An Algorithm to Estimate Satellite Rainfall Rate

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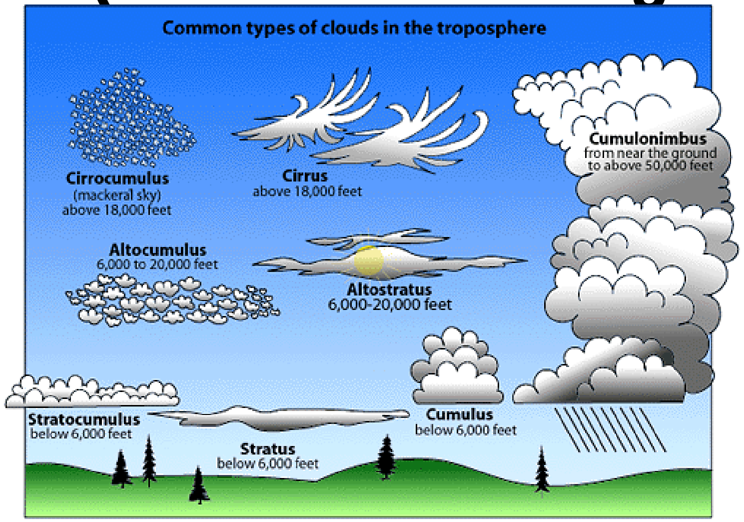
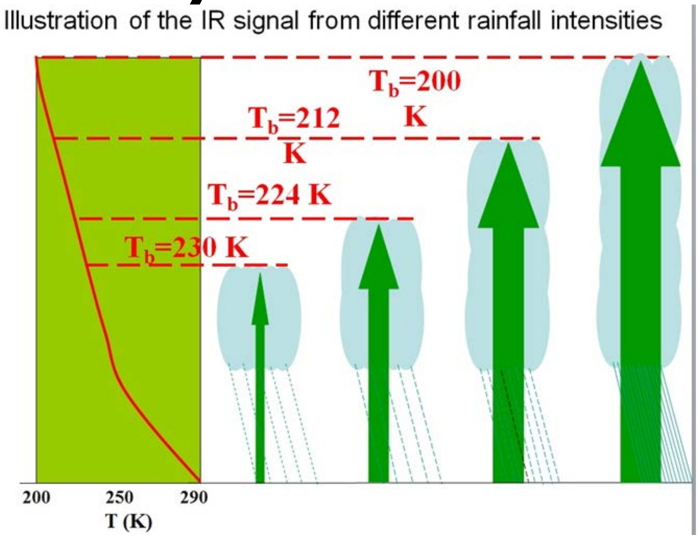
Introduction

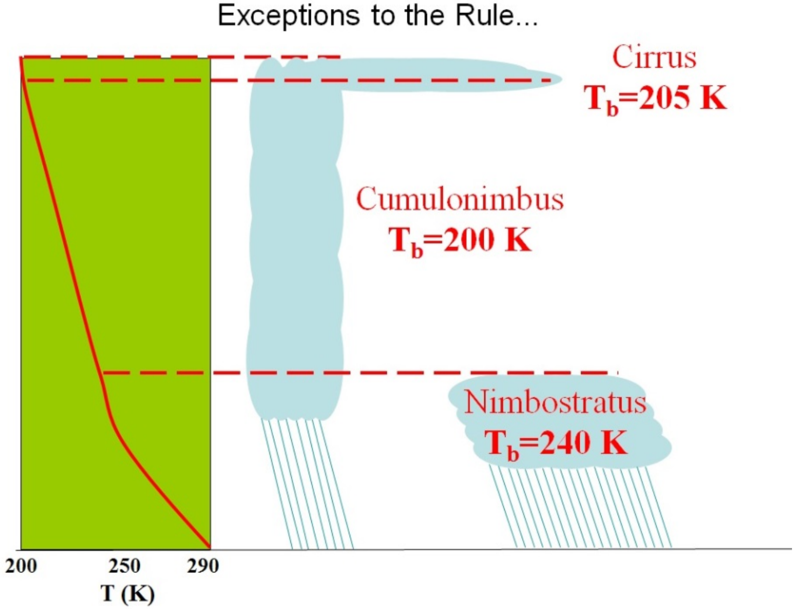
- Hydro-Estimator (HE) has been the operational satellite rainfall algorithm of National Environmental Satellite Data and Information Services (NESDIS) since 2002 and produces rainfall estimates at the full spatial and temporal resolution of the Geostationary Operational Environmental Satellites (GOES) over the continental United States and surrounding regions, including Puerto Rico (Scofield and Kuligowski 2003).



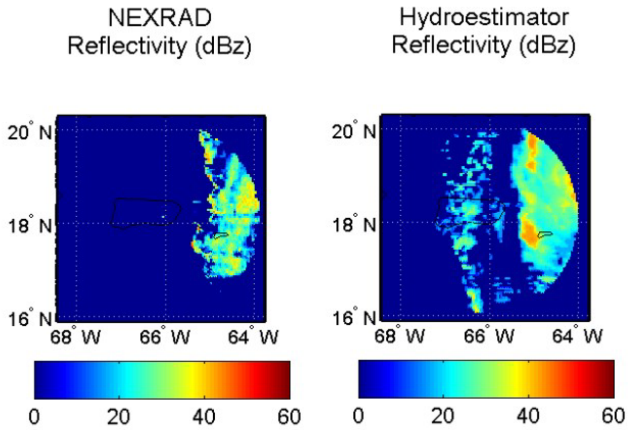


http://www.star.nesdis.noaa.gov/smcd/emb/ff/HE_CONUS_inst.php

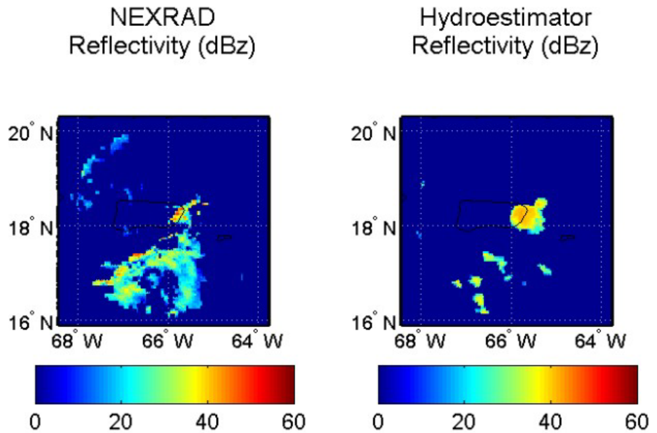
Introduction



The HE algorithm was implemented over Puerto Rico and it was found that some warm clouds were not detected by this algorithm. Since the warm clouds occur frequently over a tropical region we decided to derive a new rainfall rate retrieval algorithm that takes into account the estimation of rainfall rate over warm and cold clouds.



August 21, 2011 at 16:45 UTC daytime



July 23, 2010 at 16:30 UTC daytime

Introduction

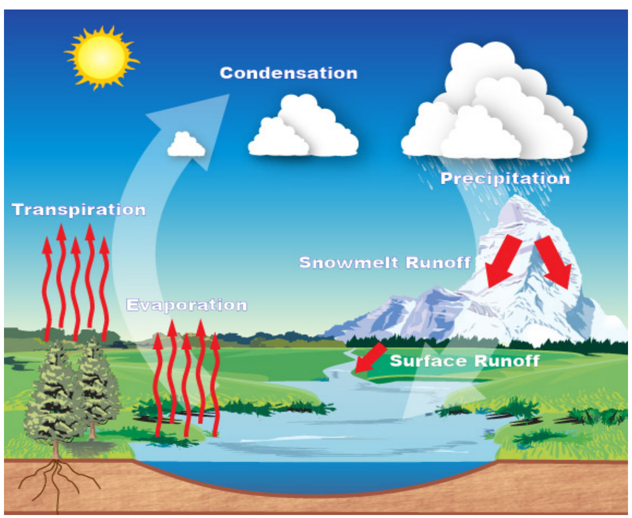
- **We proposed a couple algorithms for detecting raining clouds and rainfall rate estimation. The projection and the analog storm algorithms were developed to identify raining pixels and the time lag and exponential decay algorithms were introduced to estimate rainfall rate.**
- **The time and spatial lags model uses a sequence of visible and infrared GOES- 12 & 13 images to model the cloud advection and the cloud rainfall evolution with the purpose of estimating rainfall rate. Weather radar data are used to calibrate the time and spatial lags model.**

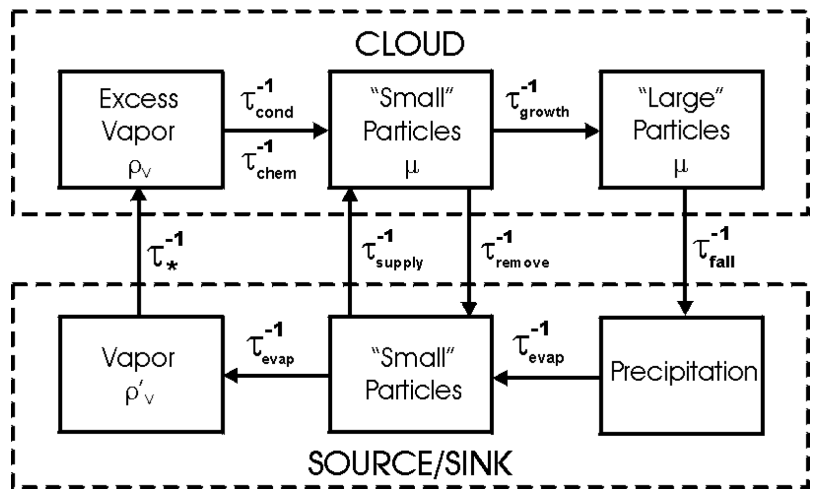
Objective

- The main purpose of this research is to develop an algorithm to improve the HE rainfall detection and rain rate estimation over tropical climate conditions by using the full suite of observations available from GOES and from a numerical weather prediction model.

Rainfall Rate Model Basics

- A cloud rainfall event is the result of a complex thermodynamic process that starts with nucleation of cloud drops, continues with drop growth, and finishes with water drop precipitation.
- Usually, the atmosphere is filled with small aerosol particles, and molecules of vapor may collect onto the surface of aerosol particles.
- Cloud drops also grow by collision among the drops. However, collision between two drops does not guarantee coalescence; it depends on whether the droplets are electrically charged or if an electrical field is present.

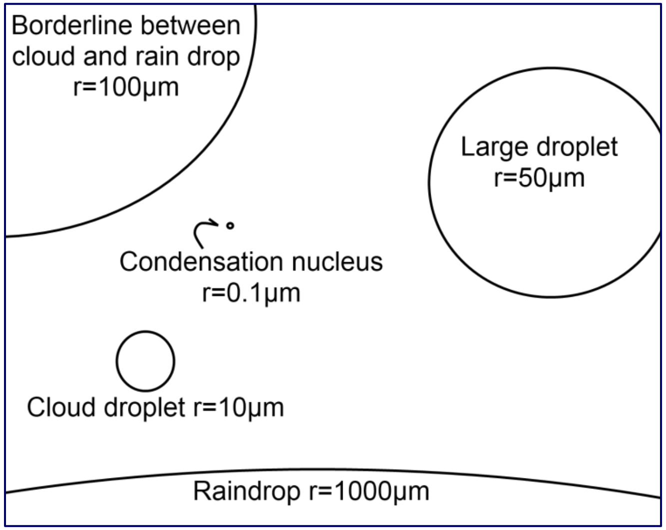




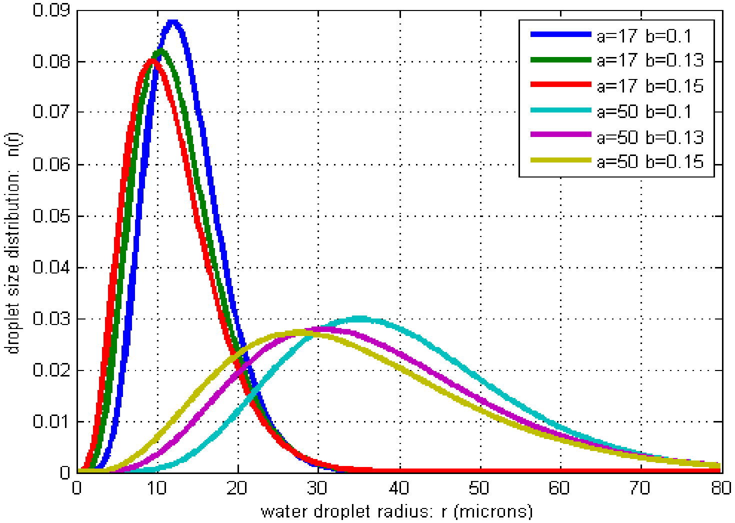
The Hydrologic Cycle: Thermodynamic processes which govern cloud microphysics.
Source: National Weather Service (2010)

Rainfall Rate Model Basics

- **Houze [1993] shows that for a drop to start the descending trajectory requires having a radius of at least of 15μm.**
- **Thus, the time period from the drop nucleation to drop precipitation may last from 30 minutes to few hours depending on the inherent conditions of the troposphere.**
- **To estimate the rain rate at a given point in time requires considering the status of the clouds at the current time and also at consecutive previous points in time as well as considering the wind vector.**



The radius of cloud droplets vary by several orders of magnitude

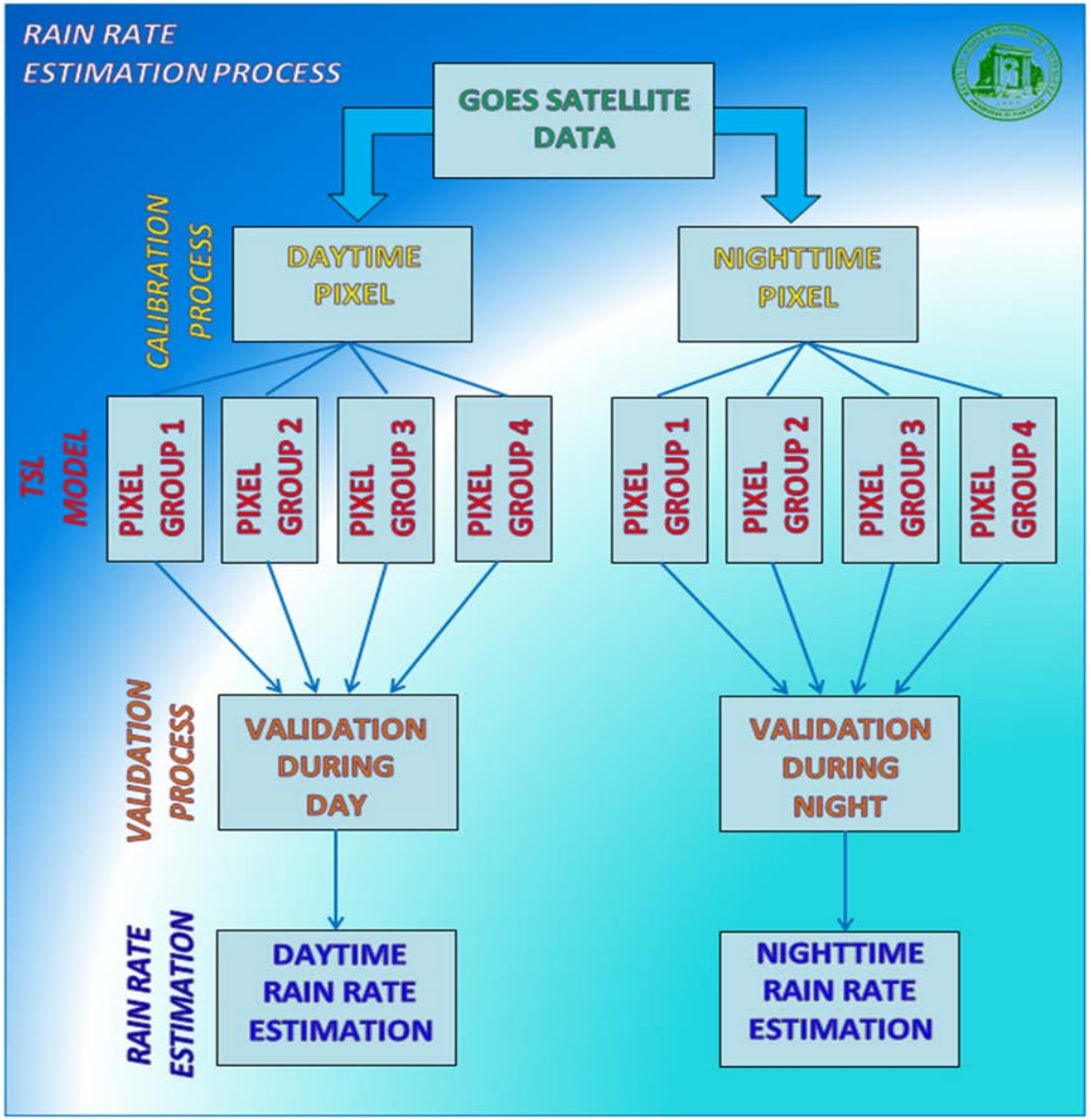


Differences in effective radius have a large effect on the shape of the drop-size distribution.

Methodology

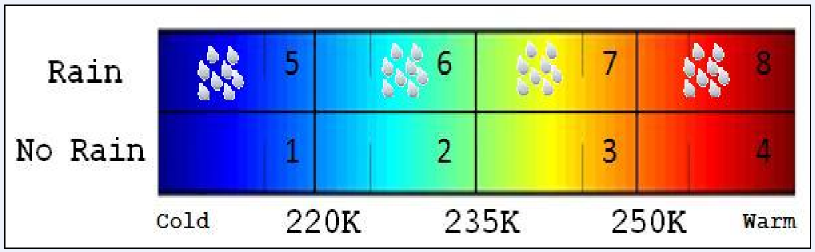
- The proposed algorithm has two major components one for determining rainy cloud pixels and the second component for estimating the rainfall rate.
- The projection algorithm was used to detect cloud rainy pixels and the time a spatial lags model was used to estimate the rainfall rate.
- A time and spatial lags algorithm for estimating rainfall rate is introduced in this research. It estimates rainfall rates by taking into account the temporal and spatial variability of the rainfall process, whereas existing satellite rainfall retrieval algorithms generally use only current satellite imagery.

Methodology



Detection algorithm: Pixel Classification

- The calibration data will be divided into eight groups to characterize all possible pixels in a given storm.
- The pixel classification includes brightness temperature from channel 4 and rain/no rain as opposed to rain/no rain alone, since the extra classification by brightness temperature improves the detection skill of the algorithm.



$$c_l = [\bar{x}_{1l},\ \bar{x}_{2l},\ ,\cdots,\ \bar{x}_{ml}\ \ \bar{s}_{1l},\ \bar{s}_{2l},\ ,\cdots,\ \bar{s}_{ml}]$$

$$\mathbf{p} = [\bar{x}_1,\ \bar{x}_2,\ ,\cdots,\ \bar{x}_m,\ s_1,\ s_2,\ ,\cdots,\ s_m]$$

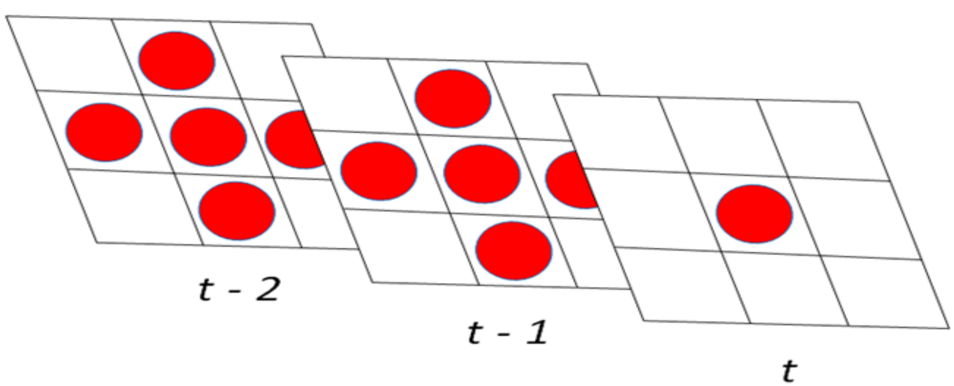
Where $\bar{x}_k$ and s_k are the average and the standard deviation of c and p variables for $k = 1, \dots, m$.

$$\theta_l = \cos^{-1}\left(\frac{\mathbf{p} \cdot \mathbf{c}_l}{\|\mathbf{p}\|\|\mathbf{c}_l\|}\right)$$

No	Variable Name	Variable Description
1	T_2	Brightness temperature from channel 2
2	T_3	Brightness temperature from channel 3
3	T_4	Brightness temperature from channel 4
4	ΔT_3	Difference of two consecutive brightness temperature of channel 3
5	ΔT_4	Difference of two consecutive brightness temperature of channel 4
6	T_{42}	Difference of $(T_4 - T_2)$
7	T_{43}	Difference of $(T_4 - T_3)$
8	A	Albedo of channel 2 (daytime only)

Time Lag and Spatial Displacement Model (TLSDM)

- It estimates rainfall rates by taking into account the temporal and spatial variability of the rainfall process, whereas existing satellite rainfall retrieval algorithms generally use only current satellite imagery.
- Empirical analysis of radar and satellite data showed that a linear model between reflectivity and radiative variables could be developed and a nonlinear transformation then applied to convert the estimated reflectivity to a rain rate.
- To estimate the rain rate at a given point in time requires considering the status of the clouds at the current time and also at consecutive previous points in time as well as considering the wind vector.
- Reflectivity can be estimated by measuring the evolution of the cloud microphysical processes and by using the wind vectors that advect the clouds.



Time Lag and Spatial Displacement Model (TLSDM)

No	Variable Name	Variable	Time lags	Spatial displacement
1	T_2	Brightness Temperature Channel 2	0, 1, 2	$i \pm 1, j \pm 1$
2	T_3	Brightness Temperature Channel 3	0, 1, 2	$i \pm 1, j \pm 1$
3	T_4	Brightness Temperature Channel 4	0, 1, 2	$i \pm 1, j \pm 1$
4	T_{42}	Difference of $T_4 - T_2$	0, 1, 2	$i \pm 1, j \pm 1$
5	T_{43}	Difference of $T_4 - T_3$	0, 1, 2	$i \pm 1, j \pm 1$
6	A	Albedo Channel 2	0, 1, 2	$i \pm 1, j \pm 1$
7	V	Visible Reflectance Channel 1	0, 1, 2	$i \pm 1, j \pm 1$

$$
\begin{aligned}
Z_t(i,j) = a_0 &+ a_1 X_t(i,j) + a_2 X_{t-1}(i,j) + a_3 X_{t-1}(i,j-1) + a_4 X_{t-1}(i-1,j) \\
&+ a_5 X_{t-1}(i+1,j) + a_6 X_{t-1}(i,j+1) + a_7 X_{t-2}(i,j) \\
&+ a_8 X_{t-2}(i,j-1) + a_9 X_{t-2}(i-1,j) + a_{10} X_{t-2}(i+1,j) \\
&+ a_{11} X_{t-2}(i,j+1) + \varepsilon_t
\end{aligned}
$$

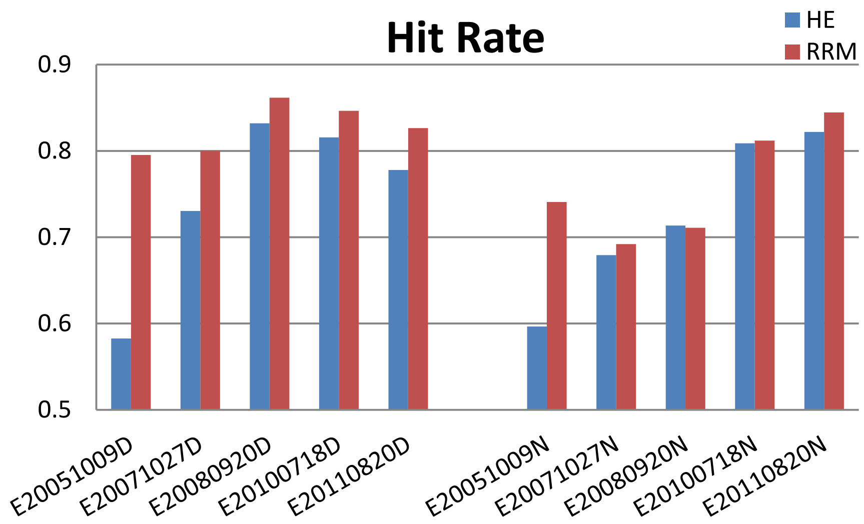
Results

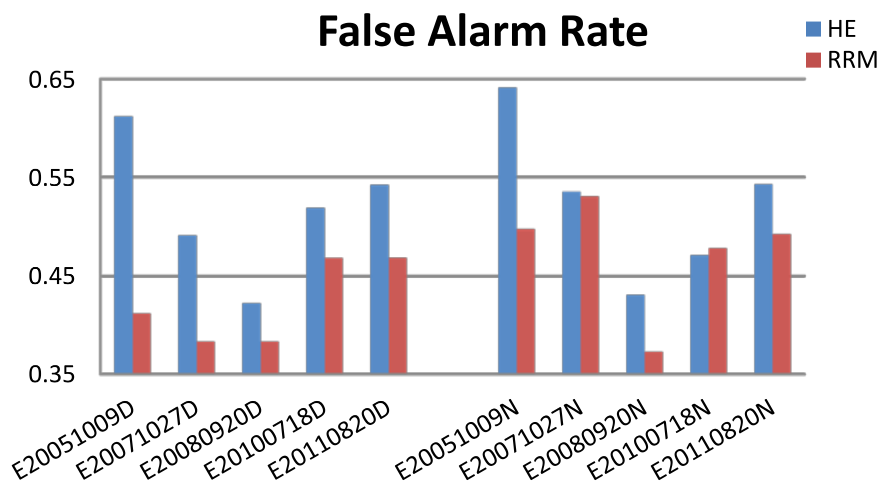
- Results are presented for calibration and validation, and also validation results are divided into rainy pixel detection and rainfall rate estimation.
- The first part of the validation results consists of estimating the number of cloud rainy pixels and comparing them with the rainy pixels identified at the same time and space by the radar.
- The second part consists of computing the projection angle for all pixels, performing pixel classification, estimation of reflectivity and finally rainfall rate for each pixel.

Results: Rainfall Events

No.	Rainfall event	Rainfall duration (days)	Type of rainfall event	Human and/or economical impacts
1	April 17-18, 2003	2	Upper Level Trough	Severe flash flooding was concentrated across several municipalities of eastern Puerto Rico. The excessive rainfall forced several hundred families from their homes and caused an estimated US $15 million in damage to infrastructure and agriculture.
2	November 11-18 2003	8	Active Tropical Wave and Upper Level Trough	Heavy rains over Puerto Rico and the U.S. Virgin Islands during the week of November 10-15, 2003 led to widespread flash flooding and numerous mud, land and rock slides. In Puerto Rico, 19 municipalities were declared Federal disaster areas, with total damage estimated around US $45 million.
3	December 5-8, 2003	4	Collateral Effects caused by Tropical Storm Odette	Odette was a rare December tropical storm that made landfall in the Dominican Republic and was responsible for eight deaths. It was the first December tropical storm on record to form in the Caribbean Sea.
4	April 19-24, 2005	6	Local Rainfall Events	No damages were reported
5	May 17 2005	1	Local Rainfall Event	No damages were reported
6	October 9-13, 2005	5	Vigorous Upper Level Low Pressure	Heavy damage was sustained by the agricultural sectors of the island. The Puerto Rico Farm Bureau estimated losses at US $20 million.
7	October 27-29, 2007	3	Strong Tropical Wave (Hurricane Noel) and Upper Level Trough	Torrential rains from Noel produced widespread damage and loss of life in the Dominican Republic, Haiti, Jamaica, eastern Cuba, and the Bahamas. As of this writing, Noel is estimated to have caused a total of 163 deaths, while 59 remained missing. Noel was just a tropical wave at the time it affected Puerto Rico.
8	September 20-23, 2008	4	Tropical Storm Kyle	On September 24, 2008, Governor of Puerto Rico, Aníbal Acevedo-Vilá, requested a major disaster declaration due to severe storms and flooding beginning on September 21, 2008 and continuing. The Governor requested a declaration for Individual Assistance for eight municipalities and Hazard Mitigation for all municipalities that resulted in US $45 million in FEMA assistance.
9	July 18-24, 2010	7	Heavy Tropical Wave	The tropical wave that moved across Puerto Rico and the U.S. Virgin Islands the week of July 19th through July 23rd generated numerous showers and isolated thunderstorms, some with very heavy rain. As a result, showers and thunderstorms persisted across sections of Puerto Rico and the U.S. Virgin Islands, resulting in several days of widespread rainfall.
10	August 20-23, 2011	4	Hurricane Irene	Across Puerto Rico, heavy rains caused extensive damage to roads while hurricane-force winds toppled many trees and utility poles, leaving more than 1 million residences without power. The highest amounts of precipitation fell across eastern parts of the territory, with a peak total of 22 in. Preliminary estimates indicate structural damage could be as high as $500 million (USD), with additional losses due to the three-day labor suspensions pinned at over $60.4 million (USD).

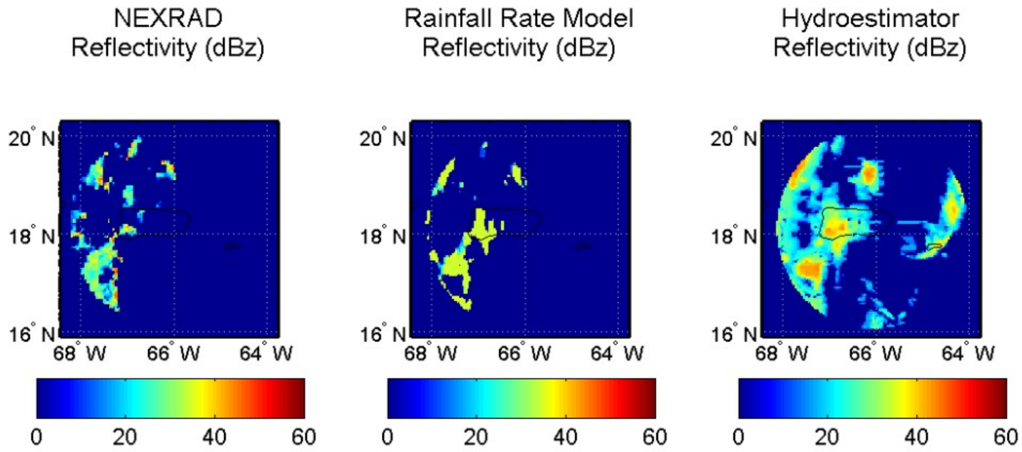
Results: Rainfall Detection



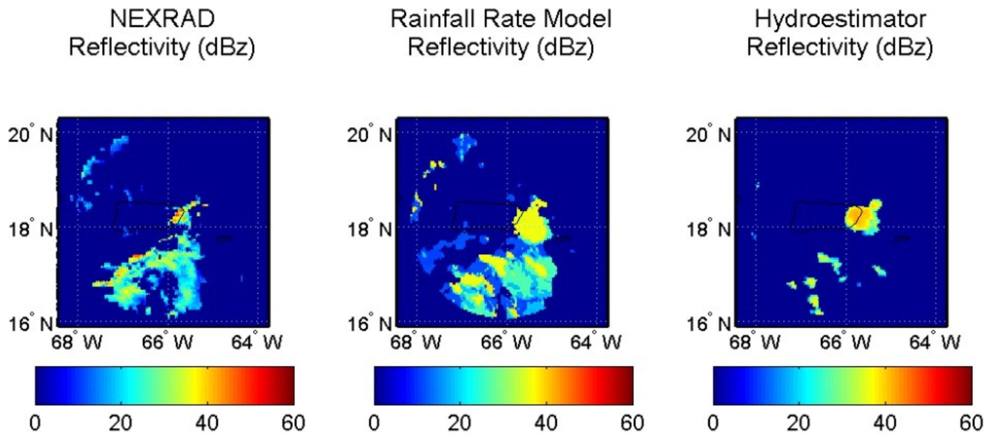


Rainfall Events	Hydroestimator						Time Lag and Spatial Displacement Model				
	HR	POD	FAR	BIAS	INDEX		HR	POD	FAR	BIAS	INDEX
E20051009D	0.8802	0.6178	0.8767	5.0086	0.4595		0.9742	0.4146	0.5193	0.8626	0.3768
E20071027D	0.9167	0.383	0.8396	2.3883	0.5133		0.9437	0.5291	0.713	1.8439	0.4134
E20080920D	0.9603	0.4401	0.6649	1.3133	0.4215		0.9766	0.6019	0.4451	1.0847	0.2889
E20100718D	0.9424	0.1584	0.7943	0.7701	0.5645		0.9539	0.5782	0.57	1.3444	0.346
E20110820D	0.9446	0.3743	0.7892	1.7752	0.4901		0.9718	0.6049	0.5123	1.2403	0.3119
E20051009N	0.8573	0.3845	0.8627	2.8002	0.5403		0.9405	0.3762	0.6194	0.9883	0.4342
E20071027N	0.8779	0.4439	0.7691	1.9227	0.4825		0.9052	0.4963	0.6877	1.5892	0.4287
E20080920N	0.9143	0.2479	0.7834	1.1445	0.5404		0.9453	0.3323	0.5589	0.7534	0.4271
E20100718N	0.9054	0.2335	0.7027	0.7853	0.5213		0.9121	0.45	0.624	1.1966	0.4206
E20110820N	0.9479	0.1452	0.8022	0.7341	0.5697		0.961	0.4881	0.5425	1.0669	0.3645

Results: Rainfall Detection and Estimation



October 13, 2005, at 20:15 UTC



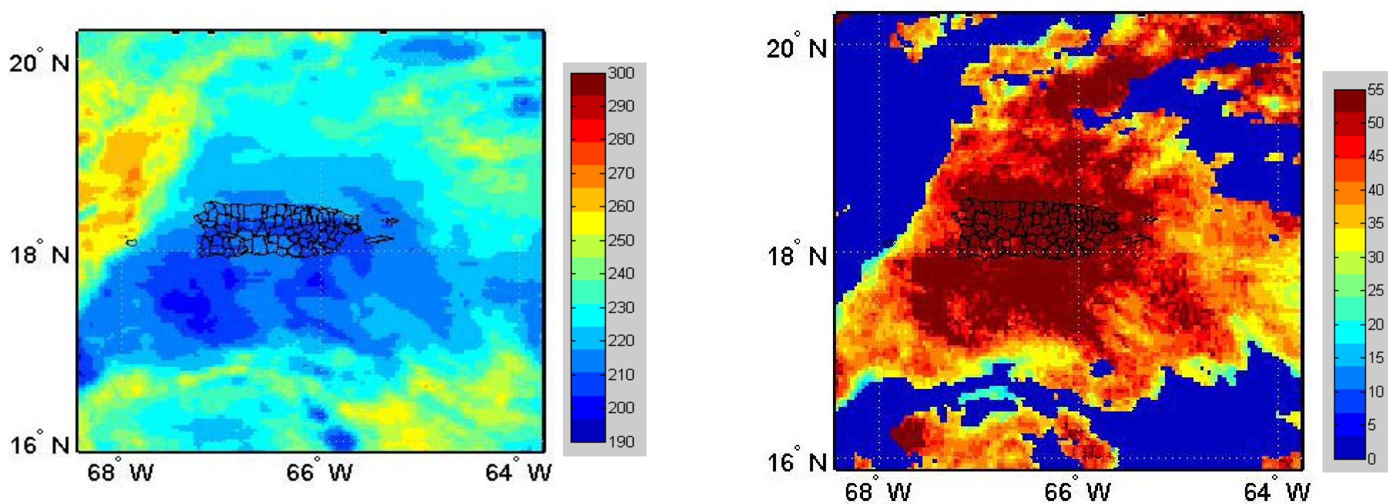
July 23, 2010 at 16:30 UTC

Conclusions:

- Validation results show that the new rainfall rate algorithm estimates slightly well than the Hydro-Estimator; specially, during the daytime.
- TSL algorithm can be used to estimate rainfall rate using visible and infrared GOES channels. A sample of mesoscale storms shows that the spatial distribution of reflectivity of the new algorithm is similar to the NEXRAD, and especially during the nighttime.

Future Work

- The motion vector can also be used to perform a short-term rainfall prediction. Reflectivity of rainy pixels can be predicted by extrapolating pixel reflectivity in the direction of the motion vector and the evolution of the effective radios, which can be derived by the Lindsey and Grasso (2008) algorithm, can be used to develop the growth and decay function for rain cells.
- We plan to increase the sample size of mesoescale convective storms to derive a robust estimation and use the new algorithm for estimating rainfall rate over the entire Caribbean basin. Estimation over this region will be useful since there are some Caribbean islands that do not have radar.



The left panel shows the brightness temperature of channel 4 and the right panel shows the effective radius. Rainfall event in Puerto Rico, during October 27, 2007 at 19:30 UTC.

ACKNOWLEDGEMENTS

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