DE correction) over the north Pacific Ocean during December 2005 over 1°x1°squares.

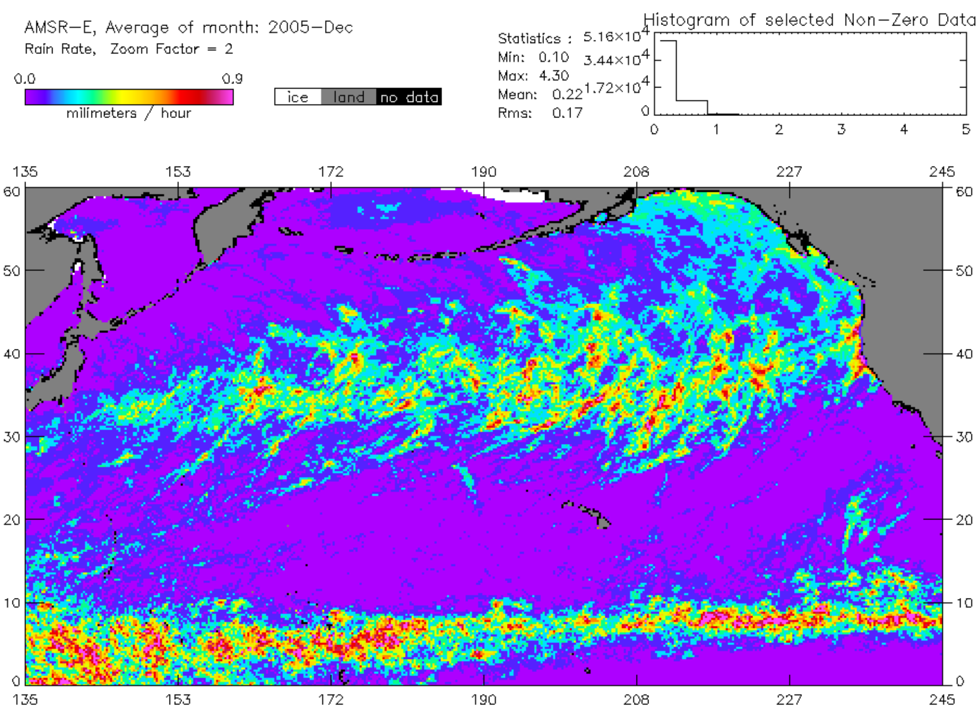


Fig. 5b December 2005 average rainfall rate derived from Aqua's AMSR-E microwave radiometer data. The average storm track can be seen between Japan and U.S west coast, but also individual, probably slow moving frontal systems stand out.

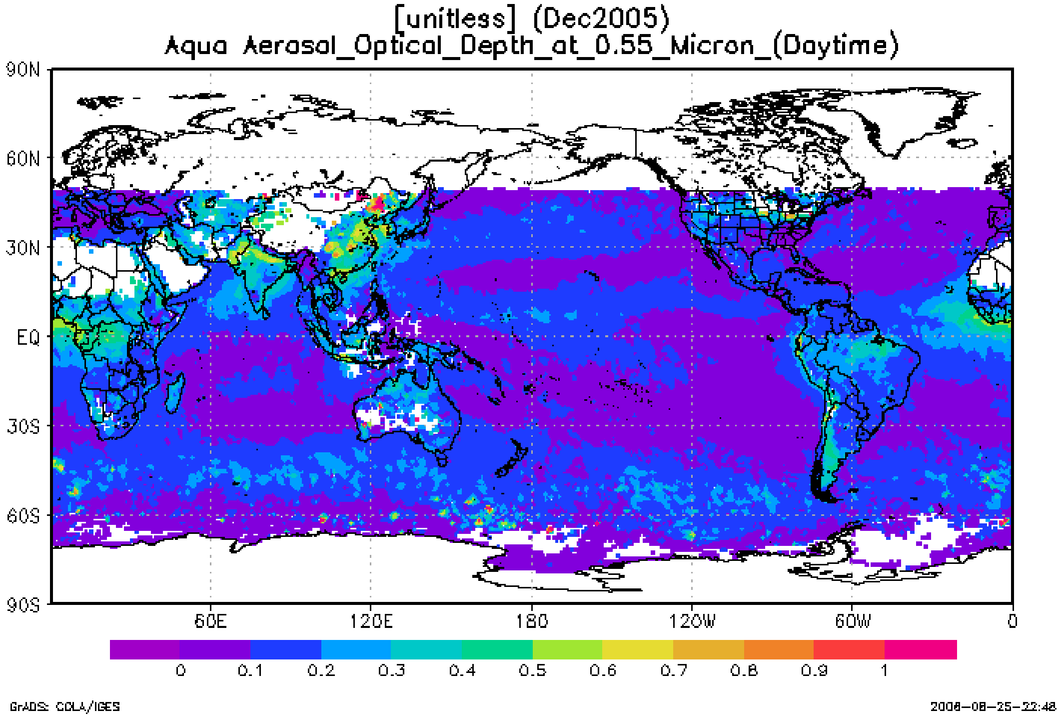
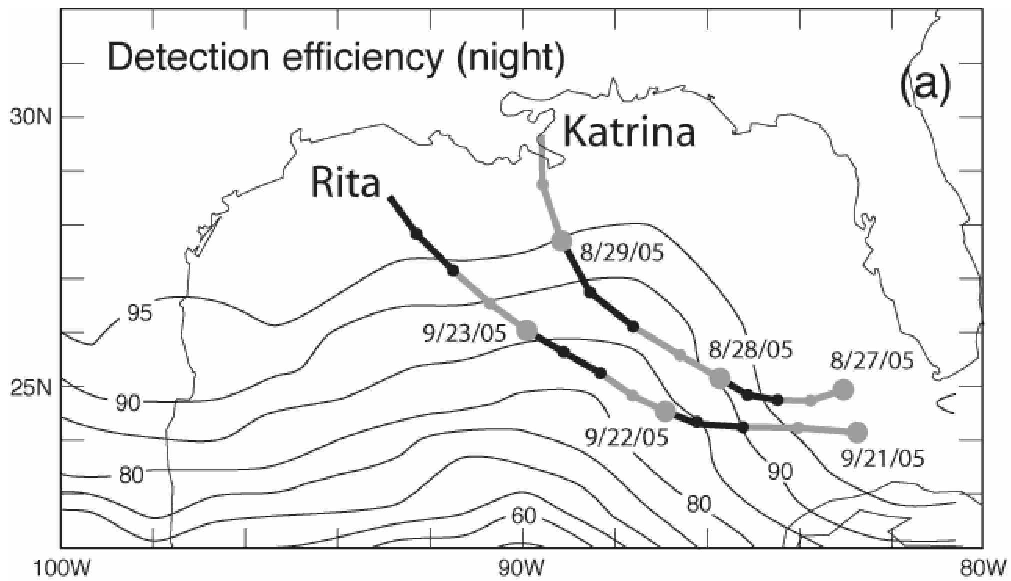


Fig. 5c Aerosol optical depth from Aqua's MODIS sensor's 0.55 μm channel for December 2005. A streak of thicker aerosol depth between Japan and U.S. coincides with the storm tracks shown in Figs. 5 a and b.



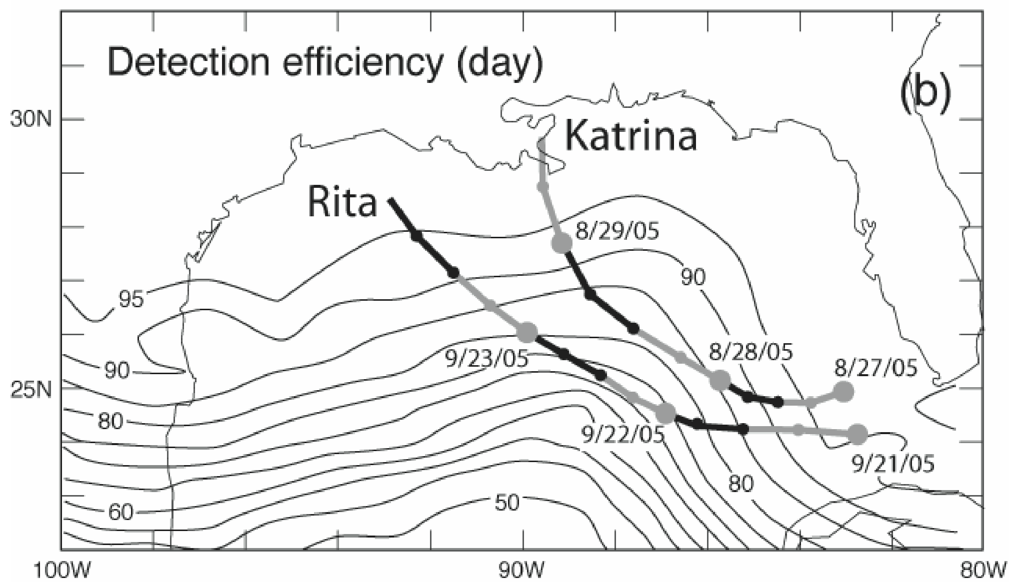


Fig. 6 Model derived detection efficiency contours (%) for the Gulf of Mexico region a) daytime b) nighttime (after Cummins, 2006). Hourly storm tracks for both Hurricane Rita and Katrina are displayed using hourly interpolations of best-track 6-h data obtained from National Hurricane Center. Strom track during times of local day (night) are represented by the black (grey) lines.

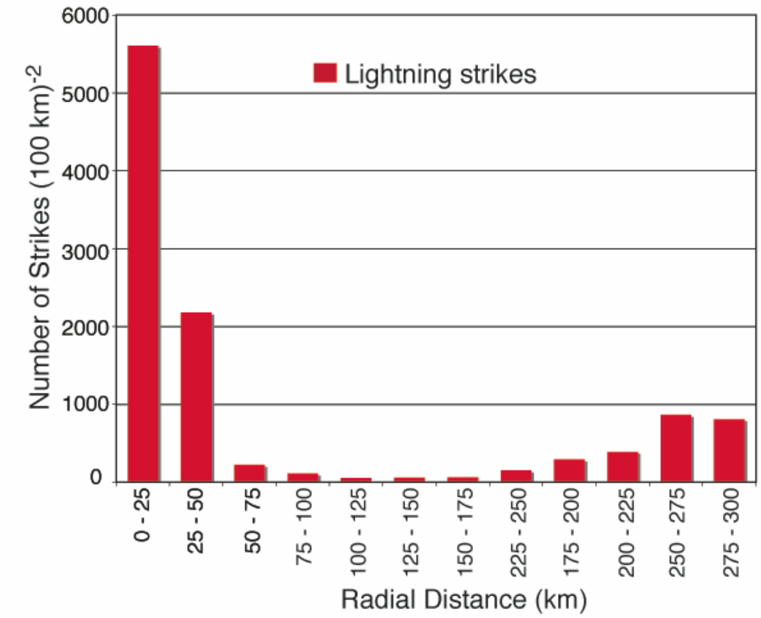


Fig. 7 Radial distribution of lightning strikes in Hurricane Rita between 1800 UTC on 20 September and 0900 UTC on 23 September. Flash totals normalized by the total number of flashes (100 km)$^{-2}$.

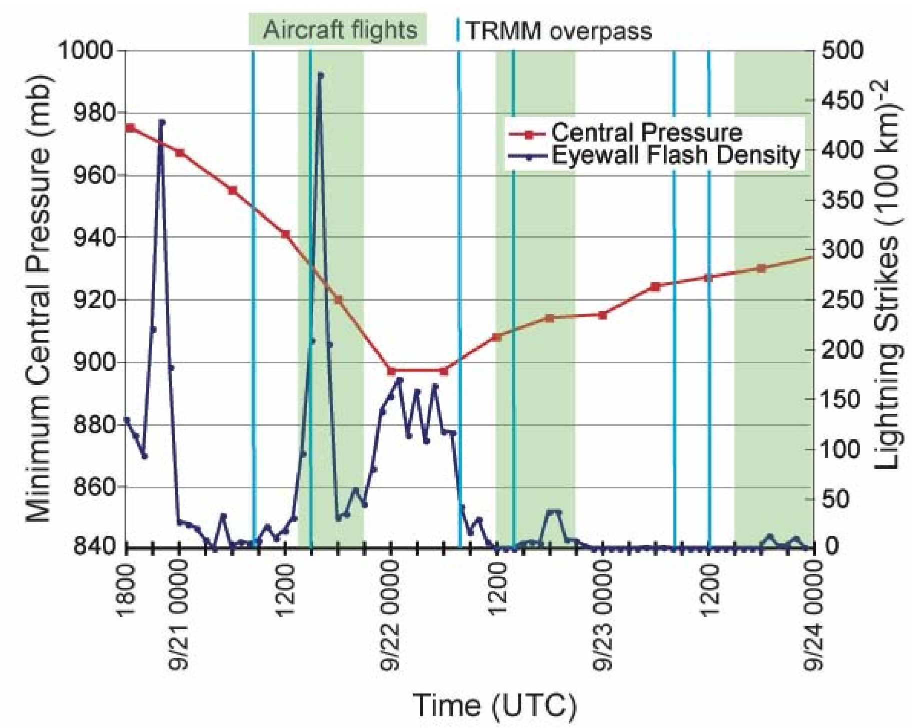


Fig. 8 Time series containing the number of cloud-to-ground flashes within 50 km of the center of Hurricane Rita (blue line), and hourly track of minimum central pressure (red line). Pressure values are linear interpolations of best-track 6 h data obtained from National Hurricane Center. Times when TRMM data (blue line) and aircraft data (green shading) were available are also indicated.

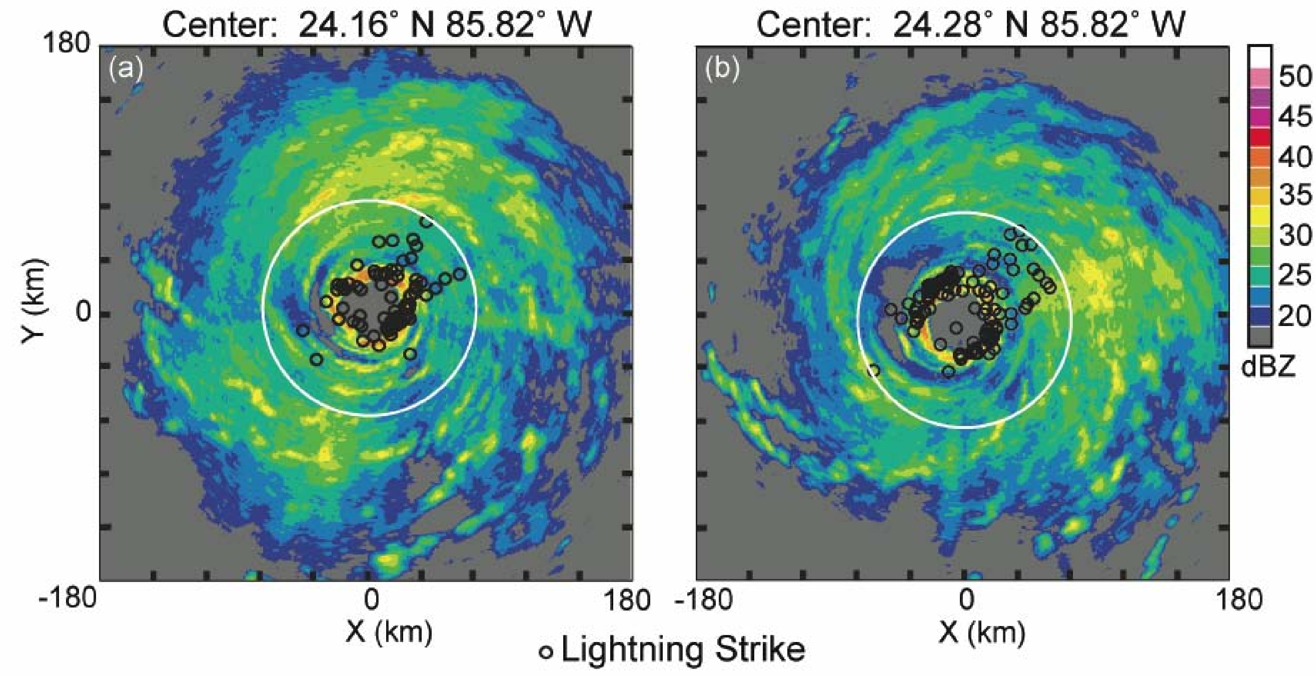


Fig. 9 NOAA P-3 lower fuselage radar reflectivity taken on 21 September while aircraft was located within the center of Hurricane Rita, at an altitude of 2,700 m. The nominal effective range of the LF radar is shown using the 70 km range ring (white circle). Superimposed onto each image is 20 minutes of lightning data (black circles) centered on the time of the image. a) Reflectivity at 1523 UTC, with flash locations from 1513 UTC to 1533 UTC. b) Reflectivity at 1602 UTC, with flash locations from 1552 UTC to 1612 UTC.

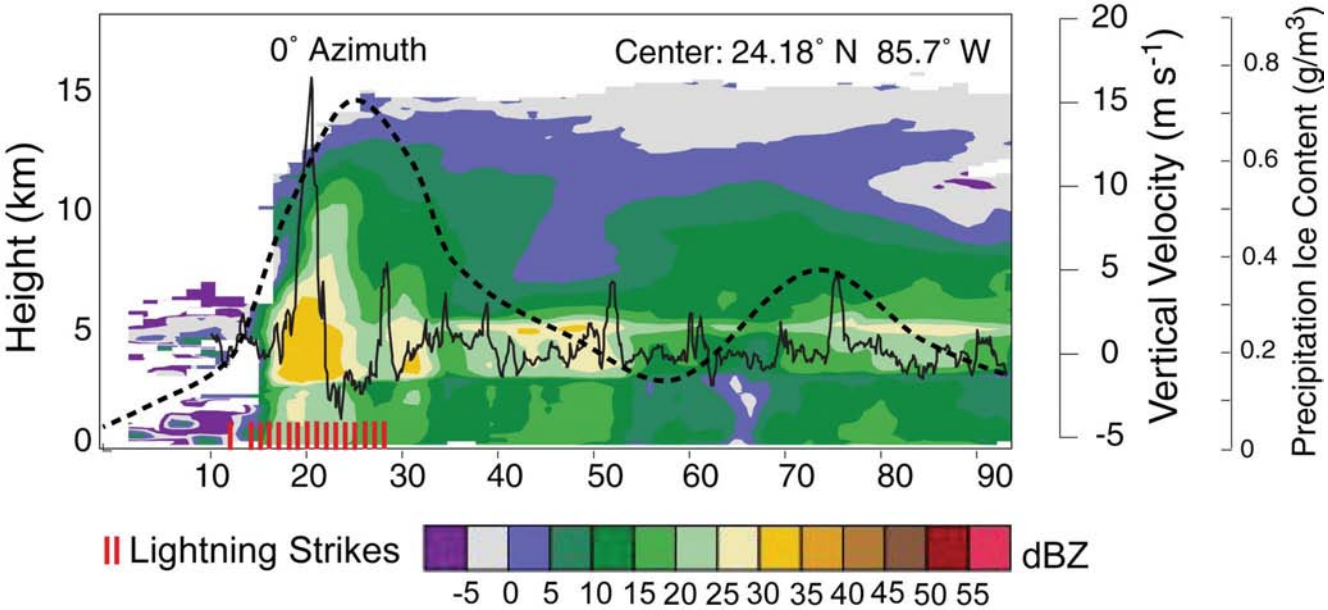


Fig. 10 Vertical reflectivity profile (VRP) composites created by the NOAA P-3 aircraft tail radar during an azimuthal eyewall cross-section flown at 1536 UTC 21 September, with aircraft altitude of 2,600 m and heading of 000˚. Overlaid onto the cross-section is flight level vertical velocity measured along the corresponding flight path (heavy solid line), radial lightning strike locations (red bars) during the time of the radial flight, and radial distribution of level 12 (8 – 10 km) TRMM PIC values (dashed line) obtained from the 1540 UTC satellite pass.

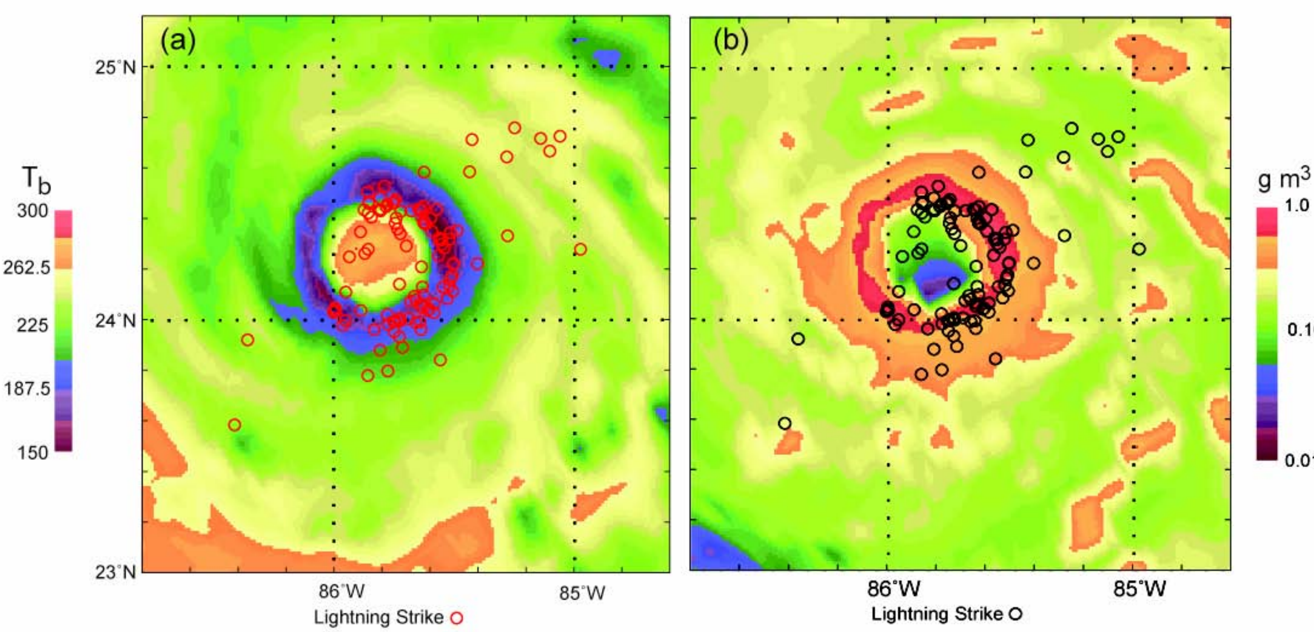


Fig. 11 TRMM data collected at 1540 UTC, with lightning strike locations from 1530 to 1550 UTC on 21 September. a) 85-GHz TMI image with lightning (red circles). b) Level 12 (8 -10 km) PIC image with lightning (black circles).