GLYDER: Global Cyclone Detection and Tracking Using Multiple Remote Satellite Data

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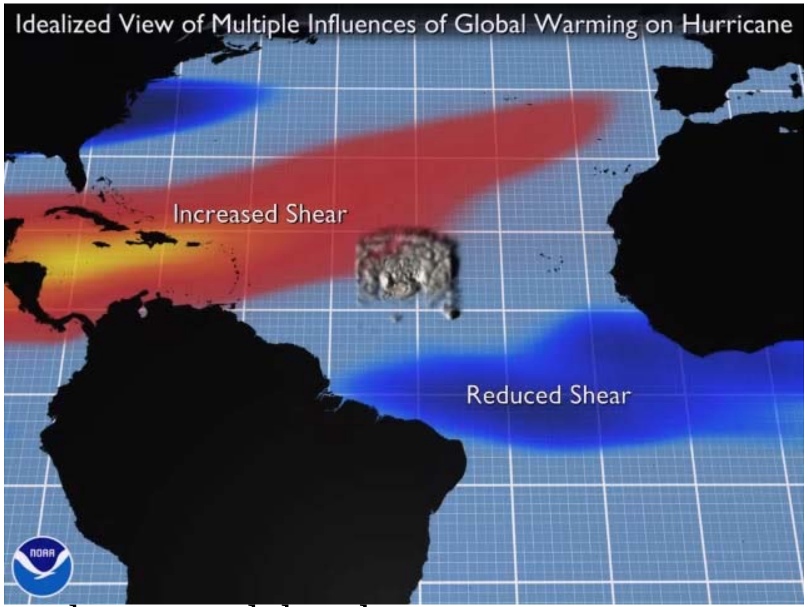
GLYDER Primary Science Motivation



- Earth's climate system exhibits intrinsic variability

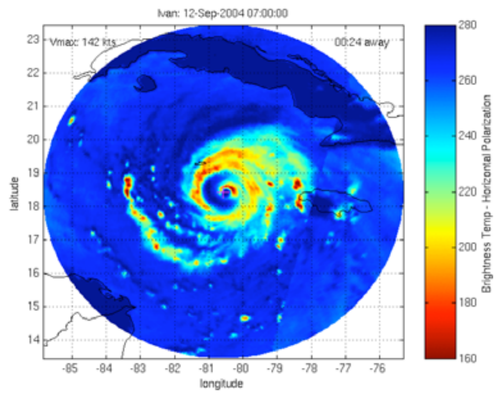
- Tropical & extra-tropical cyclones important components of Earth climate system
  - Key manifestations of oceanic air-sea interaction
  - Contribute to regional heat exchanges, which affects ocean & atmosphere dynamics
  - Complex pattern in the variability in number & intensity of global cyclone events.
    - Some regions (sub tropical northeast Pacific) experiencing increase in cyclonic frequency over last several decades
    - Moderate-strong tropical cyclones have decreased in number & intensity since the 1980s (attributed to more frequent occurrences of El Niño)

- Intergovernmental Panel on Climate Change (IPCC) has clearly identified the need to quantify the variability in global cyclones and in particular characterize changes in cyclone tracks

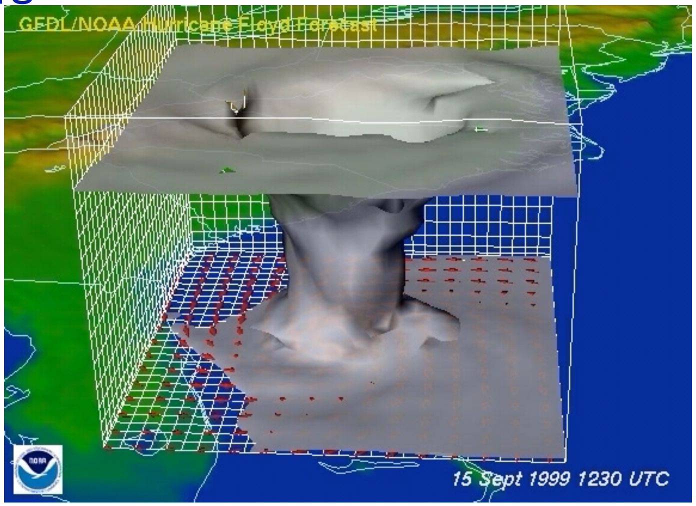
- GLYDER will provide better understanding for reasons behind and effects of global climatic variations via autonomous cyclone detection and tracking

GLYDER Primary Science Objectives

- Products to better characterize global cyclone variability



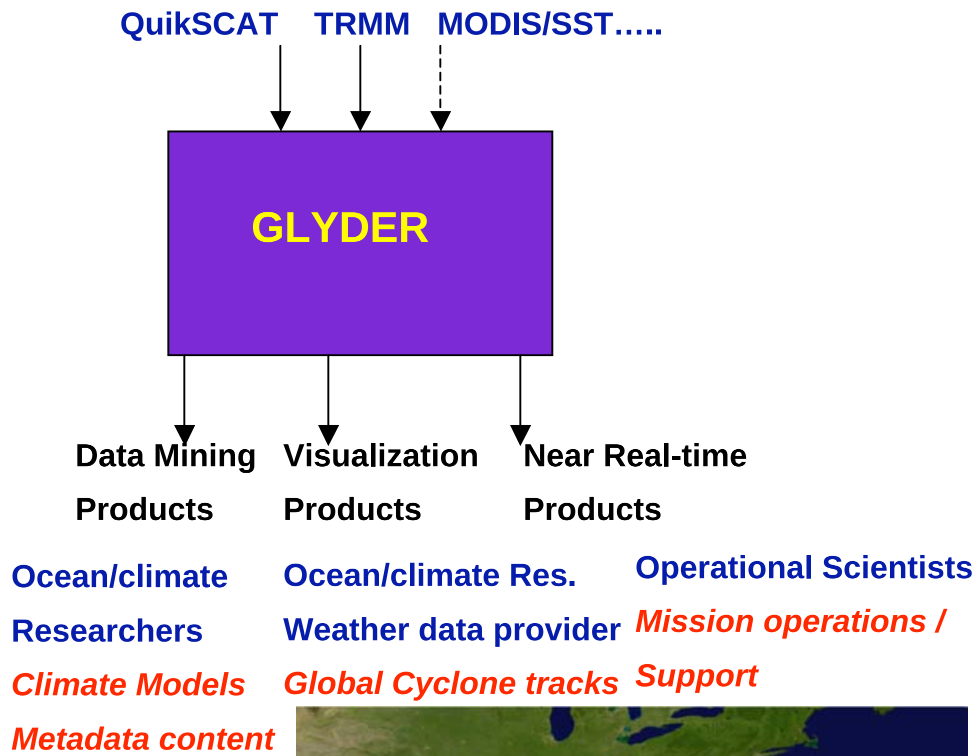
- Tools that empower JPL/NASA climate scientists to study & quantify the spatiotemporal variability of cyclones & their tracks
  - High resolution detection and tracking of cyclones
  - Enable studies and modeling of cyclogenesis
  - Long-term evolution of cyclones on a truly global basis
- Integrate observations from multiple remote sensors robustly, automatically for numerous earth science needs
  - Extend to other maritime and terrestrial event detection/tracking



- **NASA's data providers to tag metadata with information pertaining to cyclones and enable content-based searching**
  - Automatically feed information to current NASA projects including GHRSST (GODAE High Resolution Sea Surface Temperature), Earth Science Datacasting and PO-DAAC

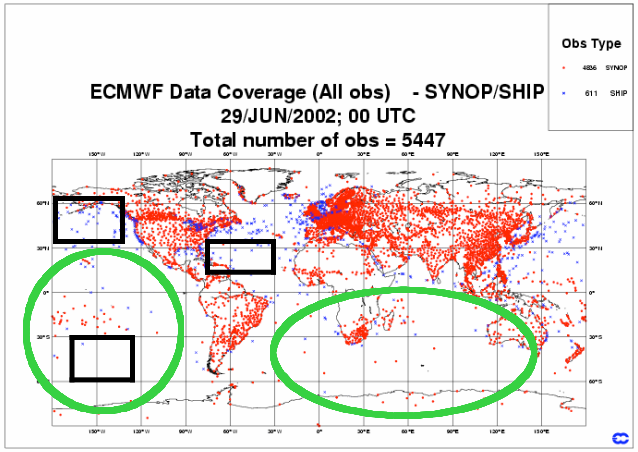
GLYDER Customers and End Users

- Ocean/Climate Researchers – need GLYDER to mine the vast data sets and extract cyclone information
- Ocean & weather data providers will use the technology to automatically generate data products and enable content-based searching
- Ocean/Climate Researchers and Ocean/weather data providers will use GLYDER for visualization of global cyclone tracks
- Application/operational scientists could potentially use the technology for real-time detection and tracking
  - Longer term end-user after proven off-line operation



Current State of Art

- Estimates of cyclone variability currently derived from analyses of surface level pressure (SLP) fields
  - Model output fields from NCEP/NCAR Reanalysis Project based on in-situ inputs
  - Analyses assimilate observational and in-situ data into a physical model to produce atmospheric fields
  - Data span more than 50 years
  - Measured every 6 hours on a 2.5˚×2.5˚ (~275 km) global grid
  - Accuracy of analyses is severely limited over the oceans,
  - Lack of assimilated pressure and radiosonde observations
  - Mean cyclone size varies from 120 – 440 km [Liu99]
    - Resolve up to a maximum of only 50% of the global cyclones.
  - Satellite remote sensing provides global coverage and greater spatial resolution, potentially allowing detection of most/all global cyclones



Map of daily pressure observations used by ECMWF Reanalysis forecast (6-29-02). Under sampling in the worlds oceans especially in the Southern Hemisphere is evident, as shown in circles. Boxes indicate regions of interest for GLYDER

Remote Sensors for Cyclone Detection

- Individually remote sensing datasets have limited detection ability
  - Poor temporal or spatial resolution
  - Loss of data due to environmental effects.
- GOES – visible cloud formation
- AVHRR – cloud-free surface temperature or top of the atmosphere temperature
- QuikSCAT – surface wind speed & direction
- AMSR-E surface temperature
- MODIS-36 spectral bands

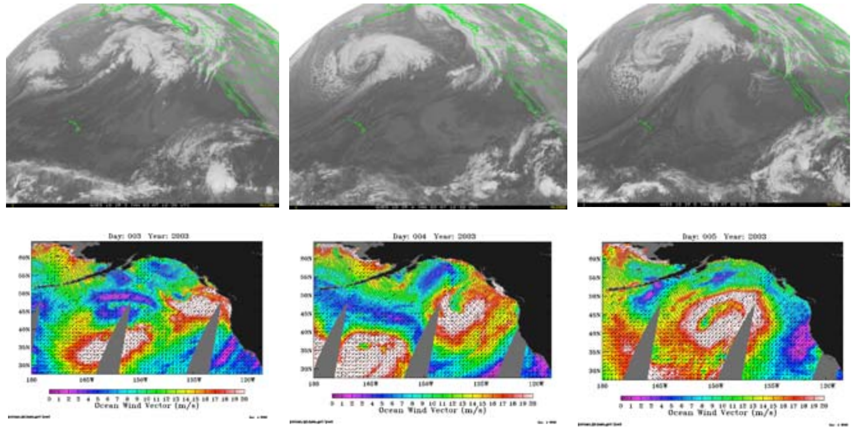


Figure 1: **GOES visible (top) and QuikScat wind speed (lower) sequences collected over the North Pacific on 4-6 Jan, 2003. The visible images show the location and extent of two cyclones and the wind image provides intensity information.**

Sensor	Parameter	Spatial Resolution	Temporal freq.	Availability
GOES	Reflectance (visible). Brightness temp. (IR)	6 km	? hr	1979 - present
AVHRR	Reflectance (visible). Brightness Temp. (IR)	4 km	6 hr (2 satellites)	1985 - present
QuikScat	Wind speed and direction	25 km	12 hrs	1999 - present
SSMI	Brightness Temp, wind speed	25 km	12 hrs	1987 - present
AMSR-E	Brightness Temp, wind speed	25 km	12 hrs	1987 - present
GLYDER (GOAL)	FUSED (multimodal)	**6 - 12.5 Km**	**3 – 6 Hrs**	

Table 1: Satellite sensor system, the parameters they measure and resolution, and GLYDER goals for multisensor co-registration and fusion

GLYDER Primary Challenges

- Data extraction for training and validation is non-trivial
  - Multiple datasets generated by different data providers
  - Different data formats and file naming conventions
  - Large data volumes
  - Initial efforts to extract relevant data from multiple sensors for training and performance verification manually intensive and laborious
- Fusion of multiple sensors non-trivial
  - Knowledge and Transfer Learning between sensors
  - Knowledge sharing between disparate sensors at different spatial and temporal resolutions
- Cyclone detection with high detection rate, low false alarm rate at reasonable spatial and temporal resolutions
- Cyclone tracking from multiple sensors

QUIKSCAT Vs. MODIS for Cyclone Classification

- MODIS (Pixel Level Product - Level 2) cloud products of interest
  - Cloud Optical Properties: E.g. Thickness. (Image 1)
  - Cloud Top Properties: E.g Temperature. (Image 2)
  - Cirrus Reflectance (Image 3)
- MODIS atmospheric water vapor (Image 4)
  - Amount derived from measurements of near-IR solar radiation reflected by the land or the cloud surface, and over extended oceanic areas with Sun glint.
- QuikScat - Level 2B (Image 5)
  - Wind Speed
  - Wind Direction

Hurricane Dean 2007

Image 1

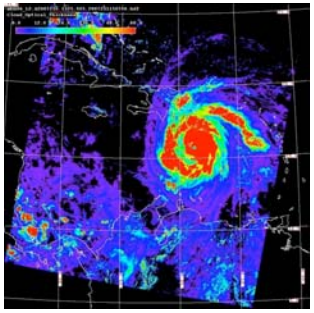


Image 2

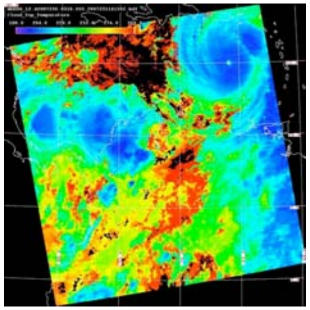


Image 3

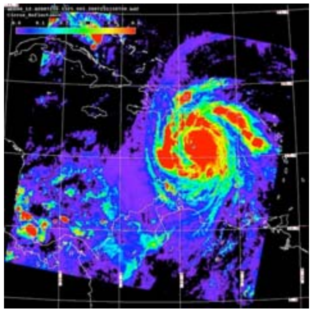


Image 4

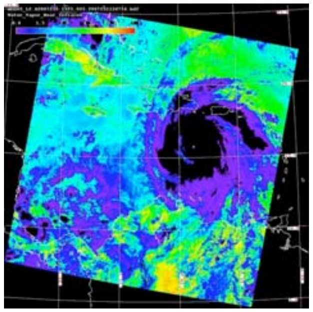
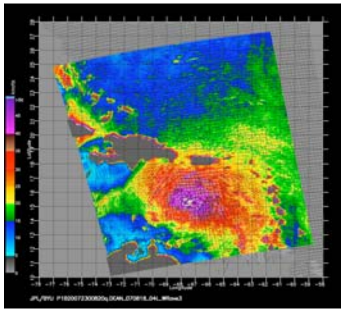
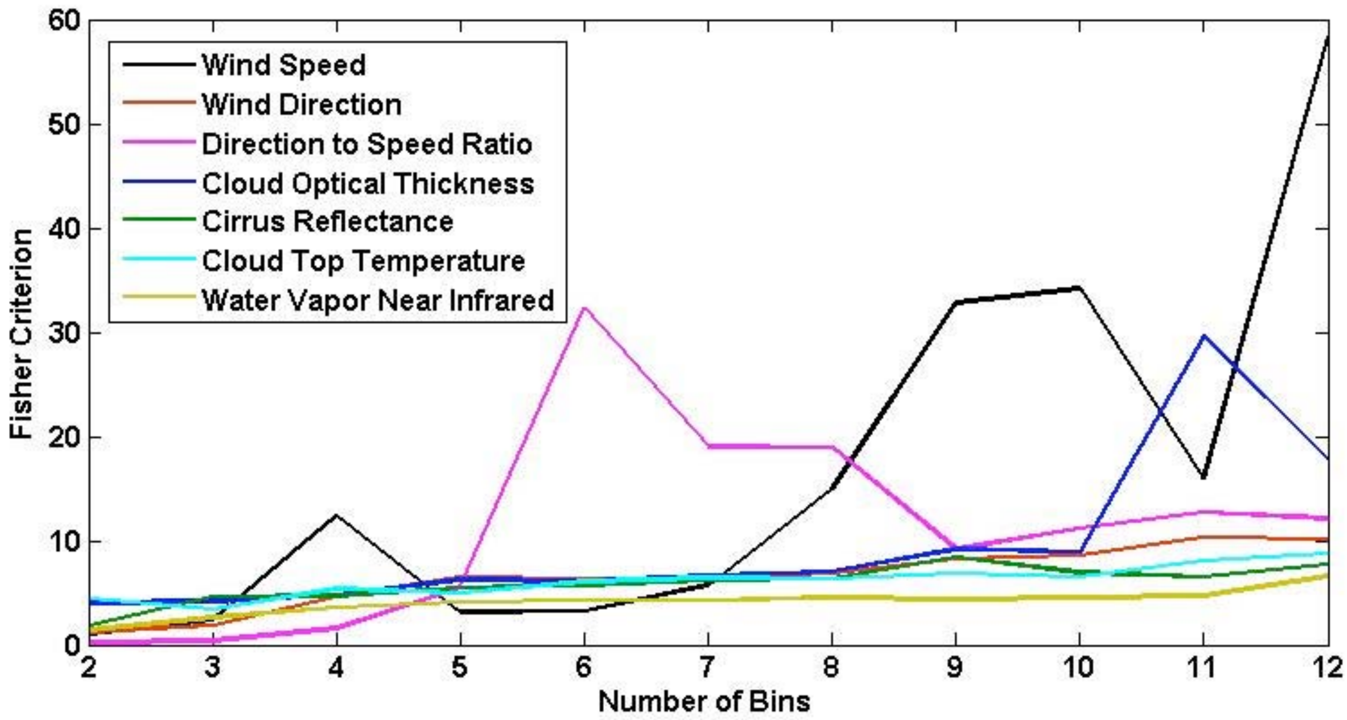


Image 5



QUIKSCAT and MODIS features Ranking



Single Sensor Cyclone Detection: QUIKSCAT

- QUIKSCAT: SeaWinds instrument on the QuikScat Satellite
  - microwave radar measuring near-surface wind speed and direction under all weather and cloud conditions over Earth oceans

- Swath Grid: 12.5km and 25km resolution

- Extract descriptive features from QuikSCAT regions

Feature (Histogram)

1. **Wind Speed Histogram (WS)**
2. **Wind Direction Histogram (WD)**
3. **Direction to Speed Ratio (DSR) Histogram with DSR at location (i,j) as**

$$DSR(i,j) = \frac{WD(i,j)}{WS(i,j)}$$

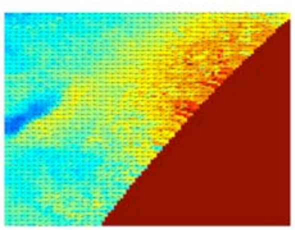
Feature (DOWD)

Let *u(i,j)* and *v(i,j)* be the u-v components of the wind direction *WD(i,j)* at location *(i,j)* with 1≤i≤ m and 1≤j≤n. One constructs a (m× n)-by-2 matrices *M* of the form

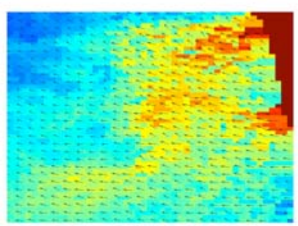
$$\begin{pmatrix} u(1,1) & v(1,1) \\ \vdots & \vdots \\ u(1,n) & v(1,n) \\ u(2,1) & v(2,1) \\ \vdots & \vdots \\ u(m-1,n) & v(m-1,n) \\ u(m,1) & v(m,1) \\ \vdots & \vdots \\ u(m,n) & v(m,n) \end{pmatrix}$$

Let λ_1 and λ_2 be the eigenvalues of matrix M such that $\lambda_1 < \lambda_2$
The eigenvalue ratio (Relative Strength of the Dominant Wind Direction (DOWD)) of a bounding box B of dimension m by n is

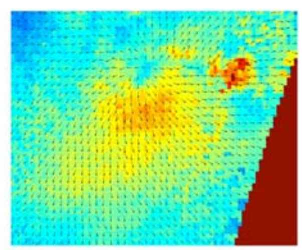
$$ER_B = \frac{\lambda_2}{\lambda_1}$$



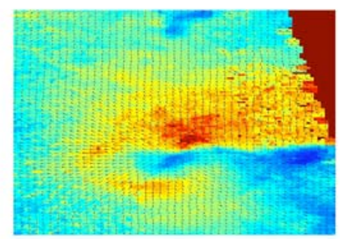
Eig-Ratio: 4.5204



Eig-Ratio: 3.5606



Eig-Ratio: 1.0402



Eig-Ratio: 1.7160

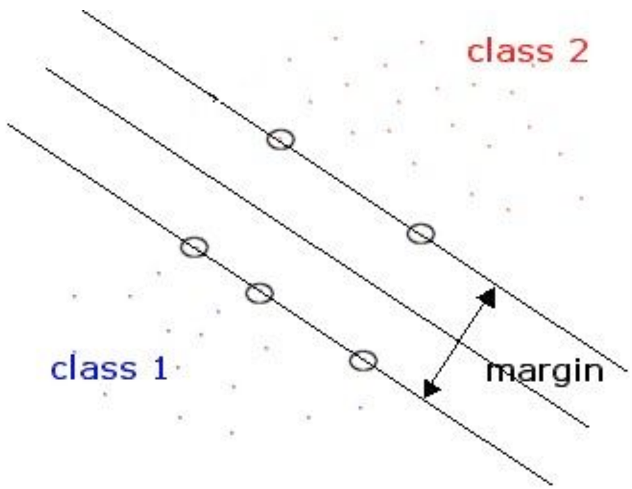
Feature (RWV)

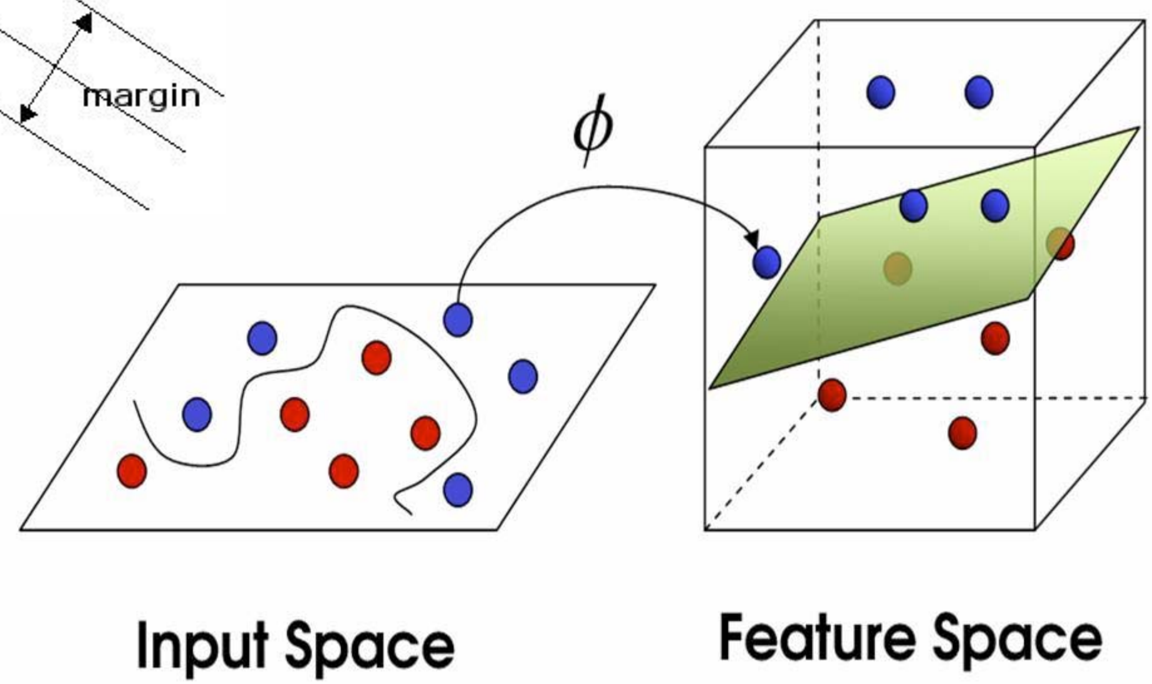
The relative wind vorticity (RWV) at location (i,j) is

$$RWV_{(i,j)} = \left(\frac{\partial v}{\partial x} - \frac{\partial u}{\partial y}\right) = \frac{1}{2d}\left(v_{(i+1,j)} - v_{(i-1,j)} - u_{(i,j+1)} + v_{(i,j-1)}\right)$$

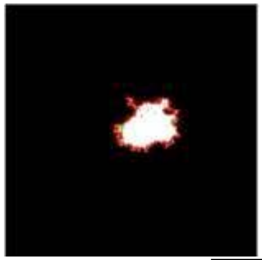
where *u* and *v* are the two wind vector components in the west-east and south-north directions, and *d* is the spatial distance between two adjacent QuikSCAT measurements in a uniformly gridded data.

Support Vector Machine Classifier: Overview

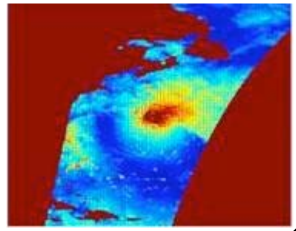




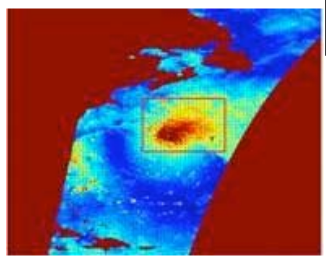
Cyclone Segmentation and Classification: QUIKSCAT



Input QUIKSCAT Image



Select Region(s) of Interest (ROI) using a threshold (T= 12 m/s) on the wind speed



Is ROI > Y x Y degrees.?

(e.g. Y = 192 Km, 2^o)

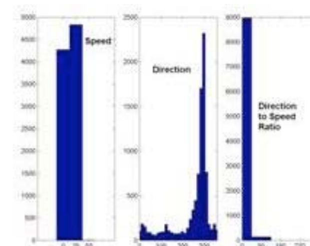
Yes

Construct bounding box(es) around ROI(s)

No

Discard ROI

Compute 1) DOWD and 2) RWV and construct 3) wind speed, 4) direction and 5) ratio histograms for each box



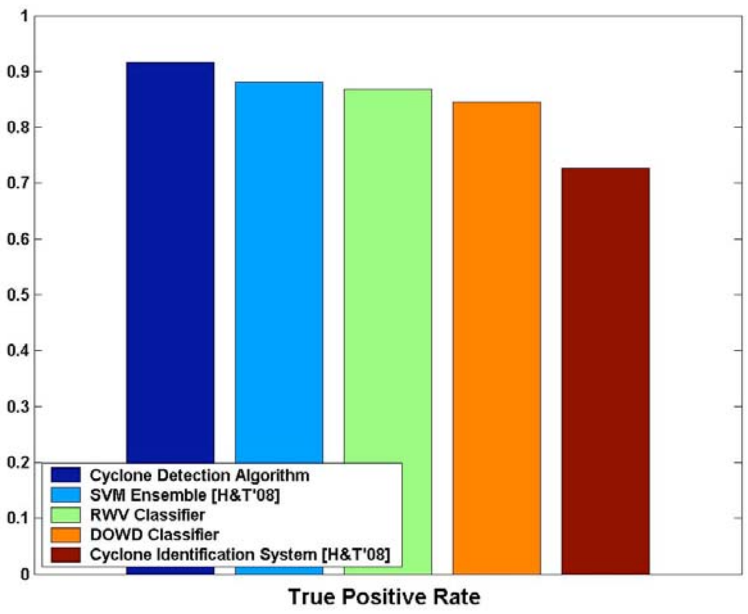
5 independent Classifiers

Classification based on majority vote

Result 1

- **Training Examples: 191 QuikSCAT images of tropical cyclones in North Atlantic in 2003 and 1833 randomly selected unlabeled examples from four days in 2003 when no tropical cyclone is reported.**
- **Testing Examples: 84 QuikSCAT images of tropical cyclones in North Atlantic in 2006.**

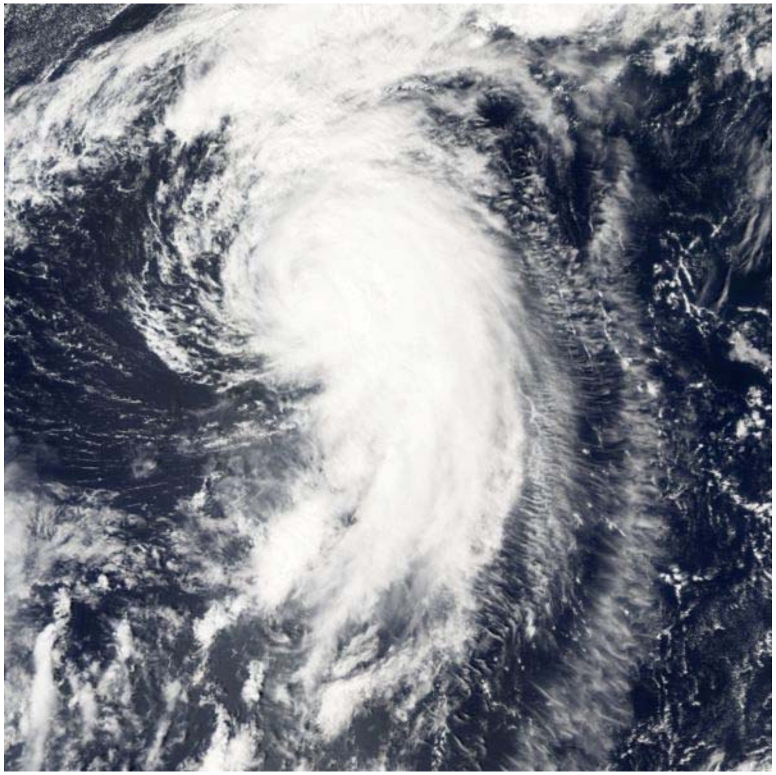
	Cyclone Detection Algorithm	SVM Ensemble [HT08]	RWV	DOWD	CIS [HT08]
TPR	0.9167 (77)	0.8810 (74)	0.8690 (73)	0.8452 (71)	0.7262 (61)



Result 2

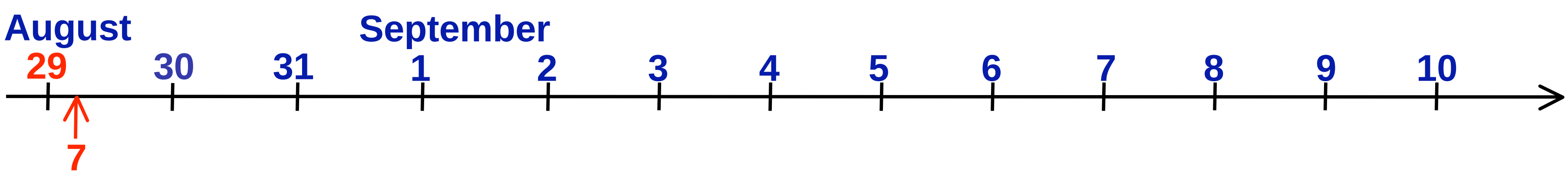
- Training Examples: 191 QuikSCAT images of tropical cyclones in North Atlantic in 2003 and 1833 randomly selected unlabeled examples from four days in 2003 when no tropical cyclone is reported.
- Testing Examples: 2141 swaths between 5-60N 0-100W (North Atlantic Ocean) in 2005.
- Overall Results:
    - All 26 tropical cyclones reported by NHC are detected.
    - 1 post-season NHC identified subtropical storm detected.
    - 2 out of 3 tropical depressions (that did not develop further) reported by NHC are detected.
- Interesting Results:
    - Hurricane Maria is detected 3 days earlier than reported by NHC.
    - Hurricane Vince is detected 3 days earlier than reported by NHC when it is an extra-tropical storm [Atlantic Tropical Weather Outlooks (NOAA) did not discuss the non-tropical precursor disturbance to Vince until it had begun to acquire subtropical characteristics].
    - One event with tropical cyclone property is detected.

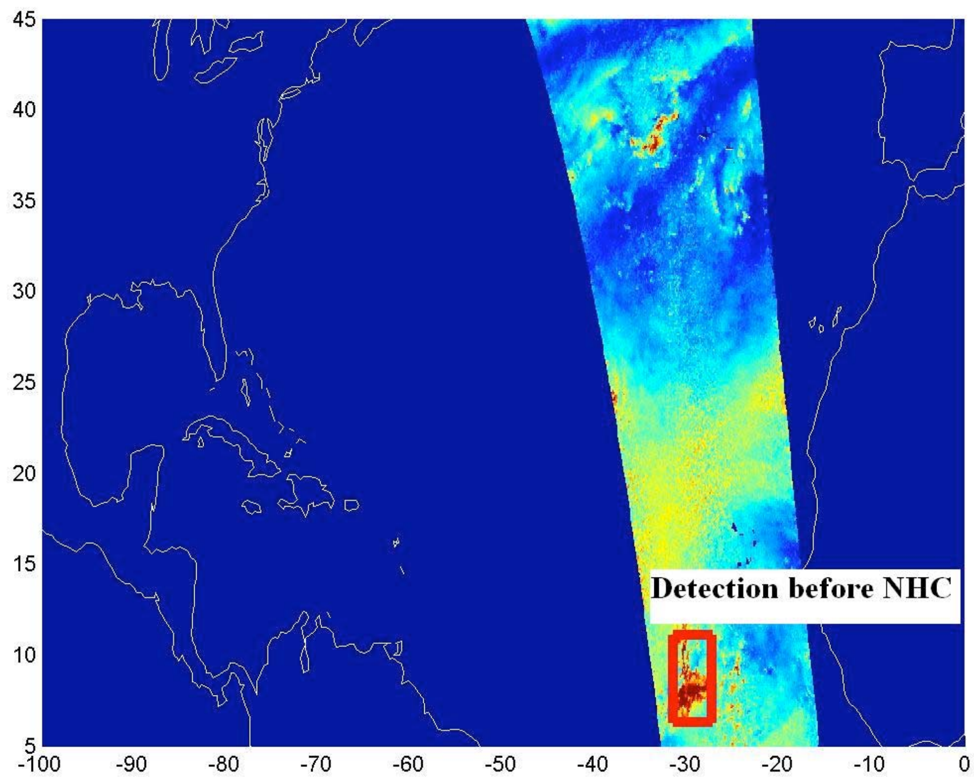
Interesting Result 1: Hurricane Maria 2005



September 6 2005

Interesting Result 1: Hurricane Maria

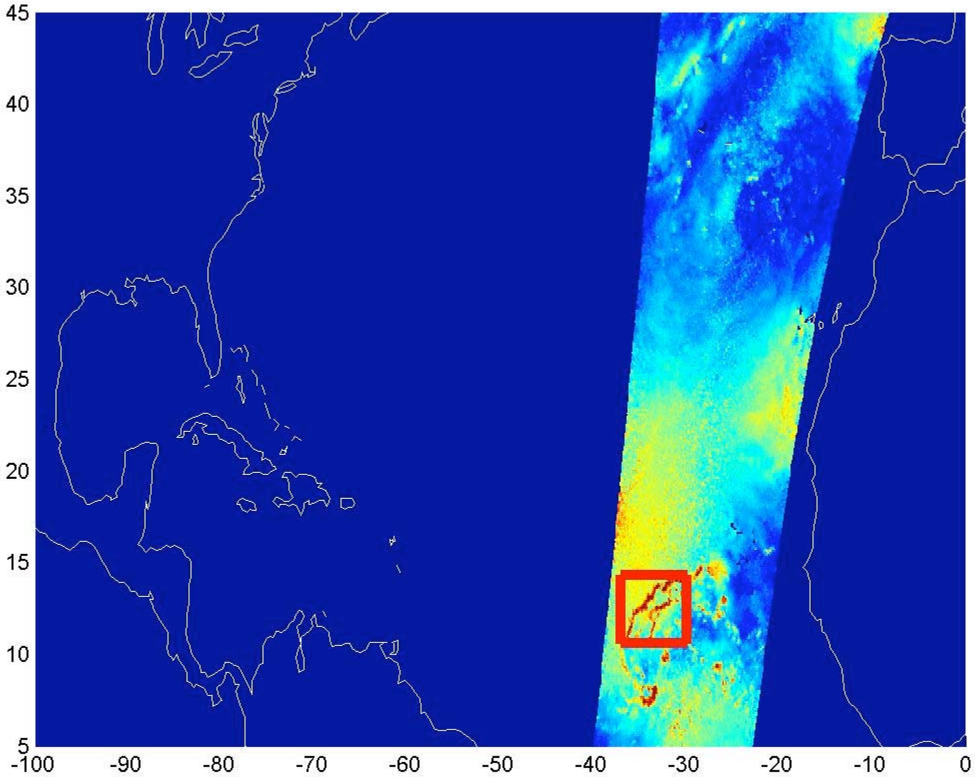




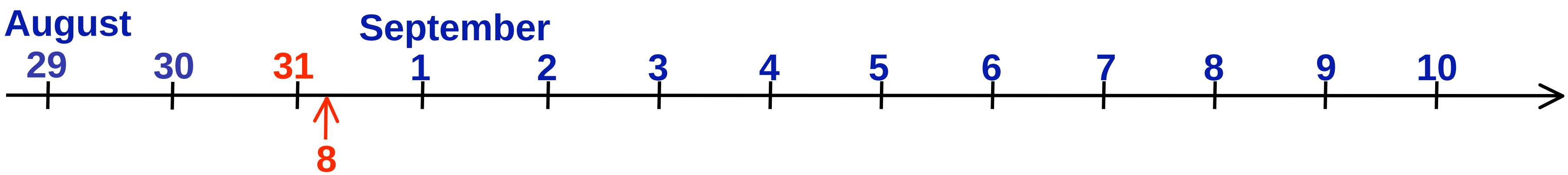
Interesting Result 1: Hurricane Maria

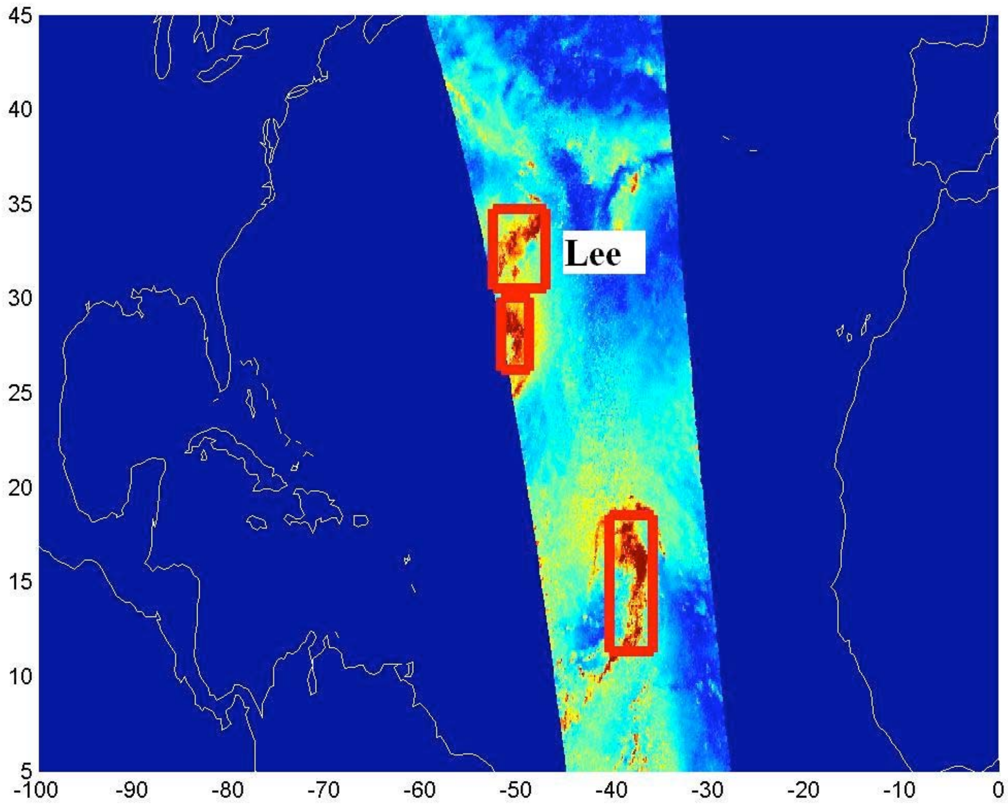
August 29 30 31 — September 1 2 3 4 5 6 7 8 9 10

19



Interesting Result 1: Hurricane Maria





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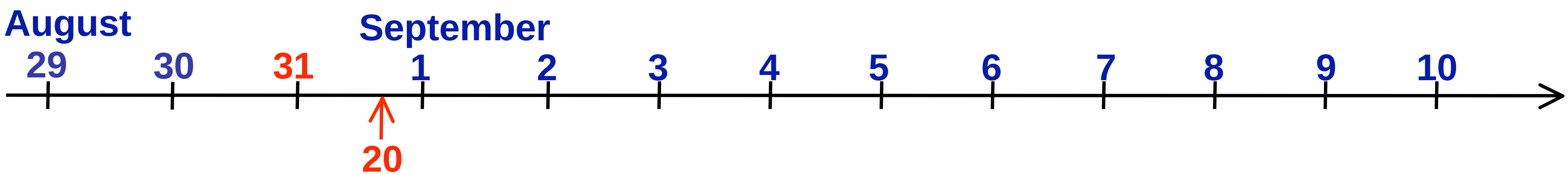
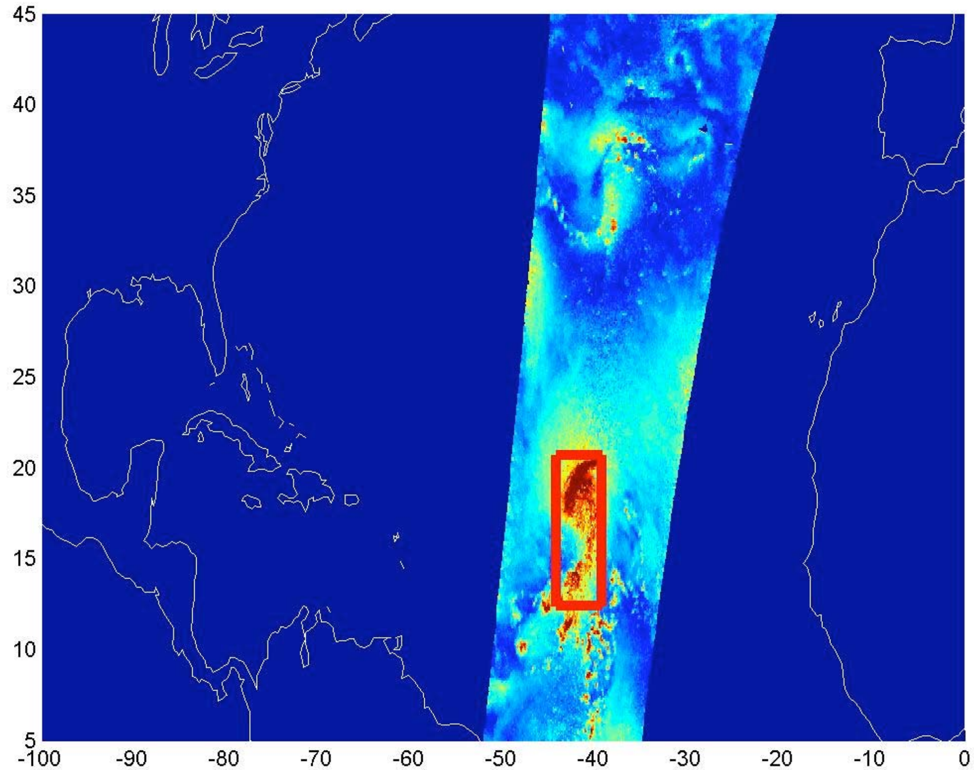
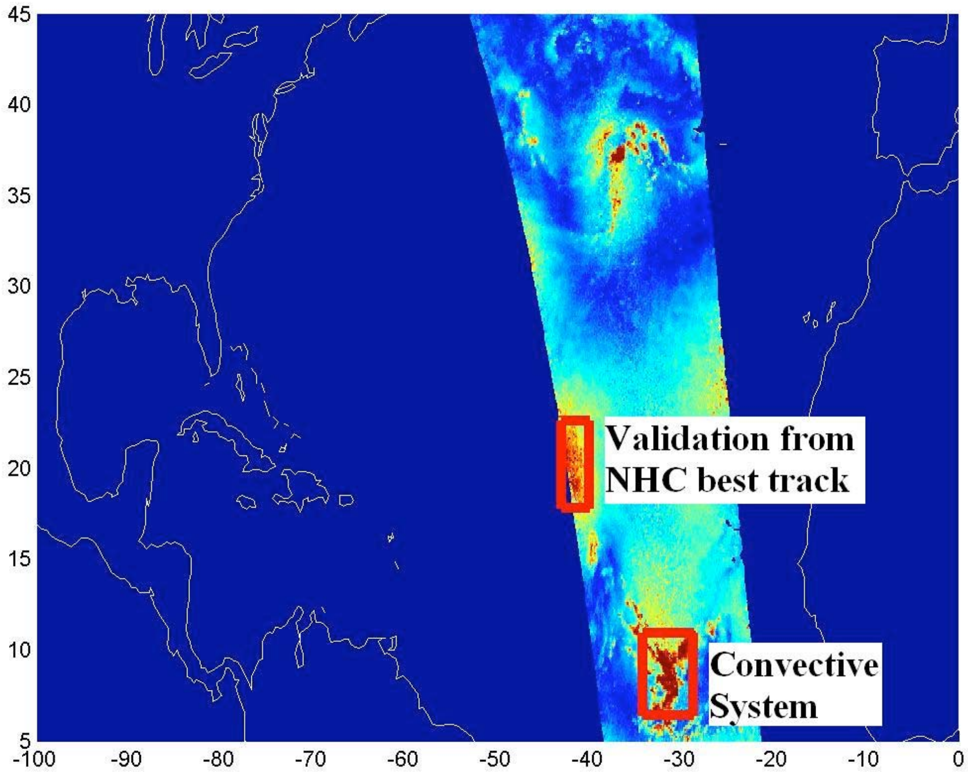




Interesting Result 1: Hurricane Maria

August			September									
29	30	31	1	2	3	4	5	6	7	8	9	10

7



Definition

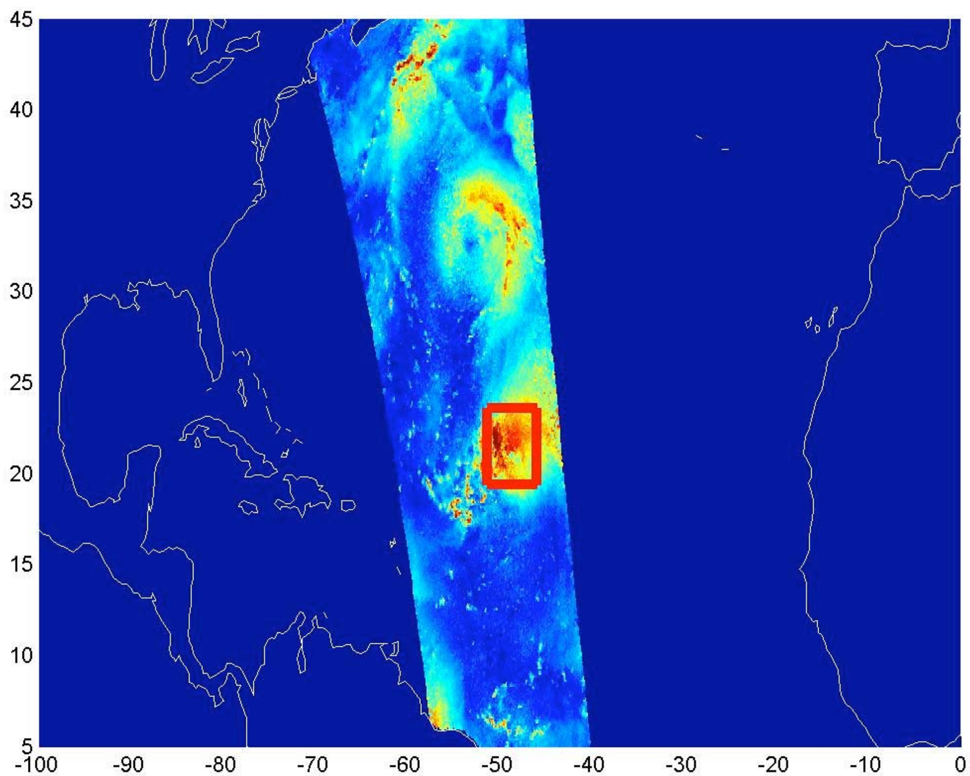
mesoscale convective system—(Abbreviated MCS.) A **cloud system** that occurs in connection with an ensemble of thunderstorms and produces a contiguous precipitation area on the order of 100 km or more in horizontal scale in at least one direction. An MCS exhibits deep, moist convective overturning contiguous with or embedded within a mesoscale vertical circulation that is at least partially driven by the convective overturning.

Interesting Result 1: Hurricane Maria

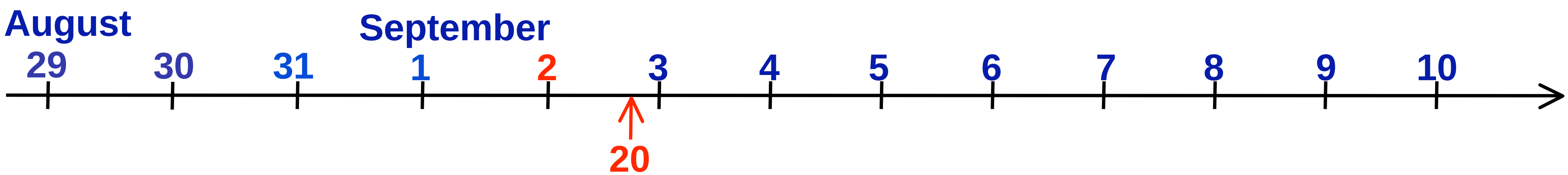
August **September**

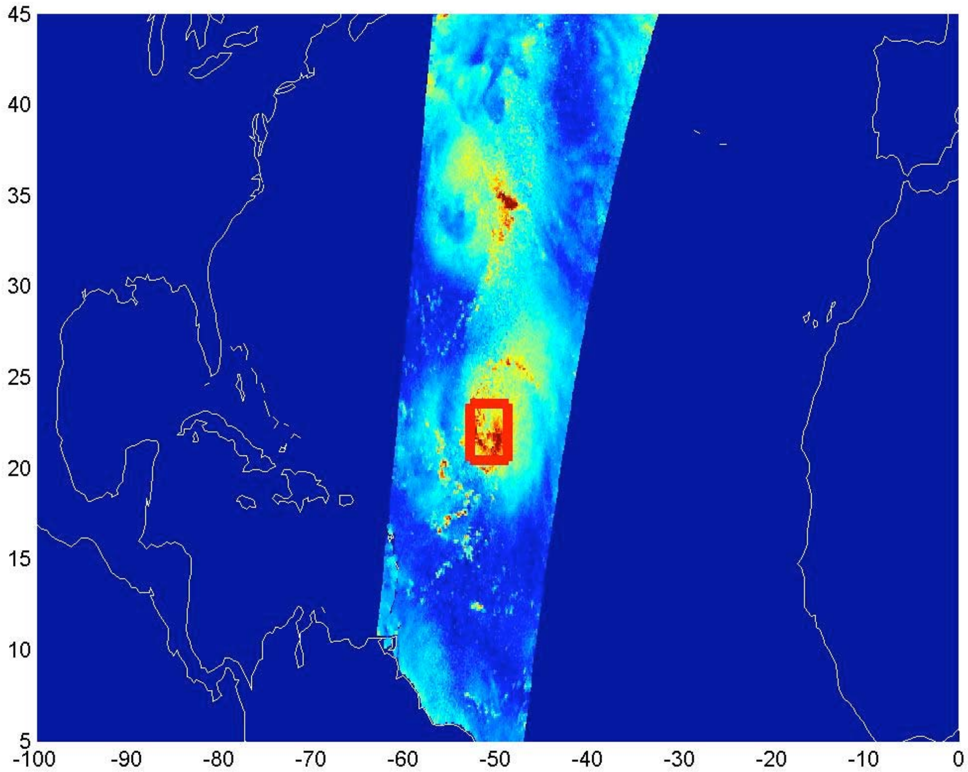
29 30 31 1 **2** 3 4 5 6 7 8 9 10

9

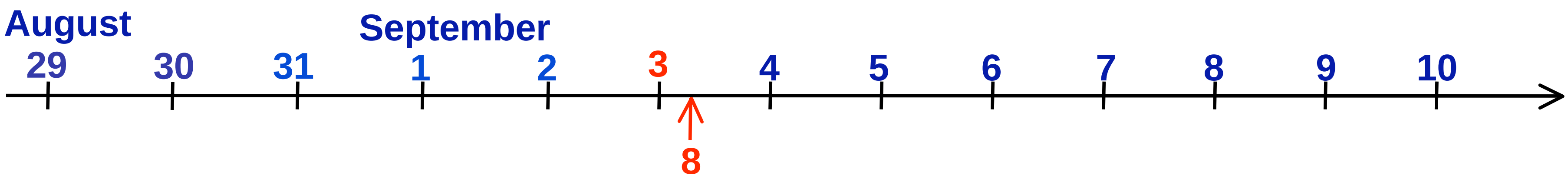


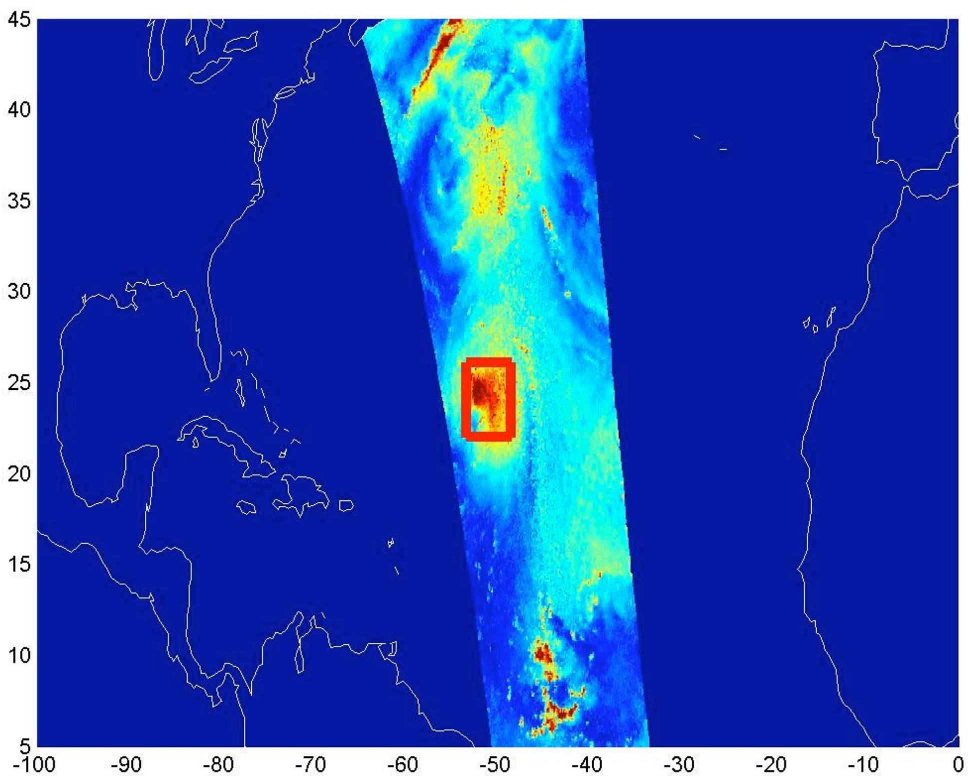
Interesting Result 1: Hurricane Maria





Interesting Result 1: Hurricane Maria





Interesting Result 1: Hurricane Maria

August 29 30 31 **September** 1 2 3 4 5 6 7 8 9 10

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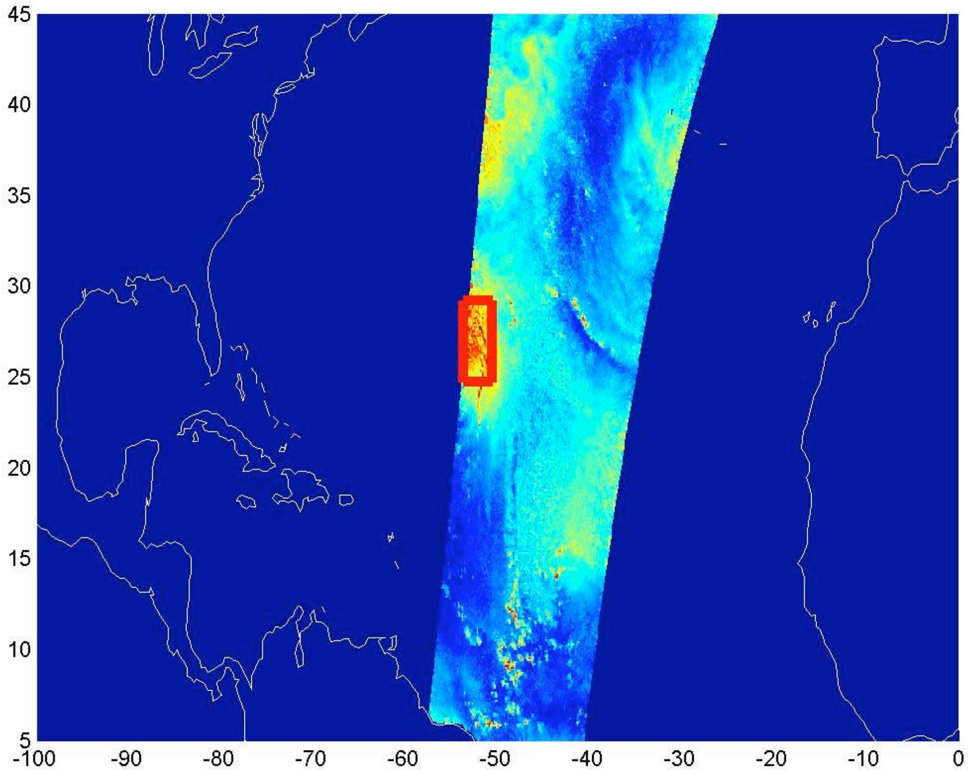

Interesting Result 1: Hurricane Maria

August **September**

29 30 31 1 2 3 4 5 6 7 8 9 10

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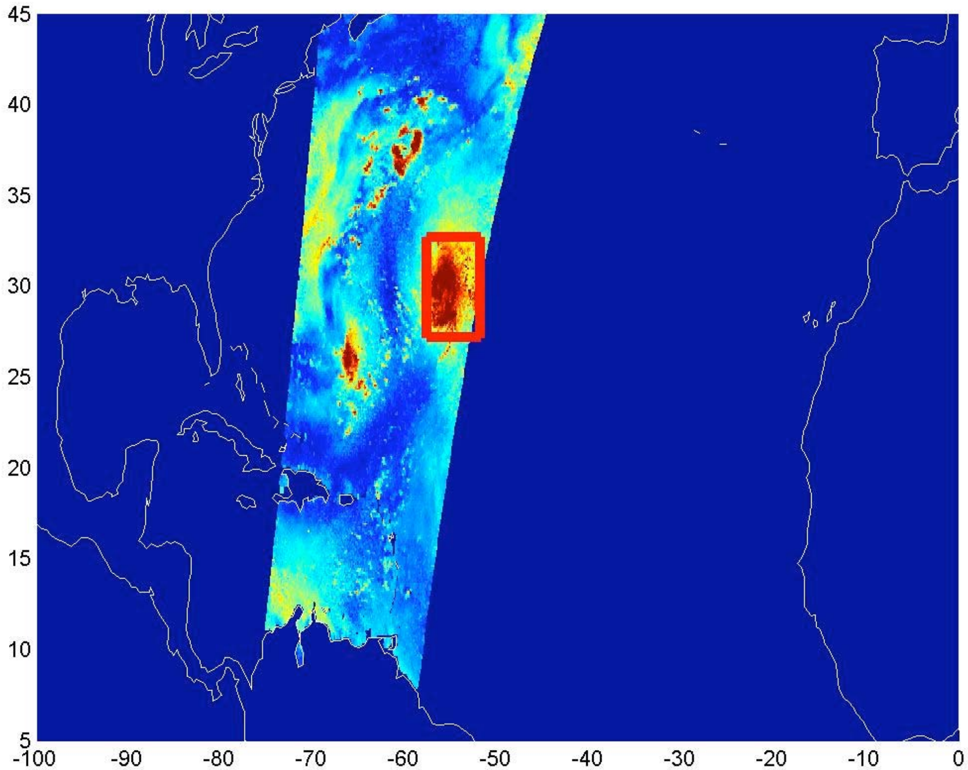
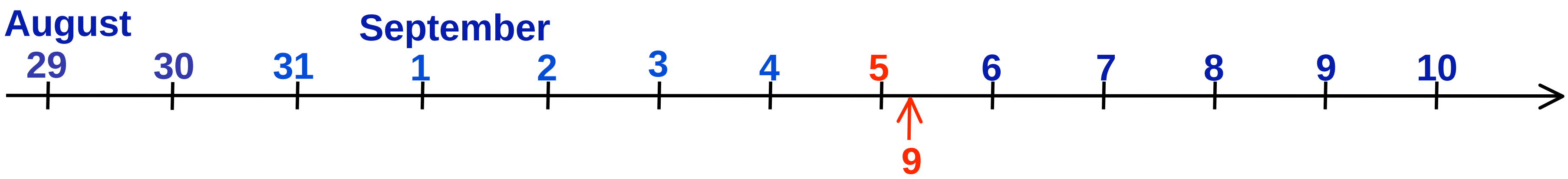
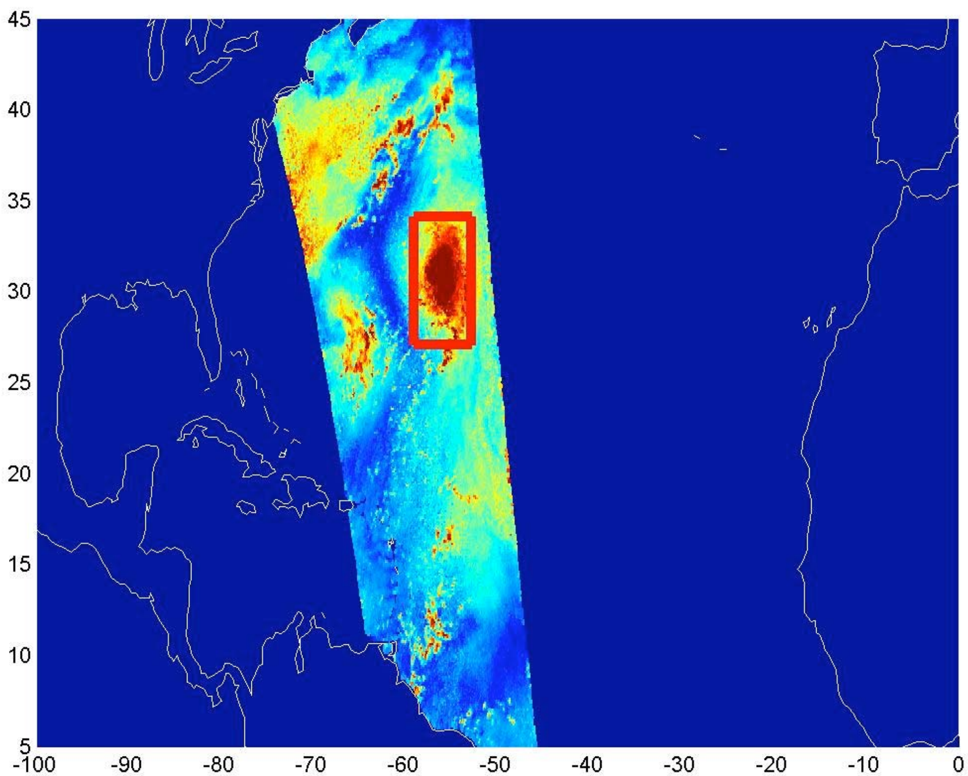
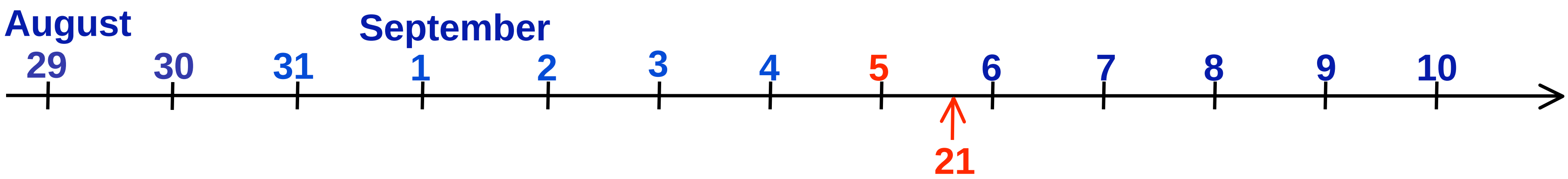


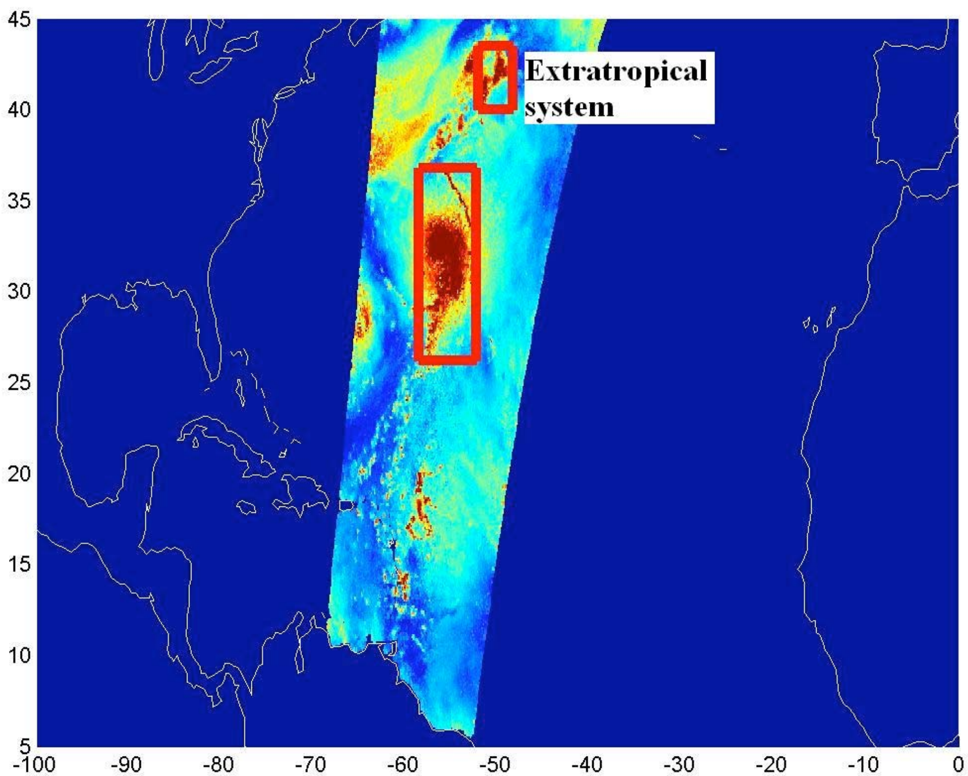
Interesting Result 1: Hurricane Maria



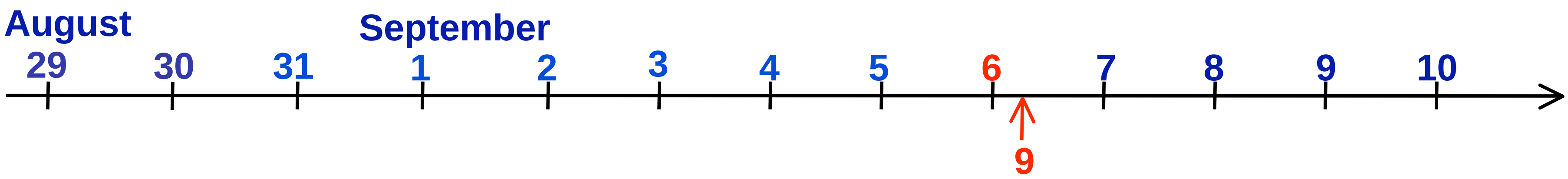


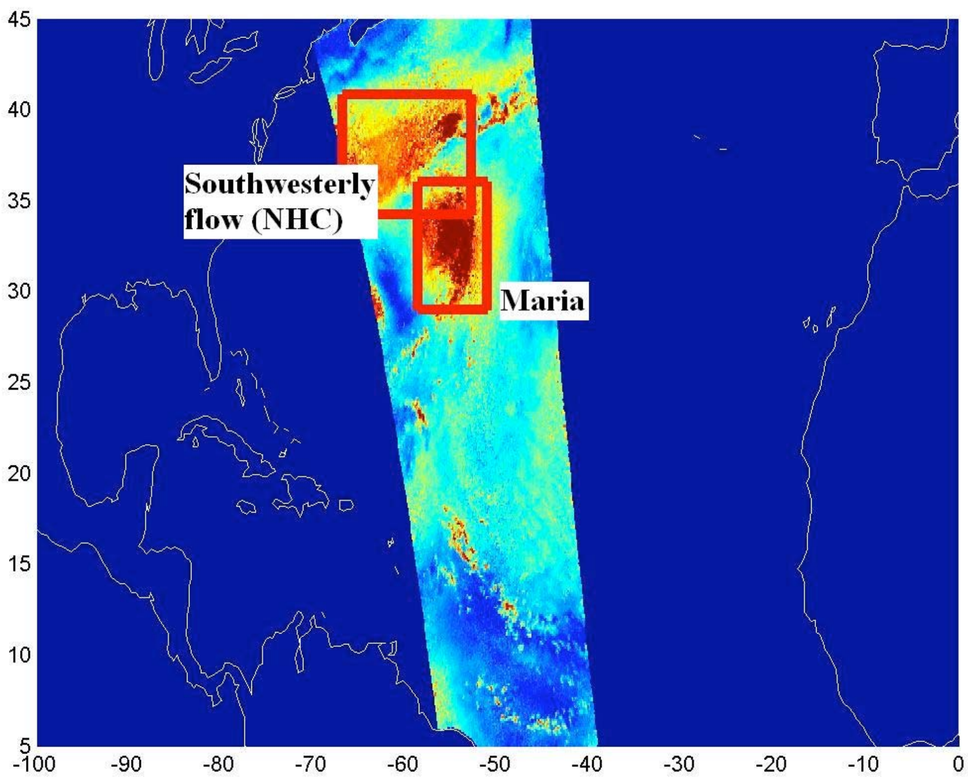
Interesting Result 1: Hurricane Maria



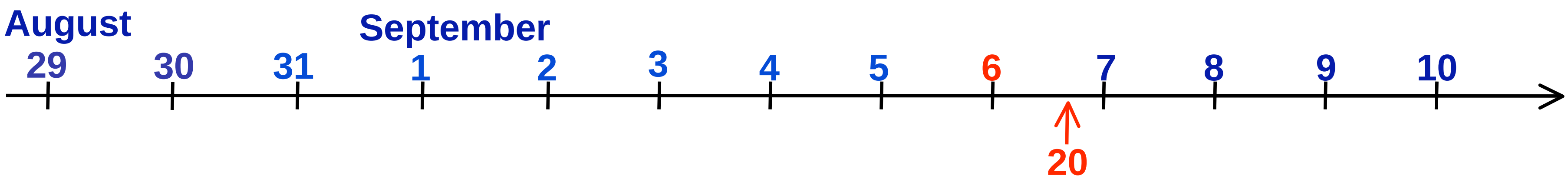


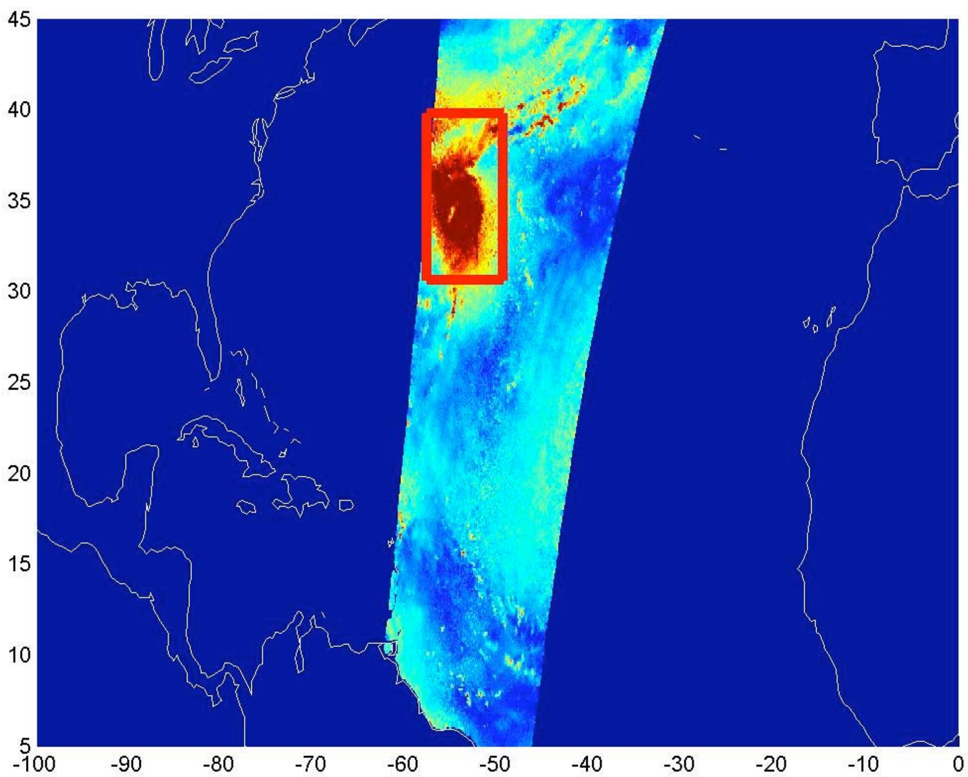
Interesting Result 1: Hurricane Maria





Interesting Result 1: Hurricane Maria



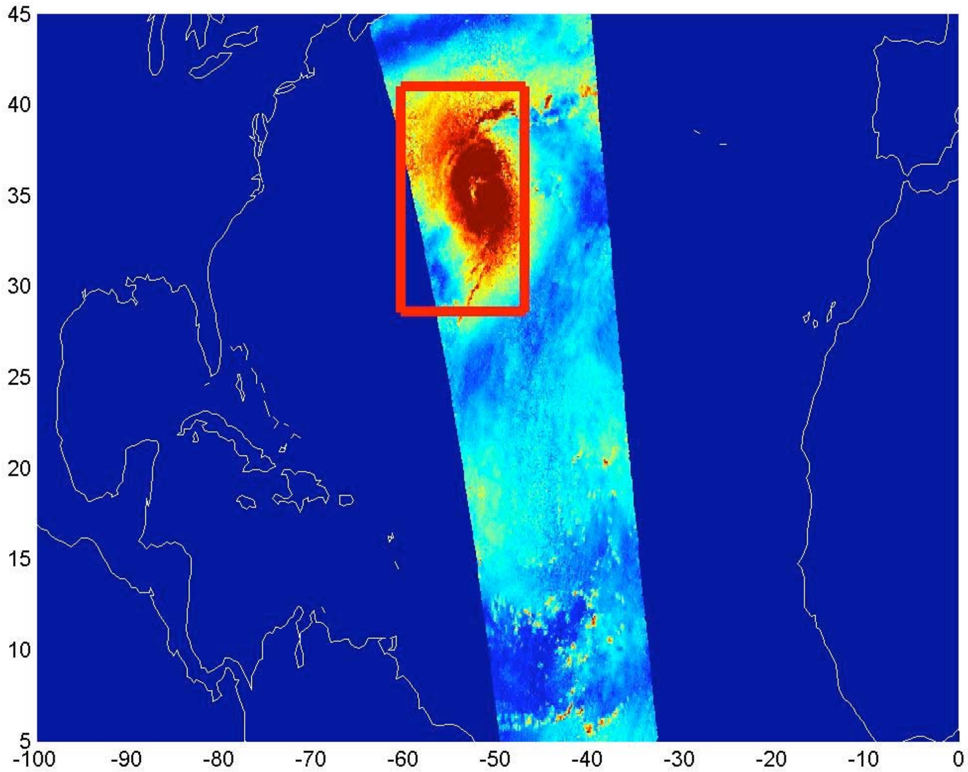


Interesting Result 1: Hurricane Maria

August			September
29	30	31	1

29	30	31	1	2	3	4	5	6	7	8	9	10

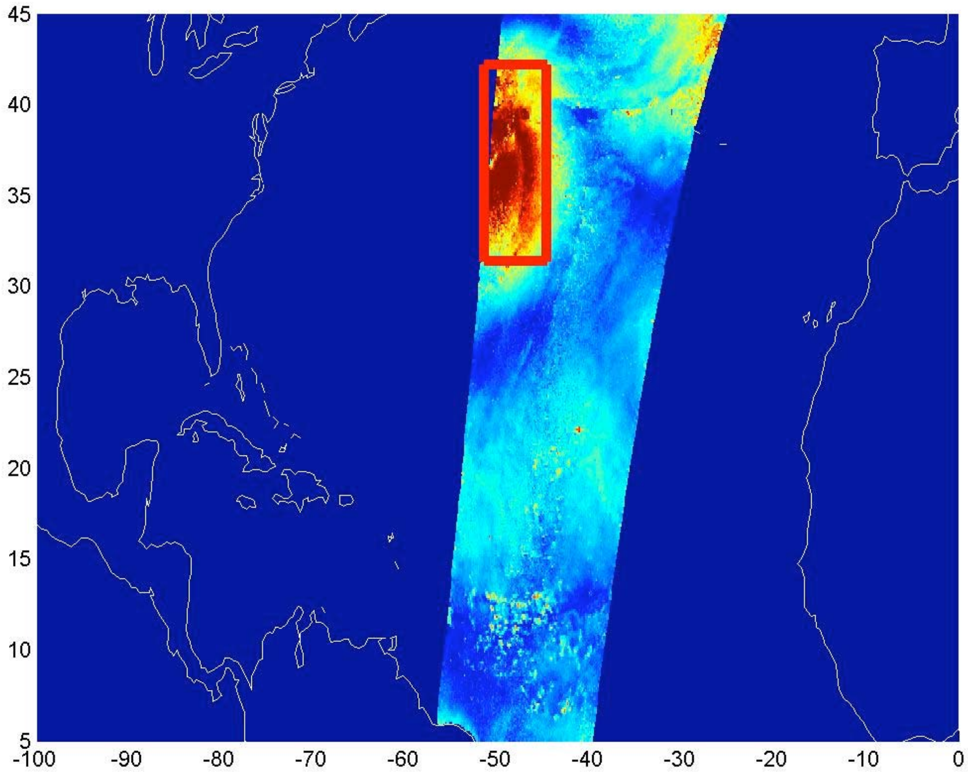
8



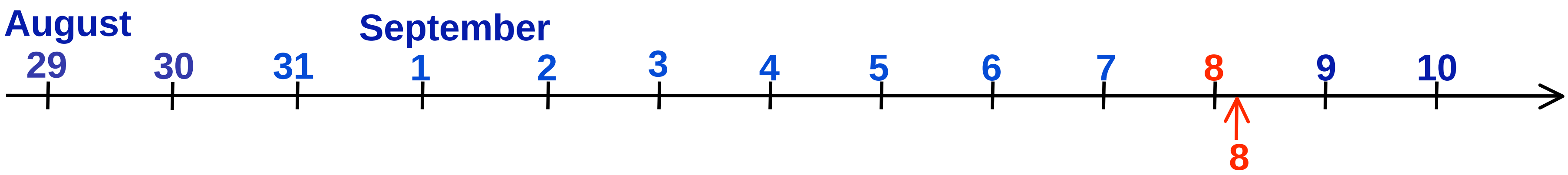
Interesting Result 1: Hurricane Maria

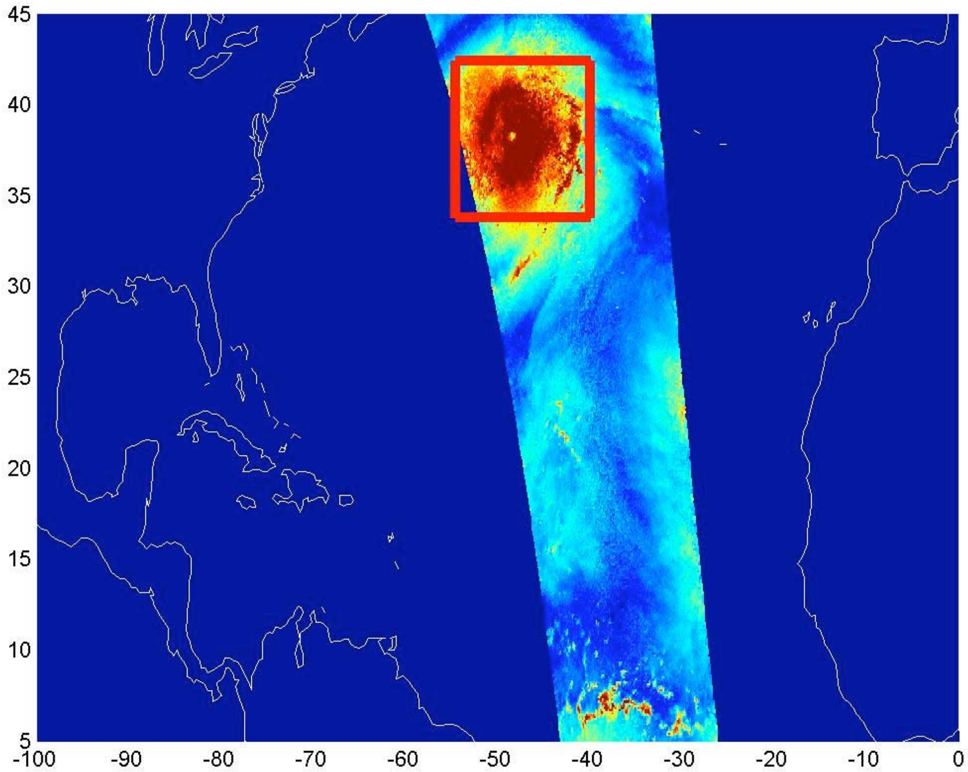
August 29 30 31 — September 1 2 3 4 5 6 7 8 9 10

20

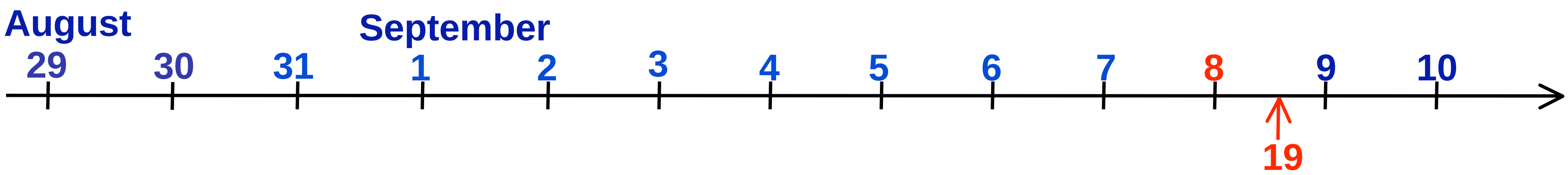


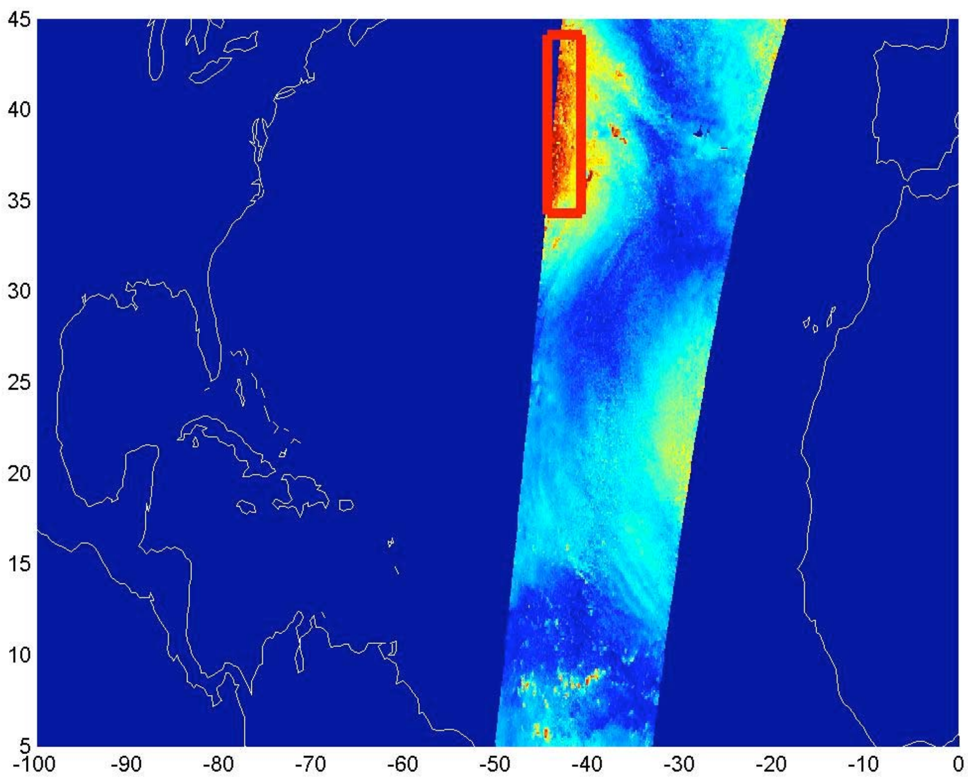
Interesting Result 1: Hurricane Maria



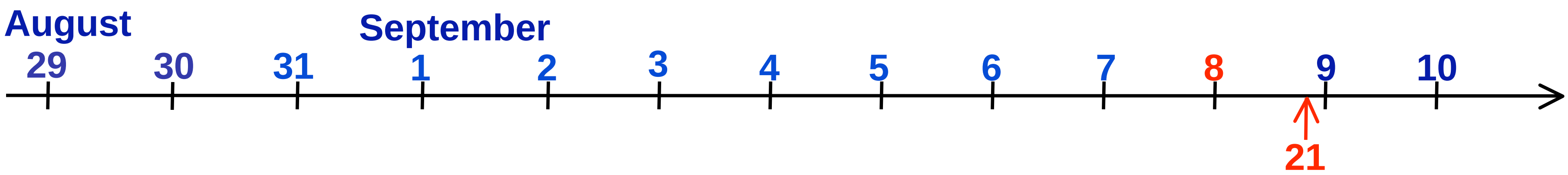


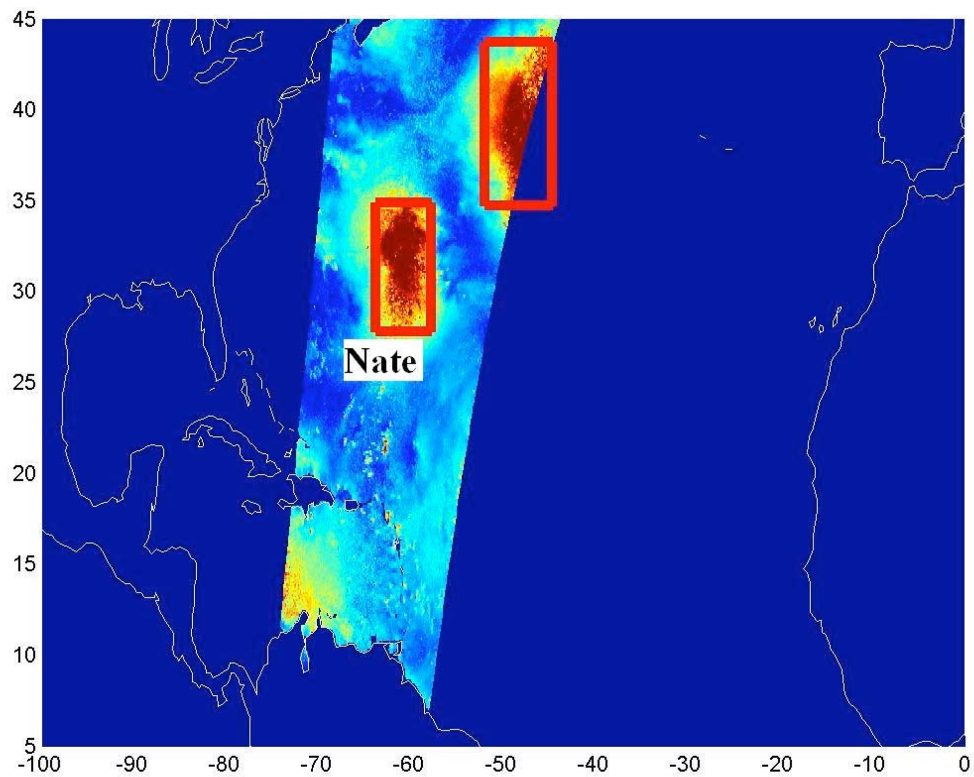
Interesting Result 1: Hurricane Maria





Interesting Result 1: Hurricane Maria





Interesting Result 1: Hurricane Maria

August
29 30 31

September
1 2 3 4 5 6 7 8 9 10

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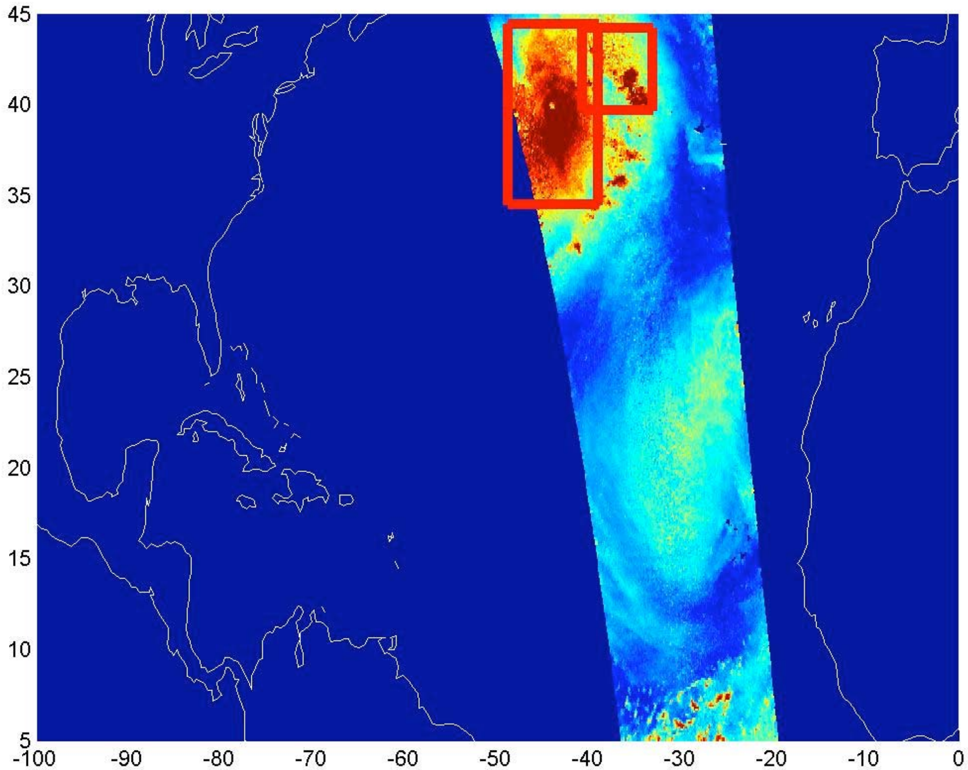
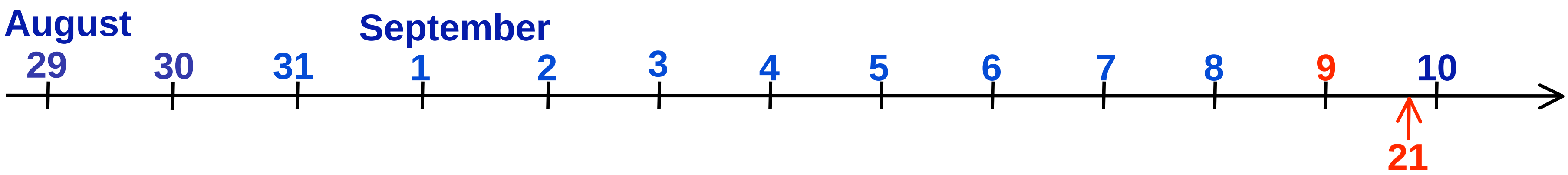
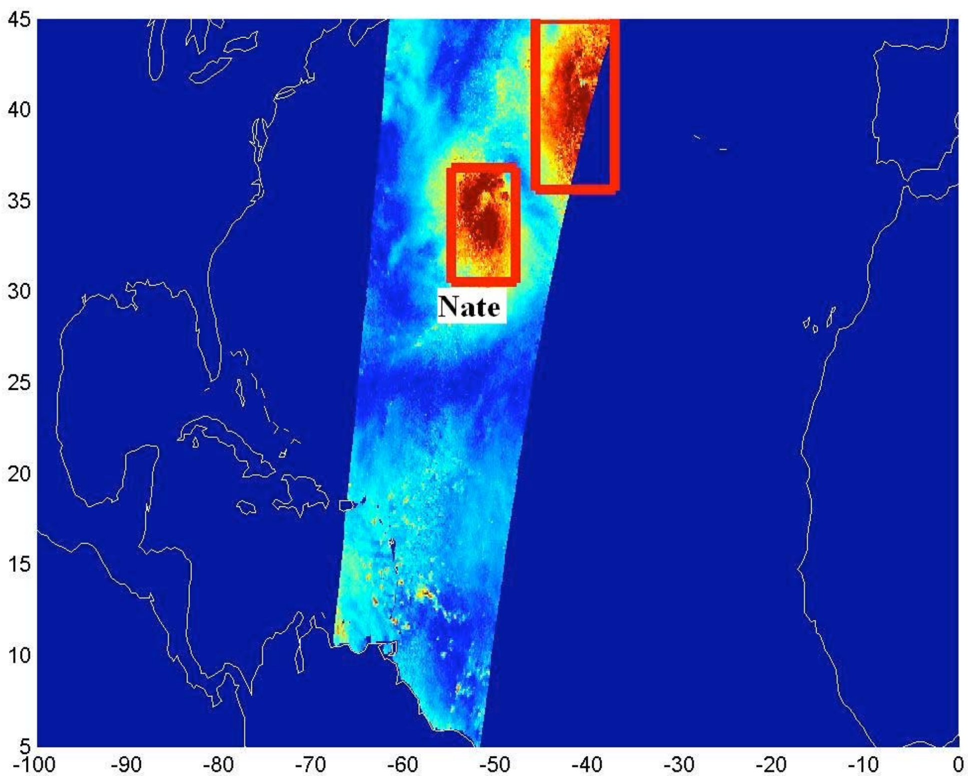
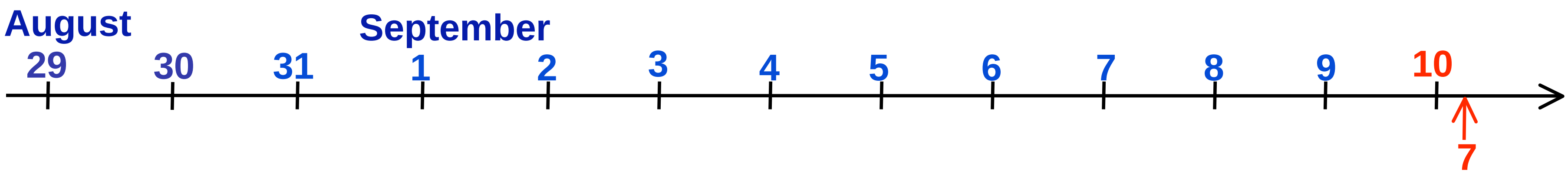


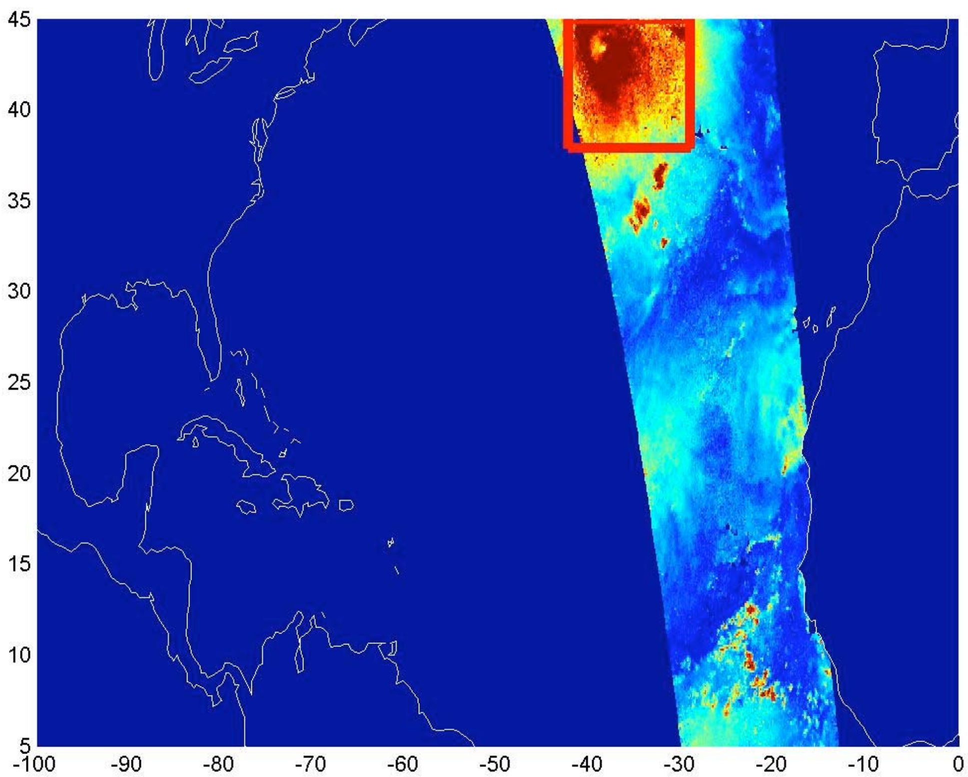
Interesting Result 1: Hurricane Maria



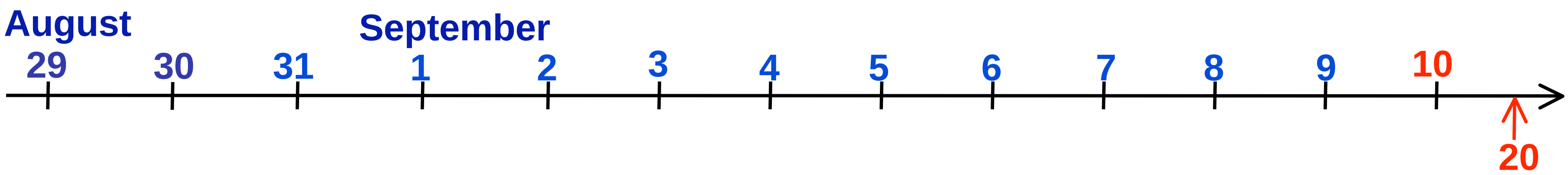


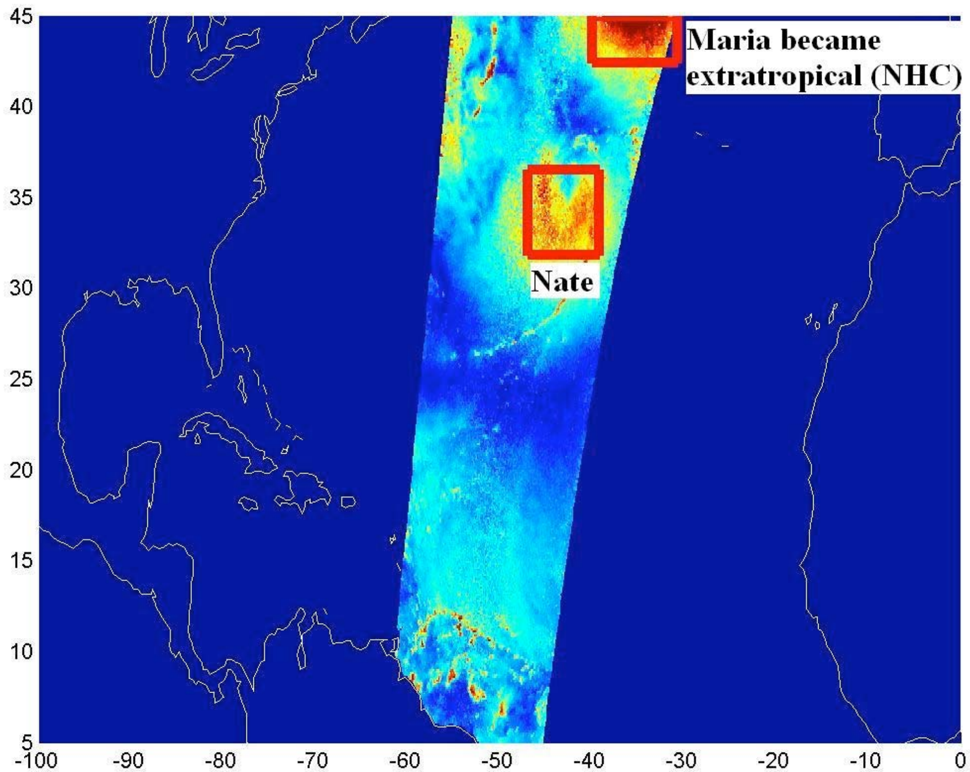
Interesting Result 1: Hurricane Maria





Interesting Result 1: Hurricane Maria





Interesting Result 2: Hurricane Vince

October 9 2005

Interesting Result 2: Hurricane Vince

October 4 5 6 7 8 9 10 11

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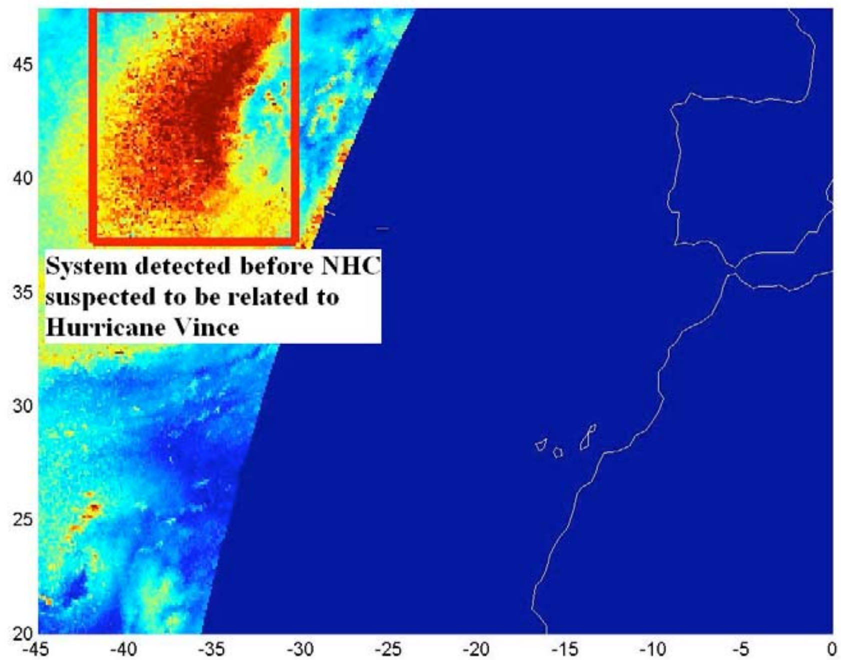
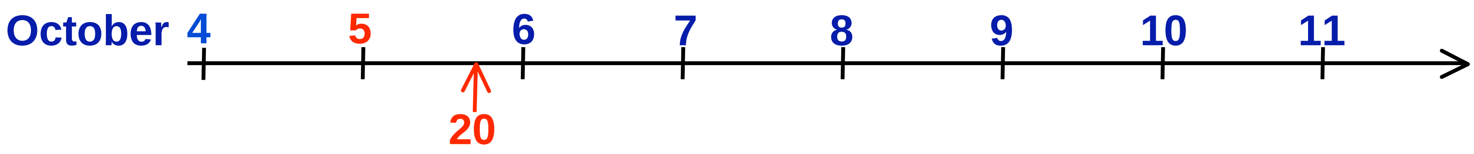
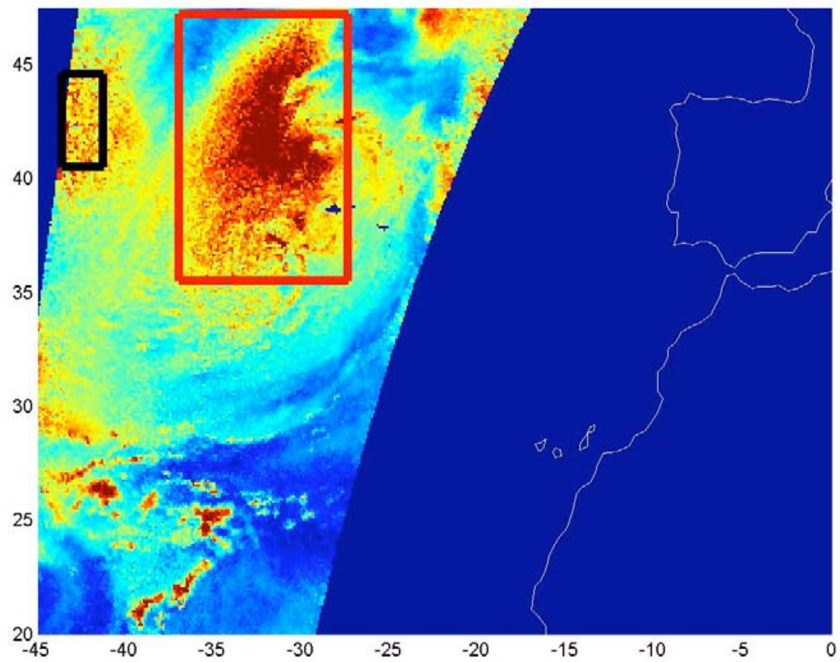


Interesting Result 2: Hurricane Vince





Interesting Result 2: Hurricane Vince

October 4 5 6 7 8 9 10 11

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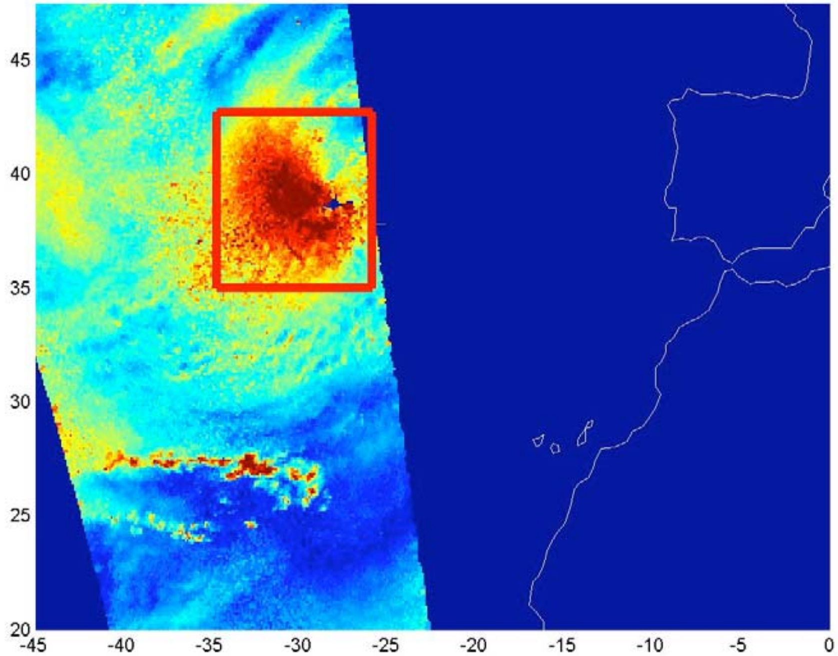
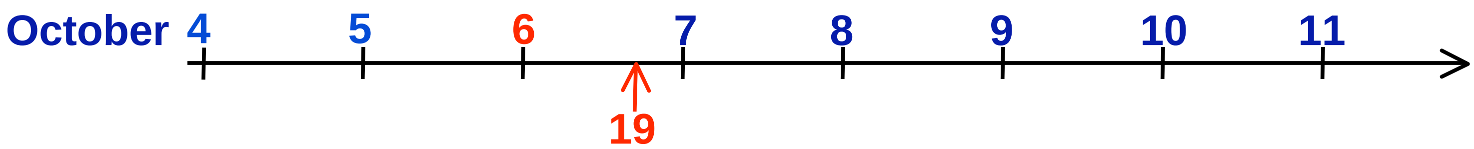
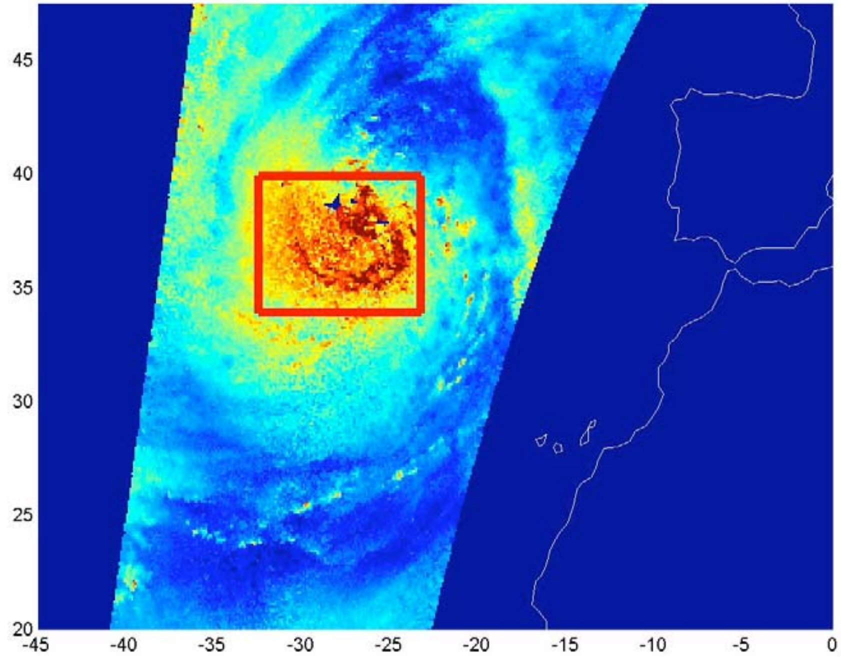
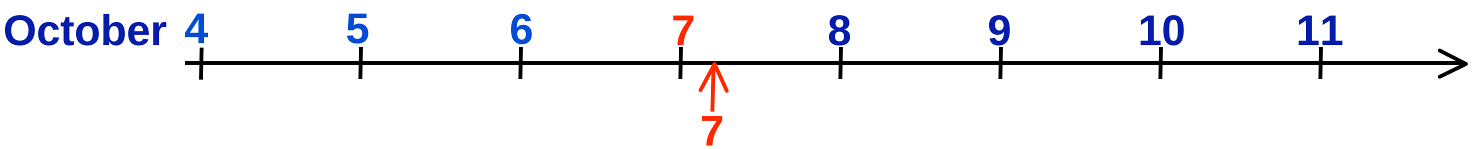


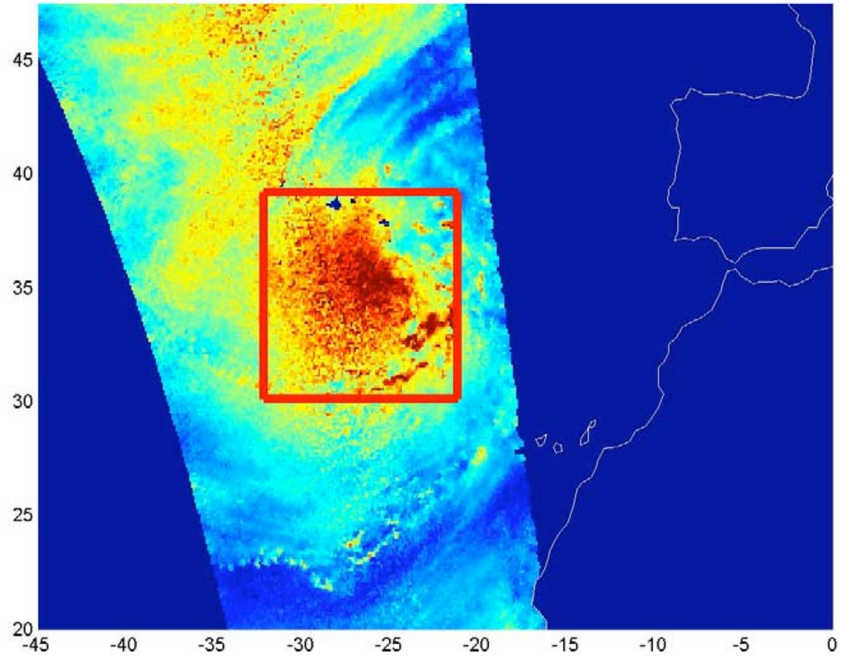
Interesting Result 2: Hurricane Vince





Interesting Result 2: Hurricane Vince





Interesting Result 2: Hurricane Vince

October 4 5 6 7 8 9 10 11

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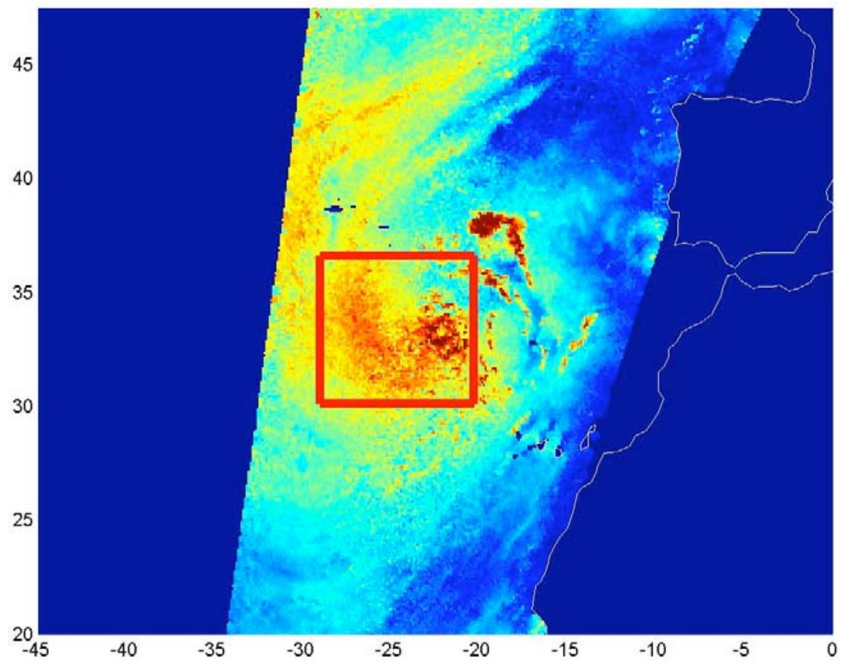

Interesting Result 2: Hurricane Vince

October 4 5 6 7 8 9 10 11

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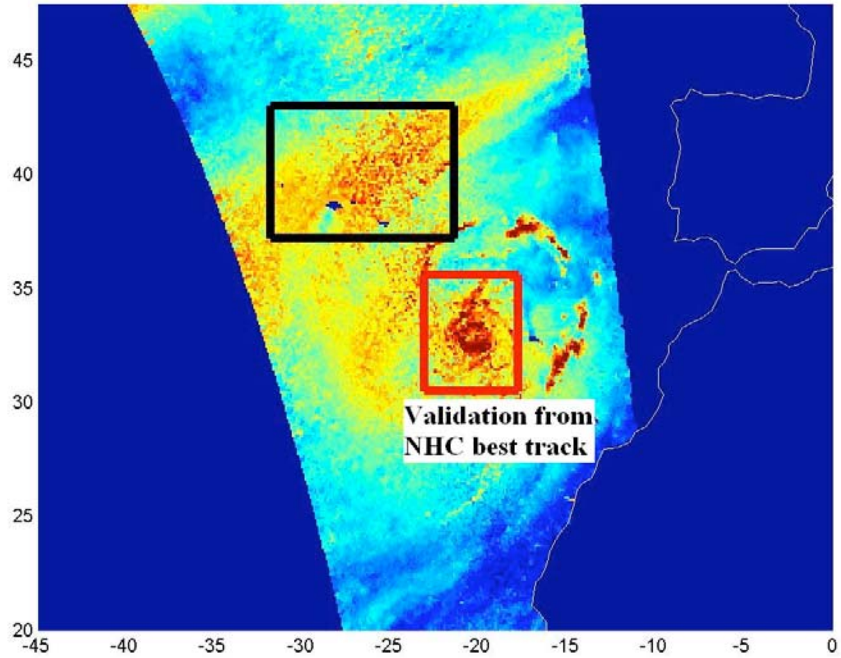

Interesting Result 2: Hurricane Vince

October 4 5 6 7 8 9 10 11

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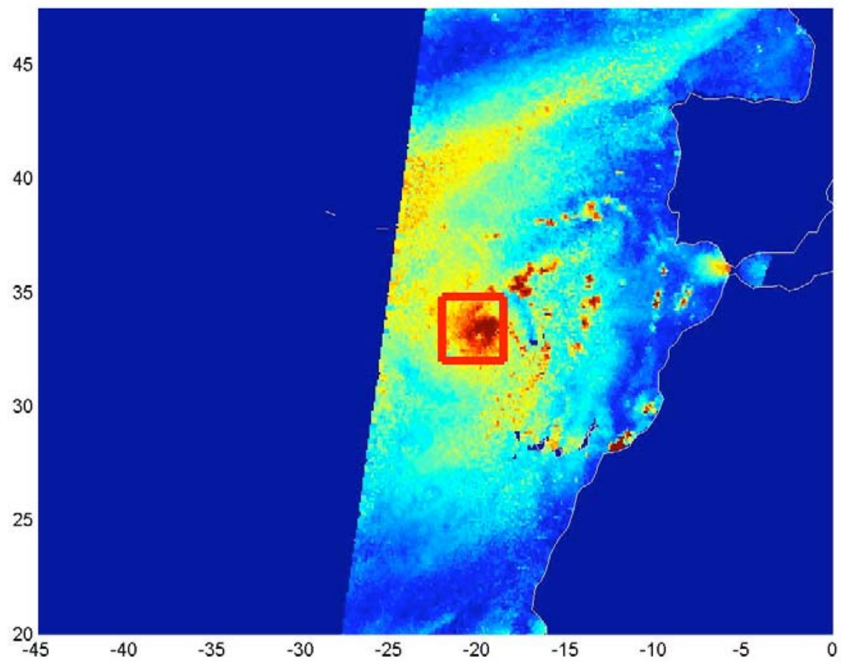
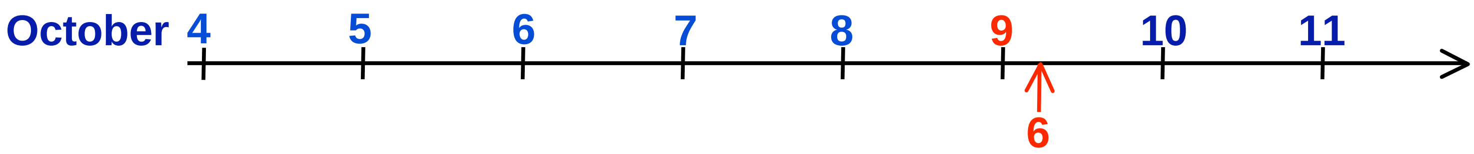
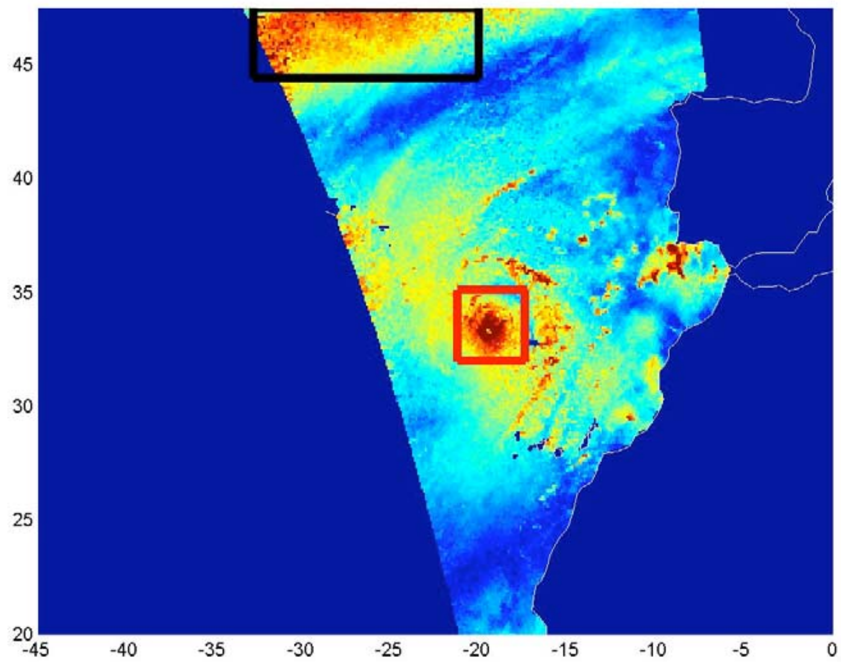


Interesting Result 2: Hurricane Vince





Interesting Result 2: Hurricane Vince

October 4 5 6 7 8 9 10 11

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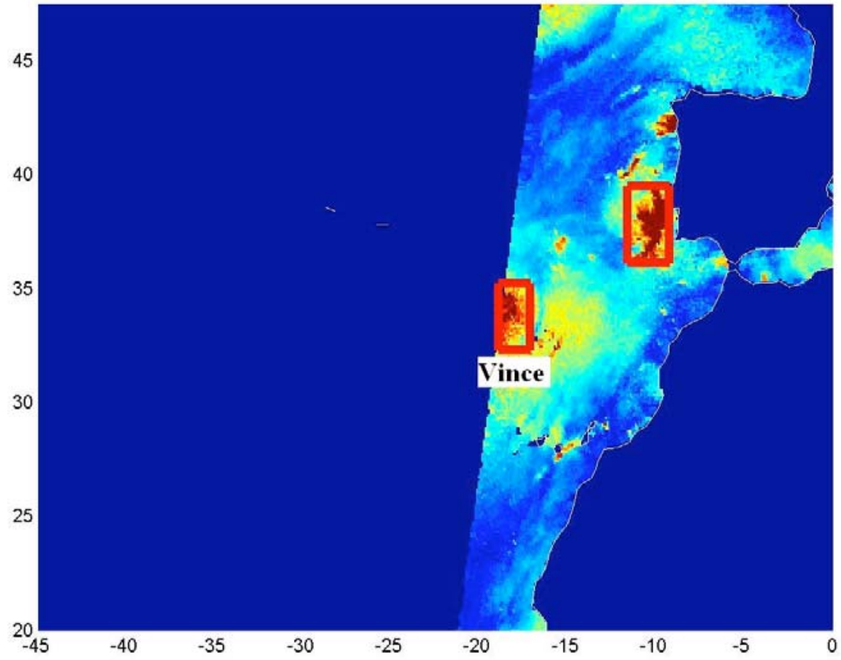

Interesting Result 2: Hurricane Vince

October 4 5 6 7 8 9 10 11

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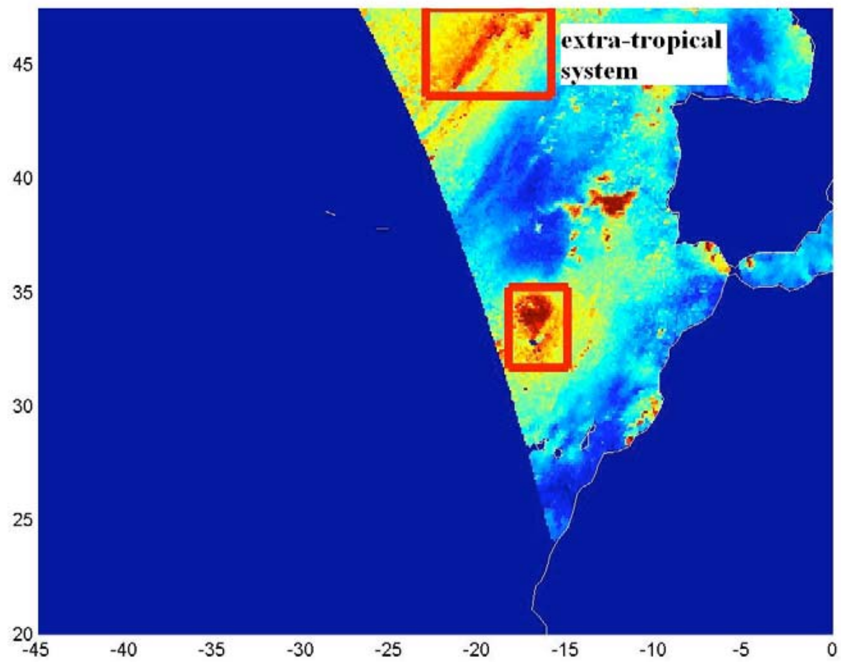
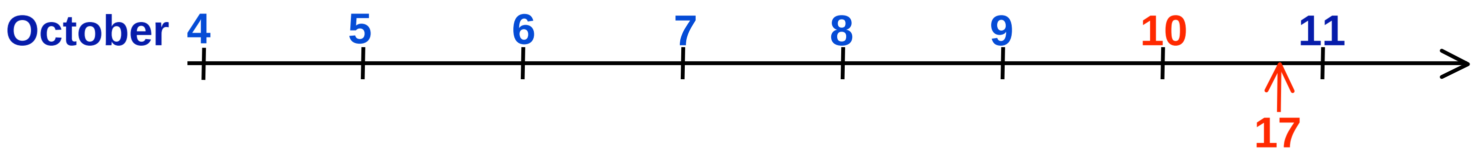
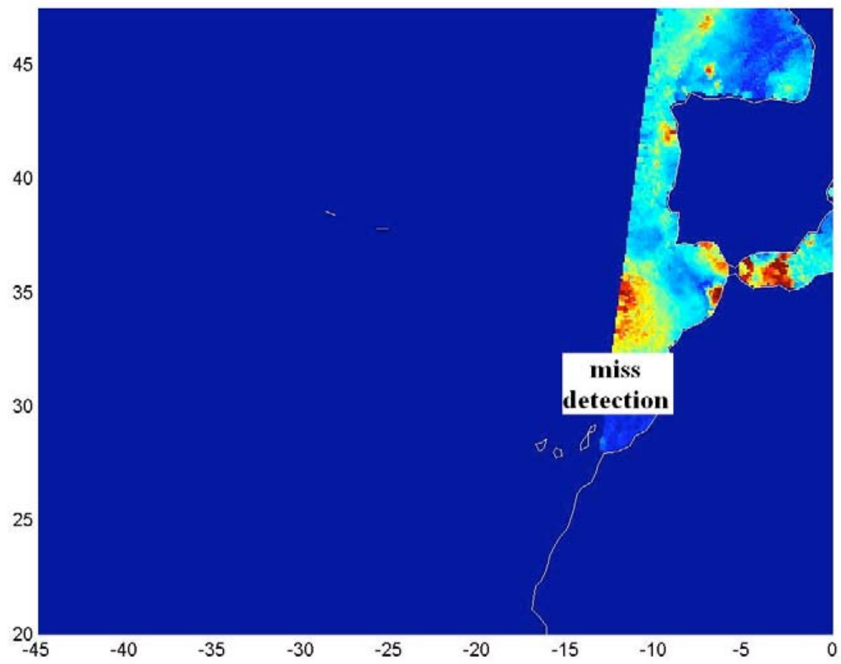
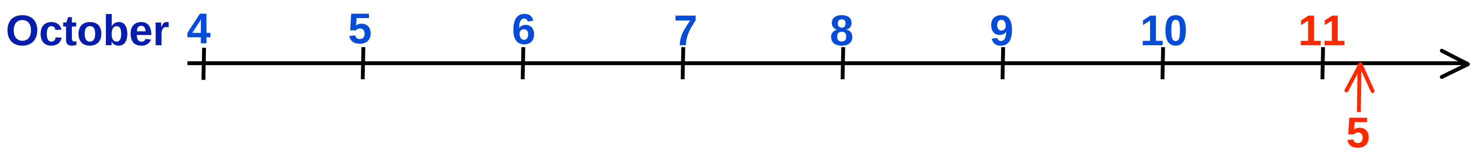


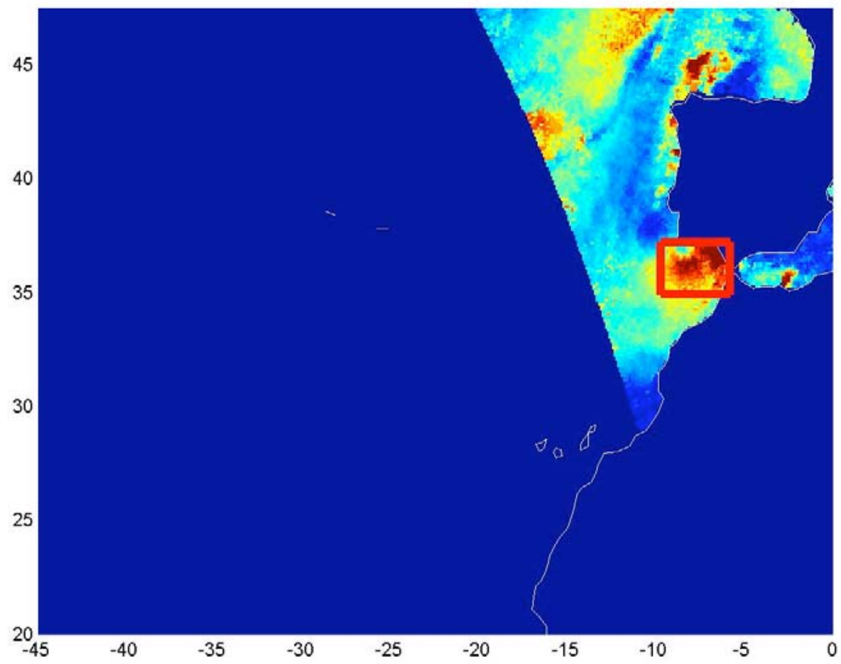
Interesting Result 2: Hurricane Vince





Interesting Result 2: Hurricane Vince

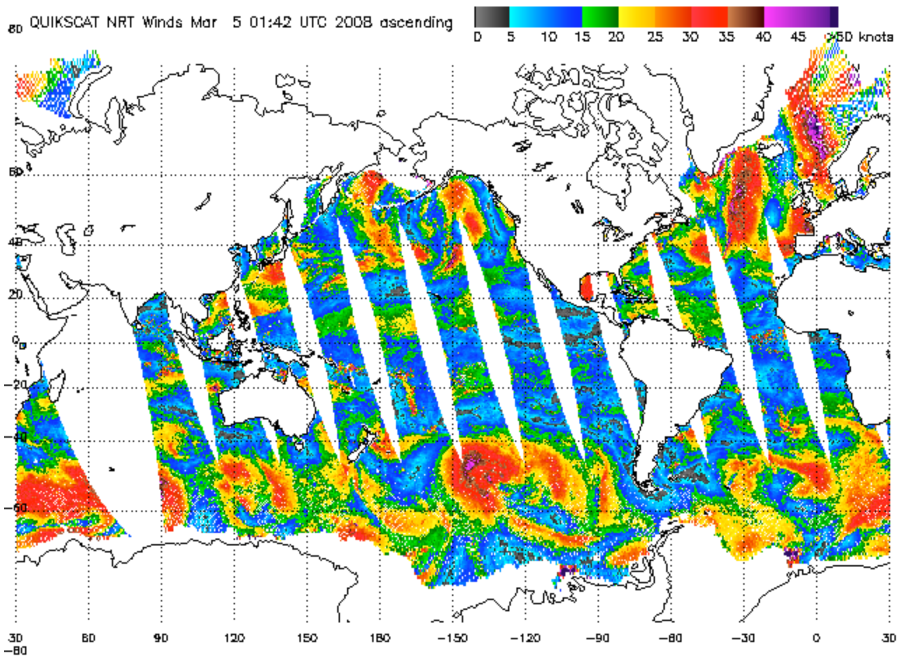




Multi-Satellite Cyclone Detection and Tracking using QuikSCAT wind and TRMM precipitation data

QuikSCAT: Issues and Challenges

- Non-continuous Region Monitoring
  - Orbiting satellite can only measure a particular region at some time instance per day
  - Misses may occur for some region of interest.

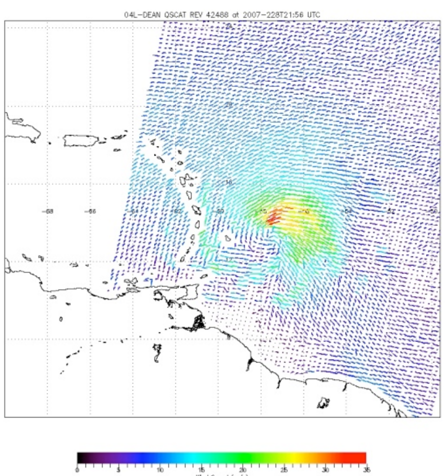


Ascending passes (http://manati.orbit.nesdis.noaa.gov/quikscat)

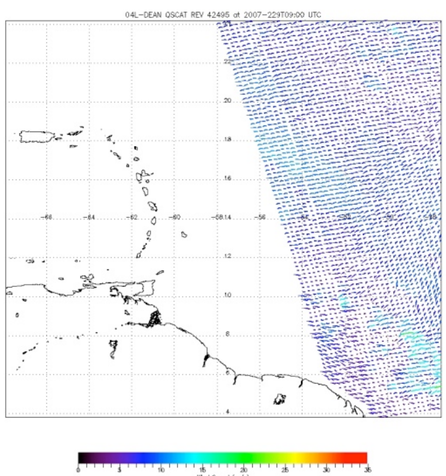
White region between any two side-by-side swaths is a region QuikSCAT fails to measure.

QuikSCAT: Issues and Challenges

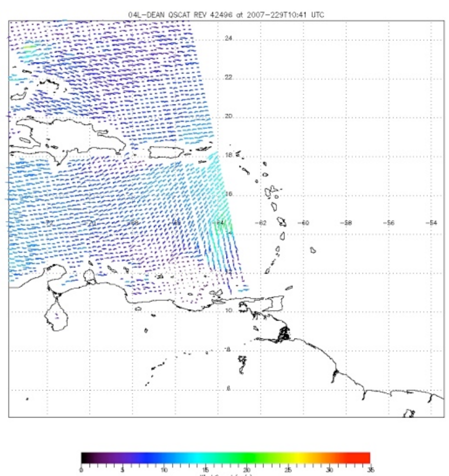
- Event Occlusion
  - Orbiting satellite can only measure a particular region at some time instance per day
  - Misses may occur for some region of interest.



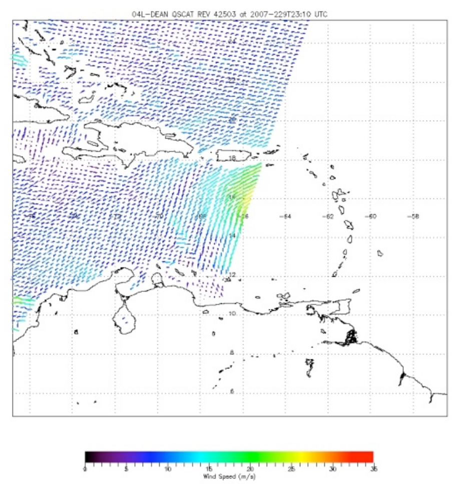
(A)



(B)



(C)



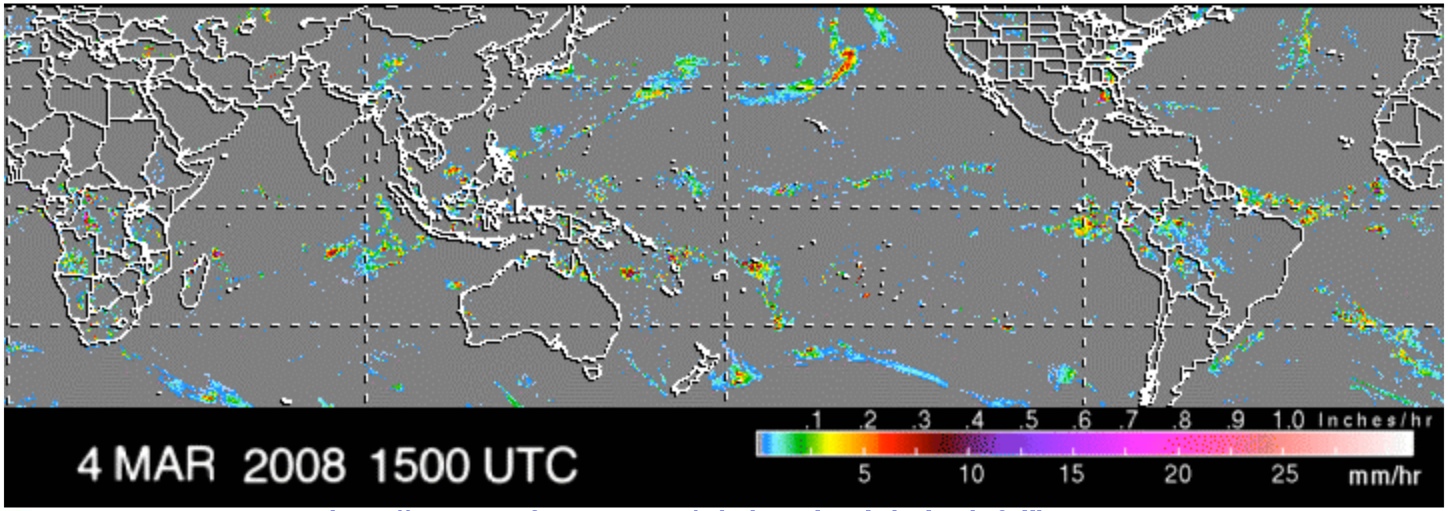
(D)

Hurricane Dean 2007 in Image (B),(C) and (D) are occluded.

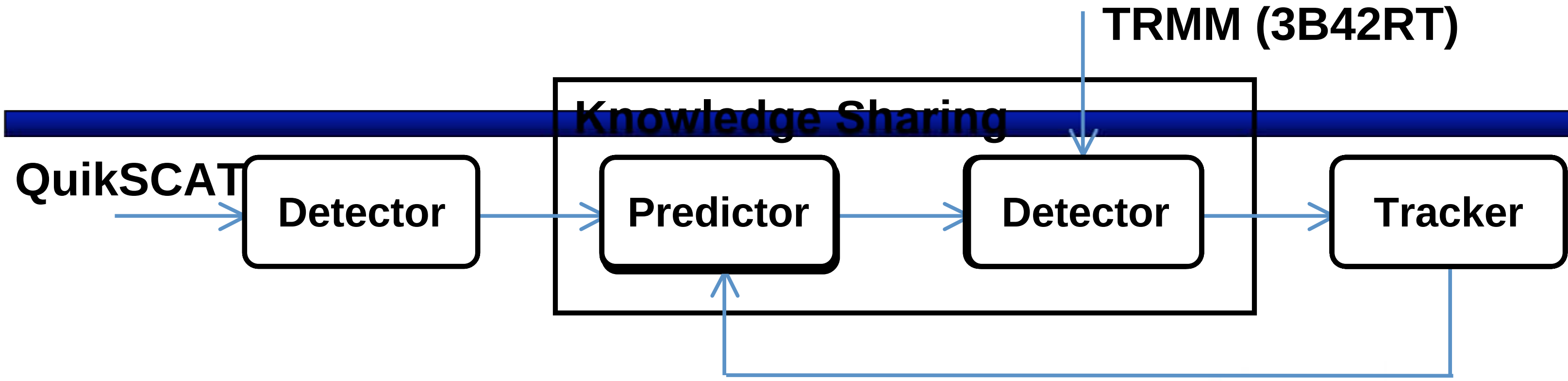
TRMM Measurement Assimilation with QUIKSCAT

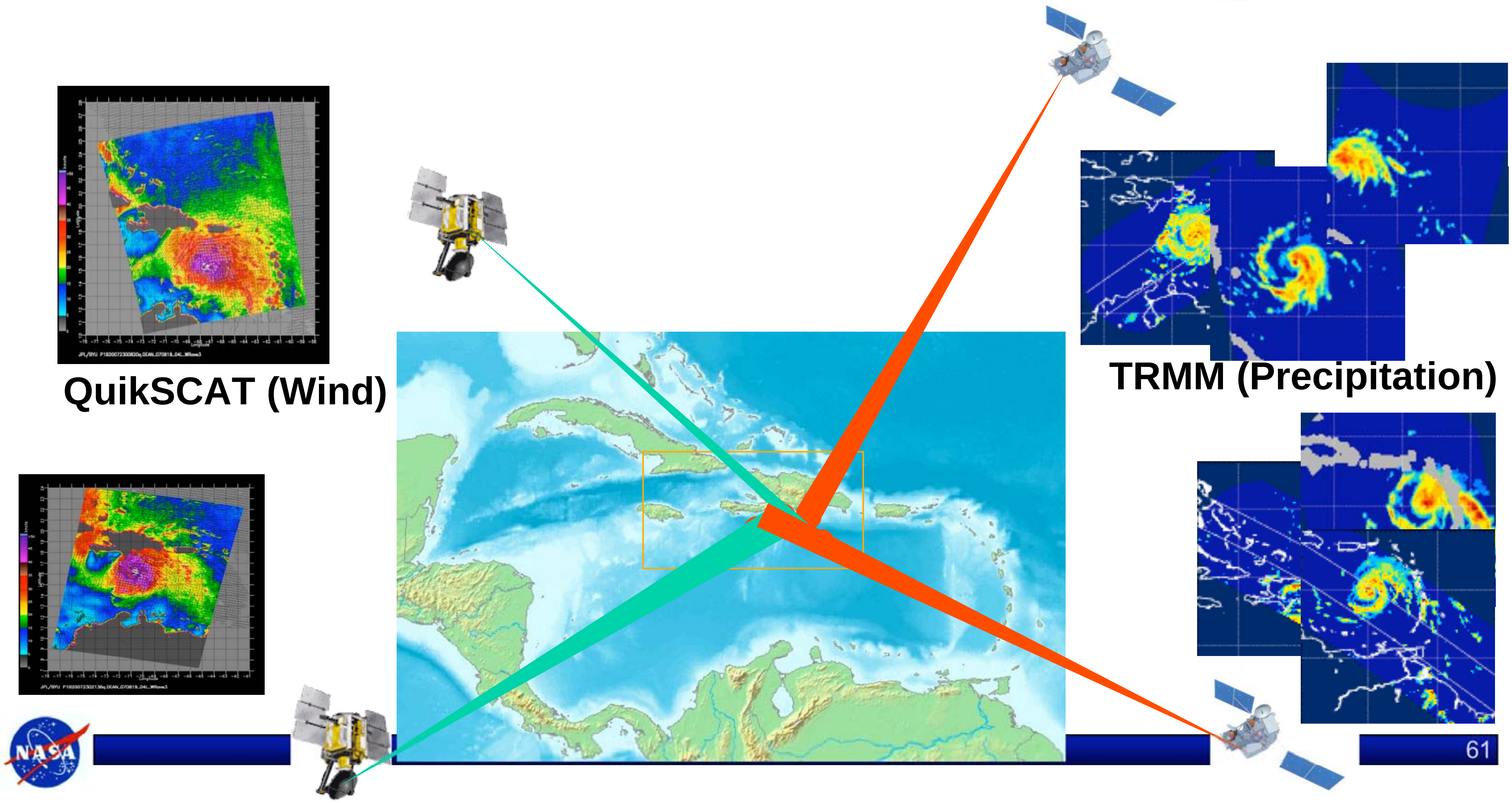
- Level 3B42 TRMM data product
  - Global Precipitation estimates from combination of instruments: PR, TMI, SSMI, AMSR, AMSU.
  - 0.25 deg x 0.25 deg per pixel
  - Every 3 hours
  - Measurement range [0, 100] mm/hr.

- Why Useful for Cyclone Detection?
  - Rainfall always associated with cyclone.
  - Improved (finer) temporal resolution in cyclone tracking



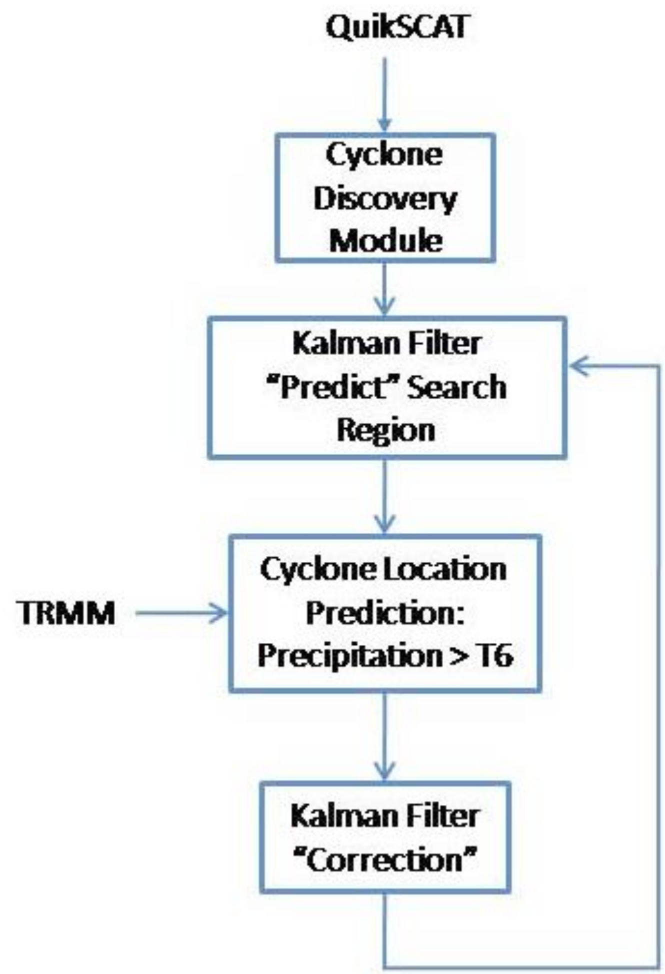
From http://trmm.gsfc.nasa.gov/ (3 hourly global rainfall)


TRMM (3B42RT)
Knowledge Sharing
QuikSCAT
Detector
Predictor
Detector
Tracker


QuikSCAT (Wind)
TRMM (Precipitation)

Knowledge Sharing Novelties

- Addresses challenges of mining heterogeneous data from multiple orbiting satellites
- Knowledge sharing between heterogeneous sensor measurements
  - for sensor measurement lacking a definitive indicator for cyclones
  - with different spatial and temporal resolutions.



Demo for

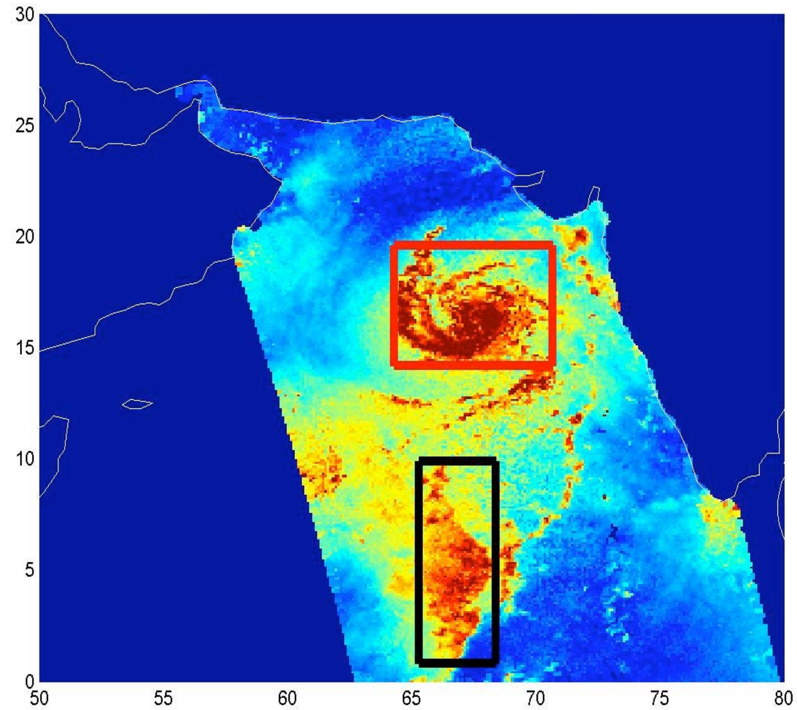
Hurricane Gonu

in

Arabian Sea in 2007

June 3 4 5 6 7

1

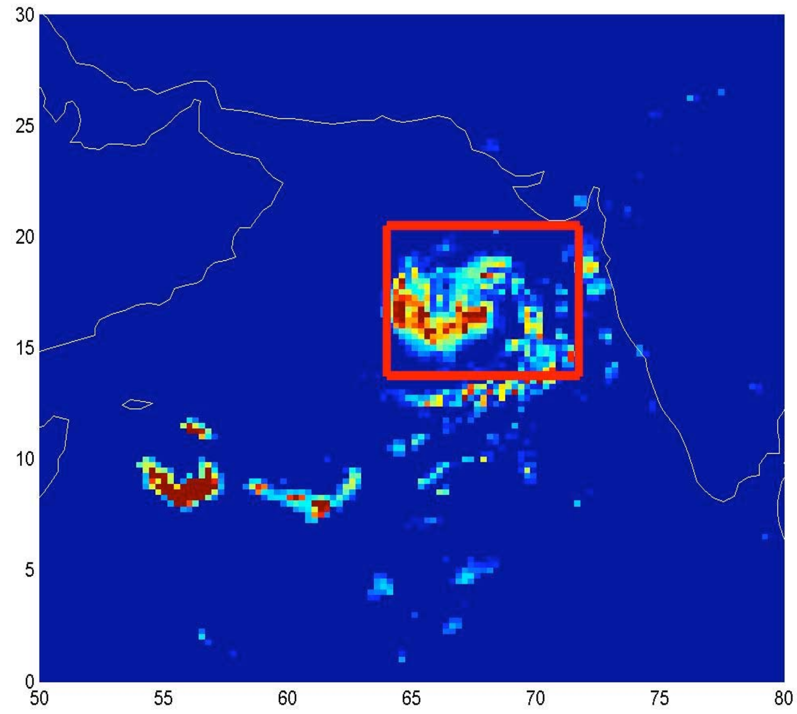


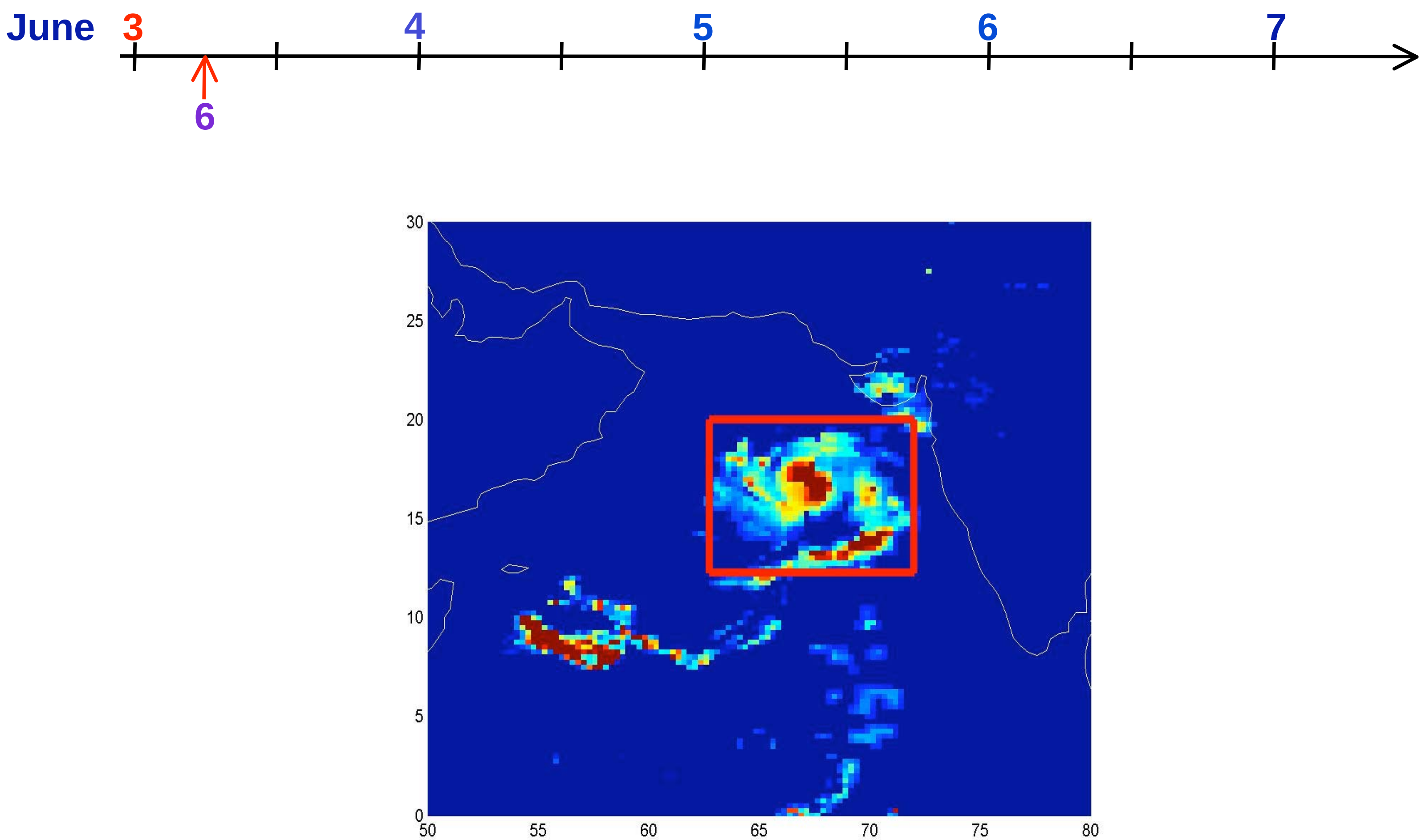
Category 1 Hurricane

Black Bounding Box: Area classified as a non-cyclone area

June 3 4 5 6 7

3

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June 3 4 5 6 7

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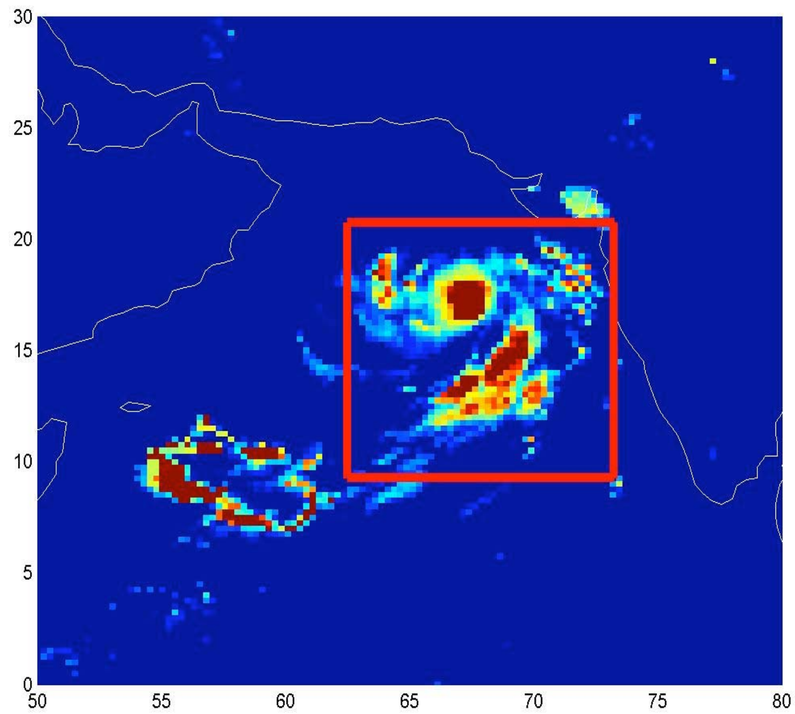

June 3 4 5 6 7

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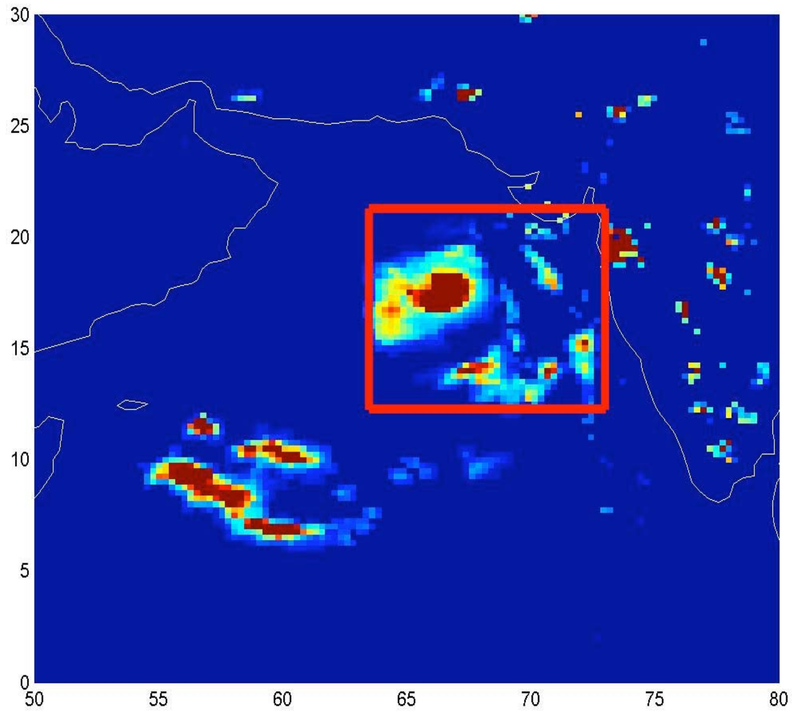
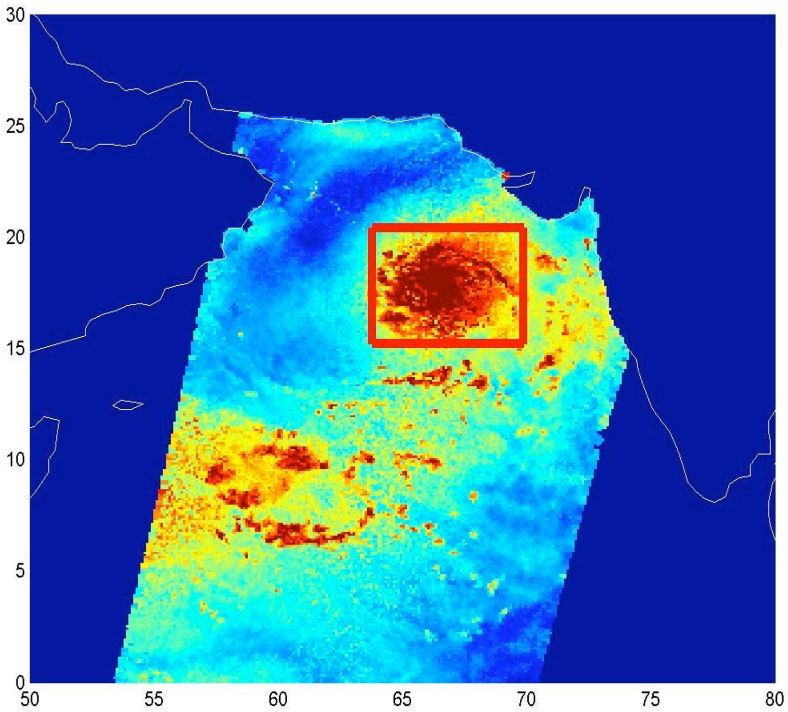


June 3 4 5 6 7

13



June 3 4 5 6 7

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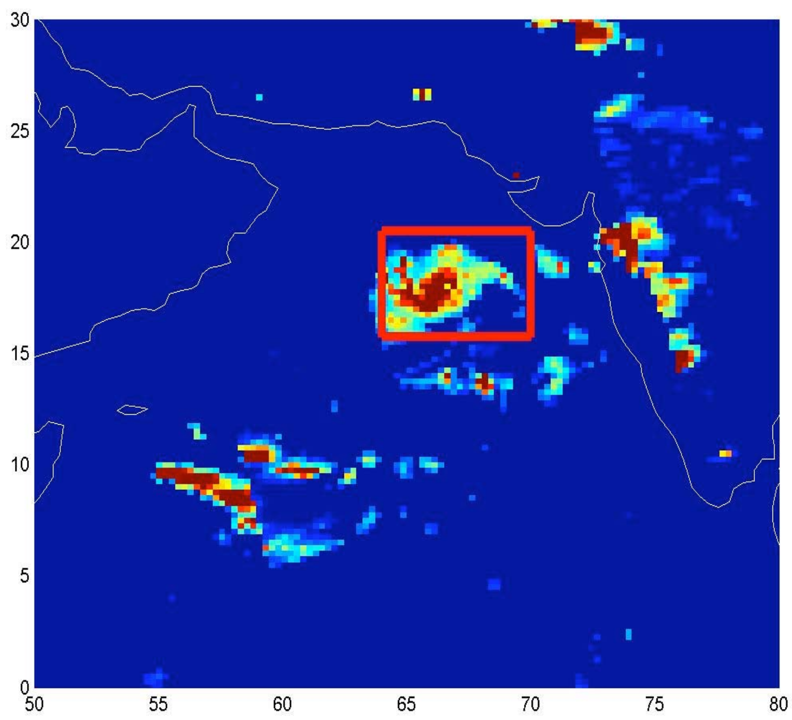

June 3 4 5 6 7

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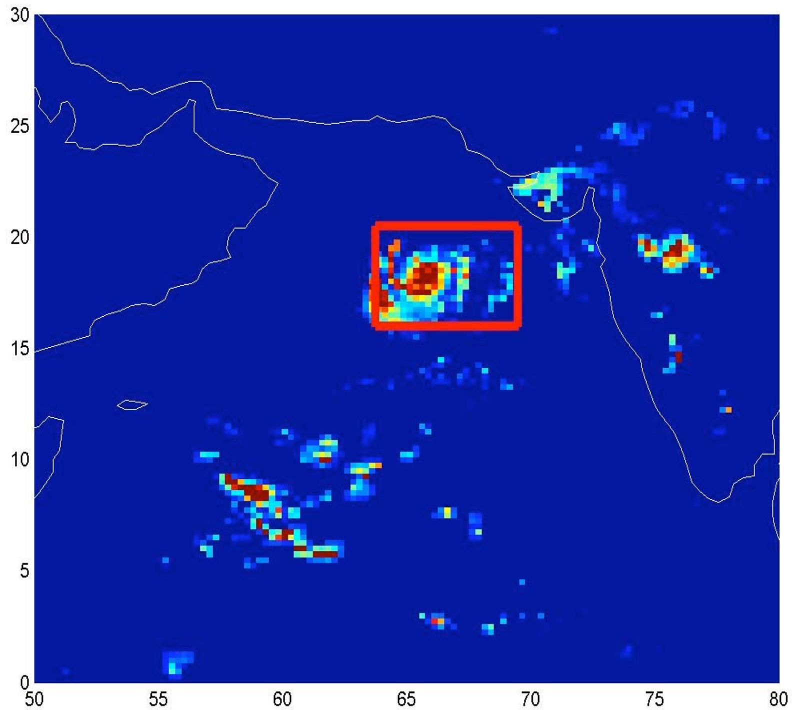

June 3 4 5 6 7

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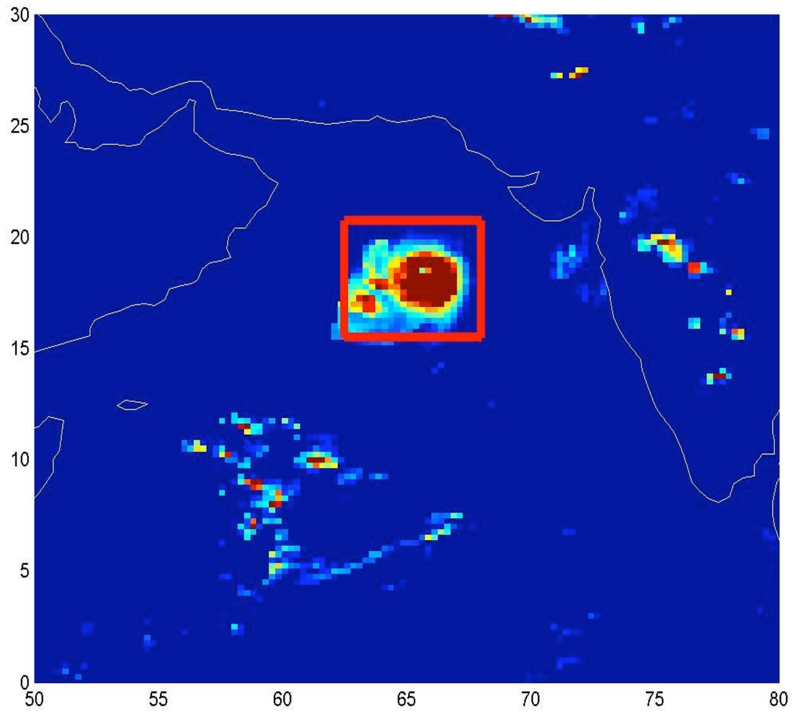

June 3 4 5 6 7

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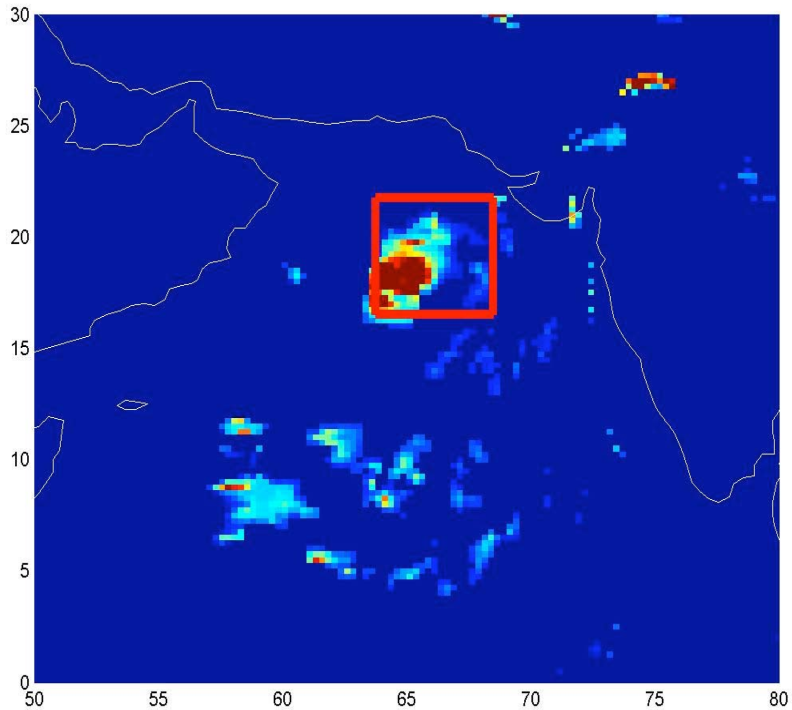

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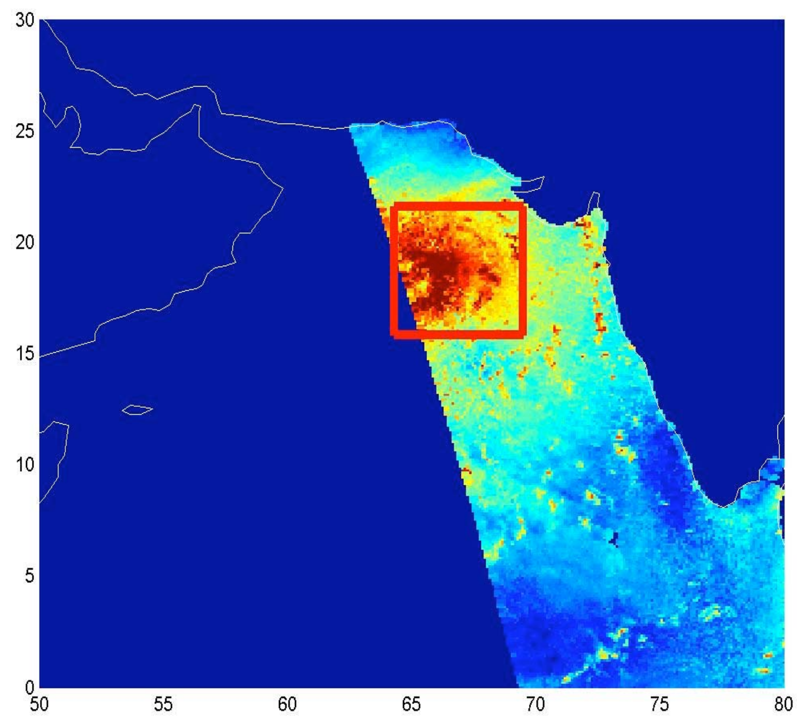

Category 5 Hurricane

June 3 4 5 6 7

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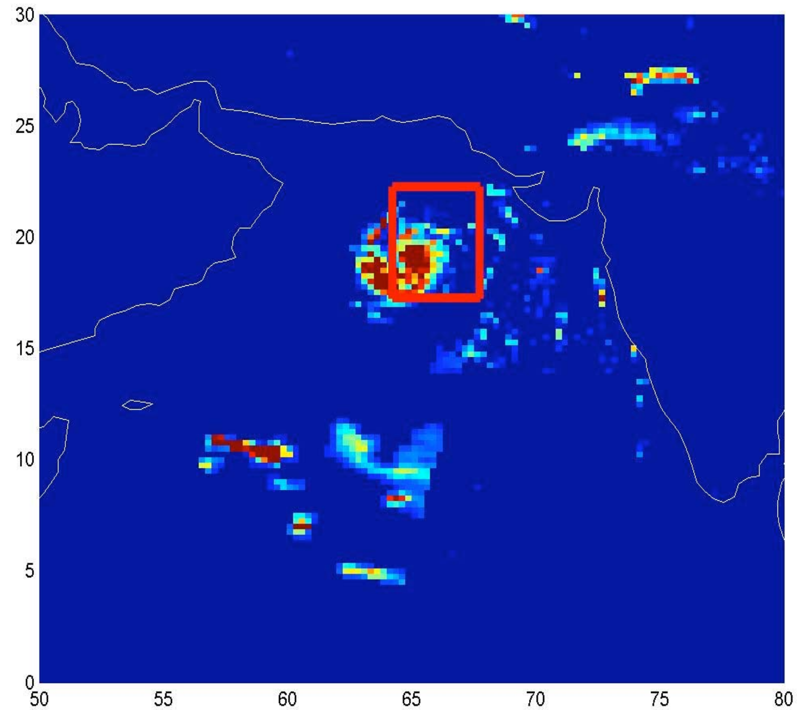

June 3 4 5 6 7

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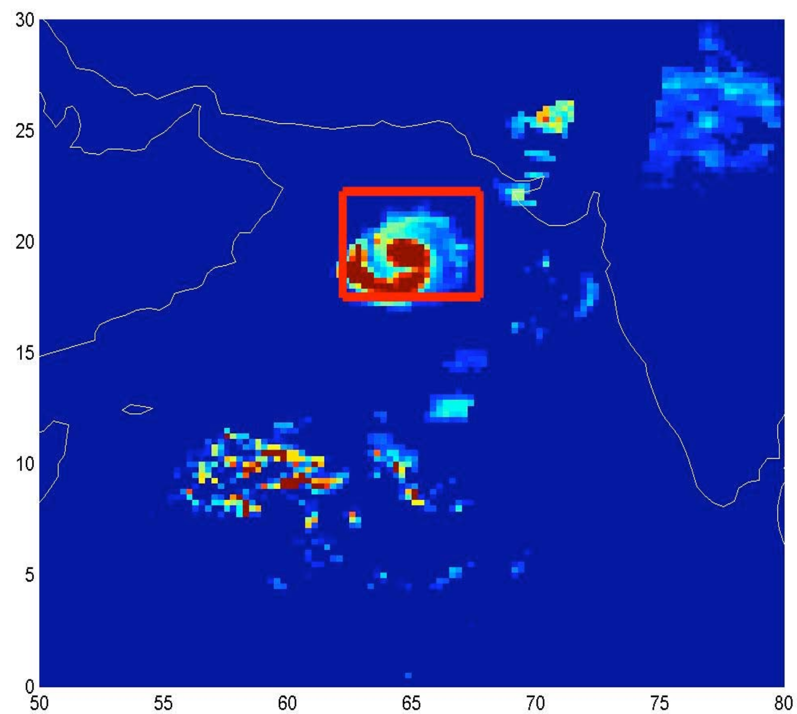

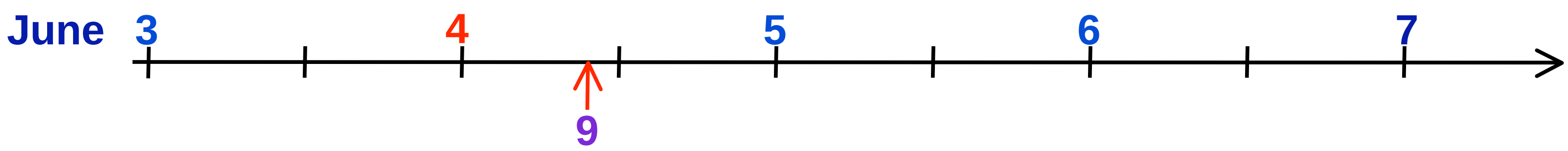
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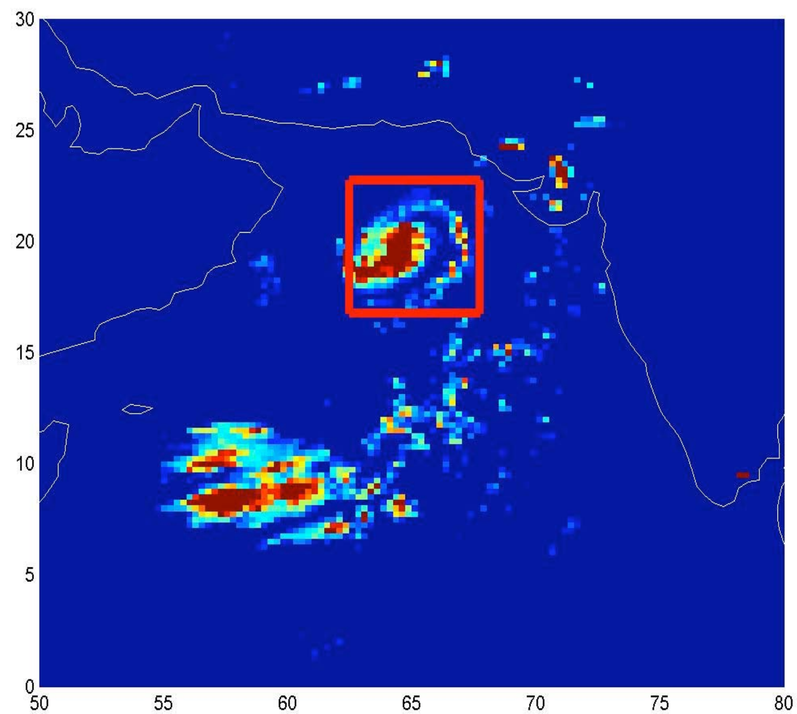
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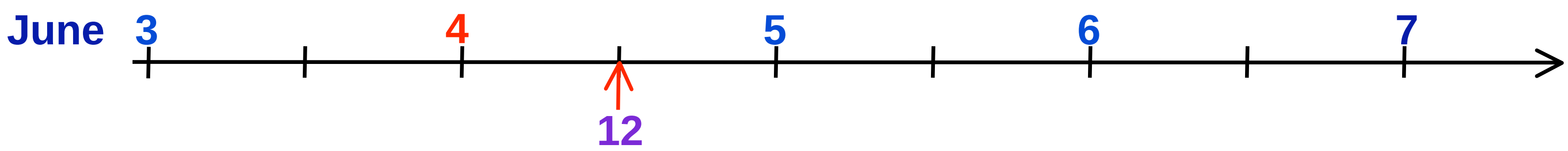
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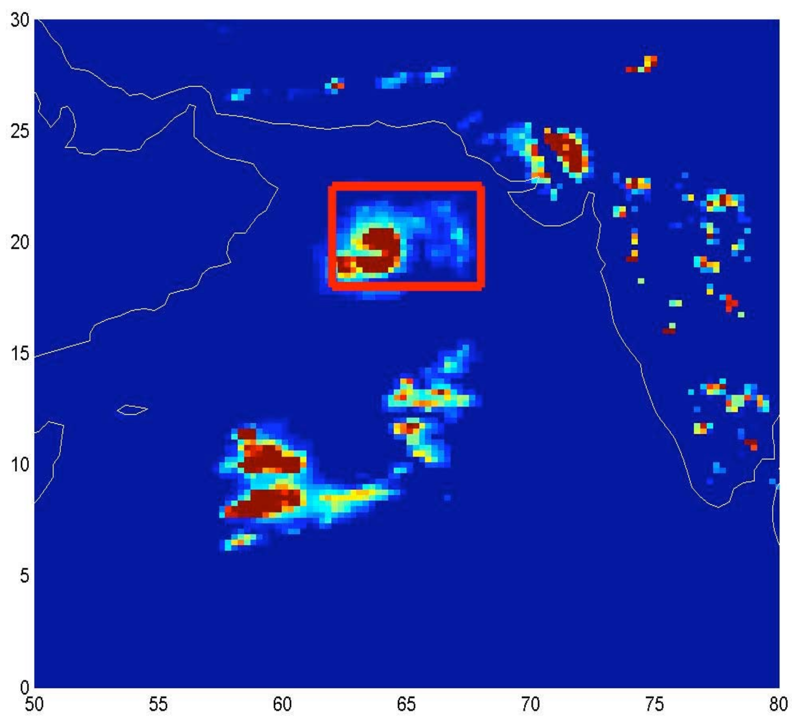
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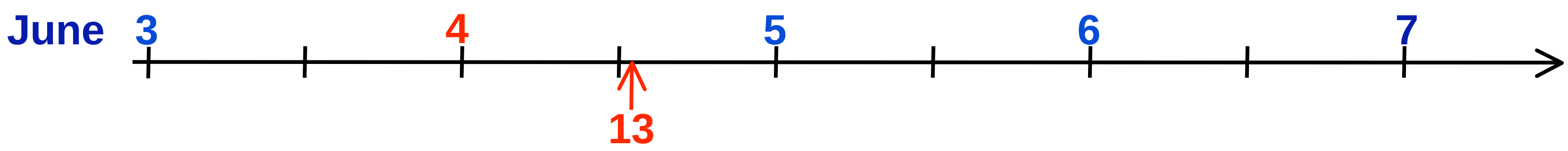
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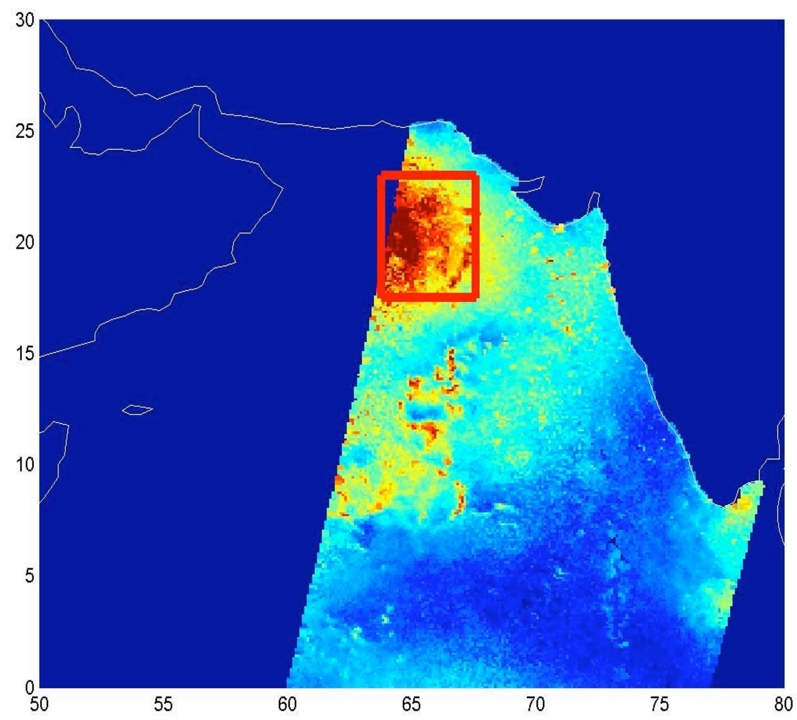
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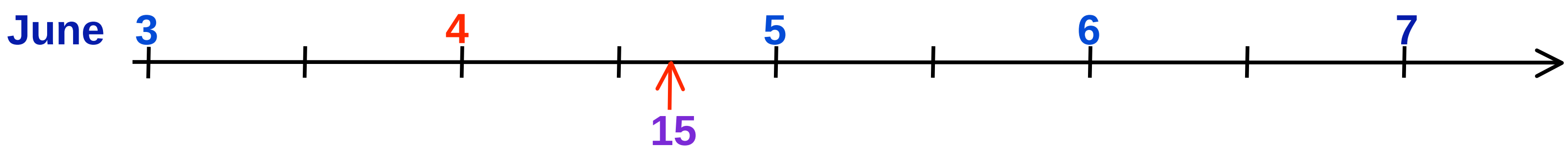

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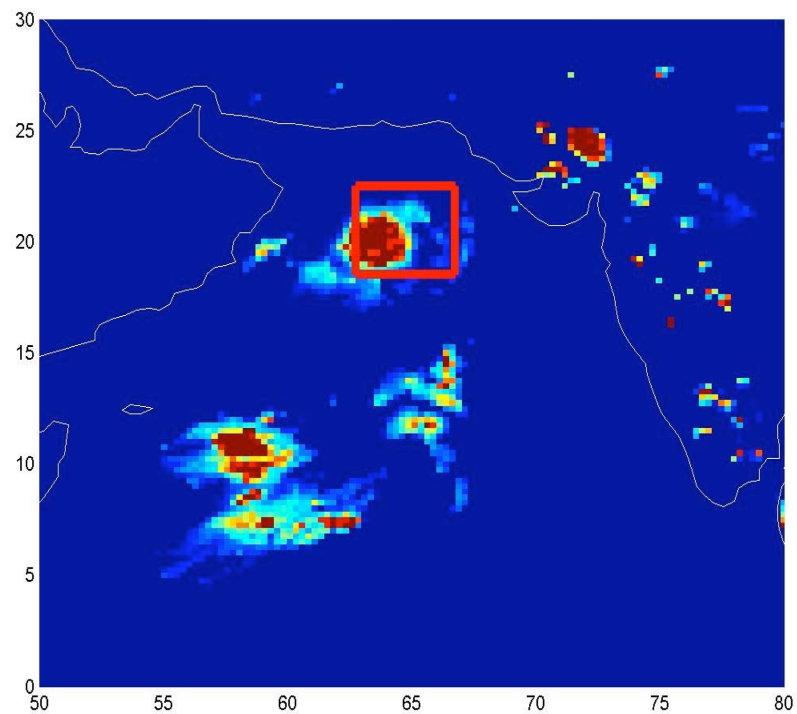

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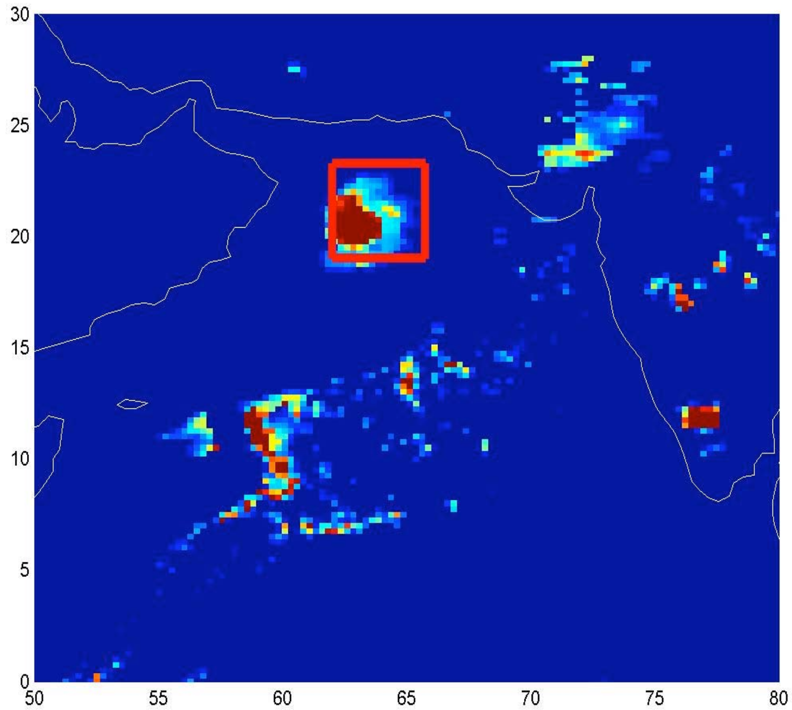

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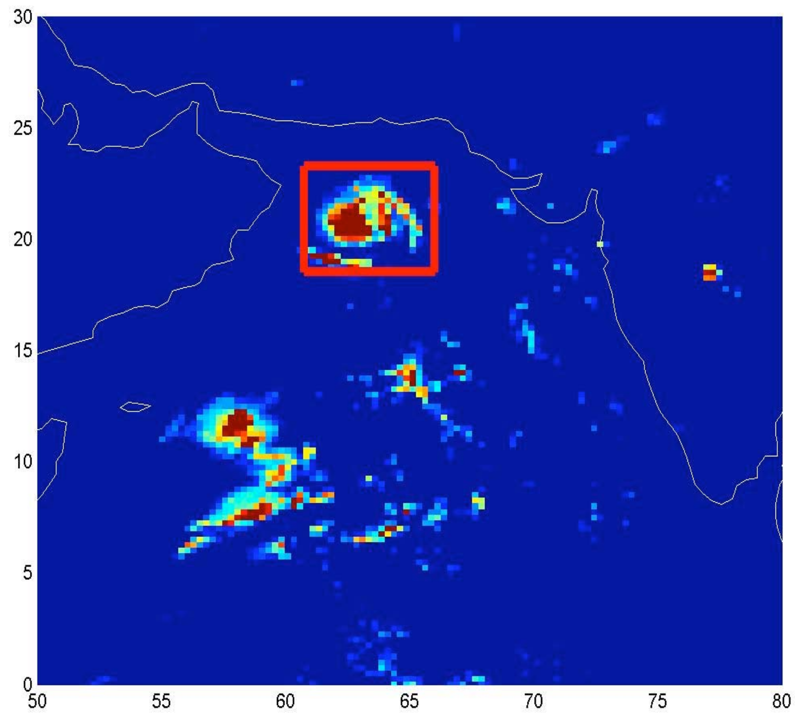

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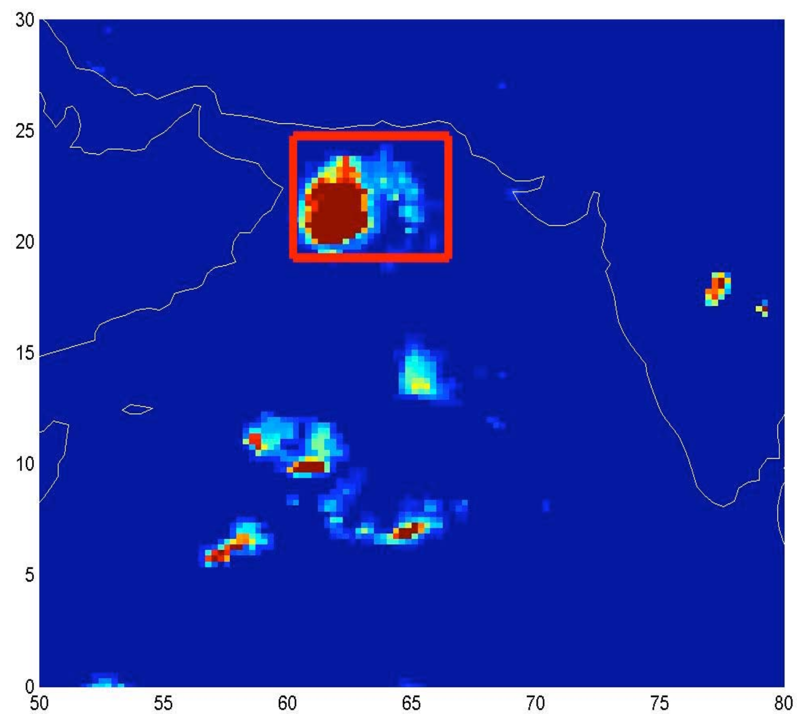

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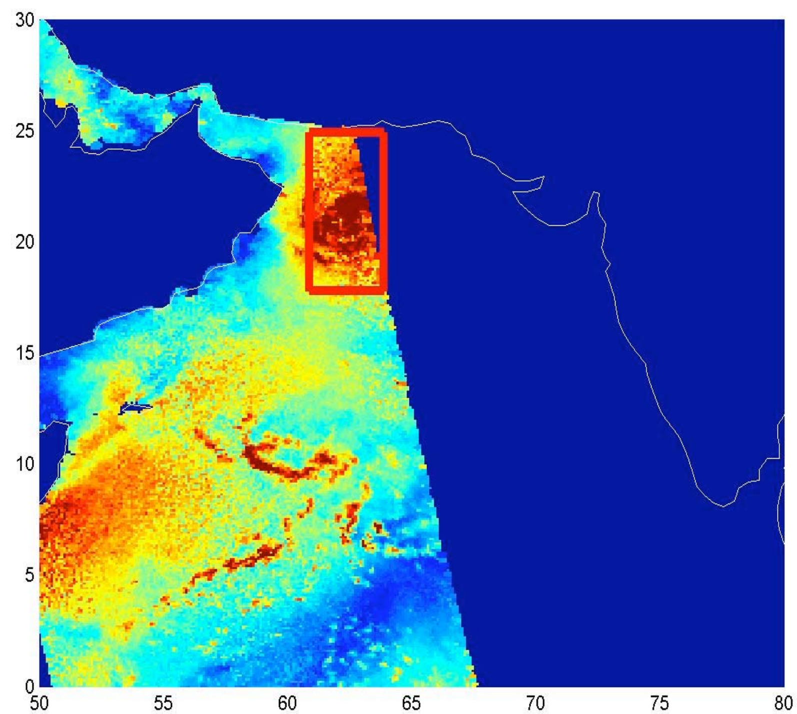

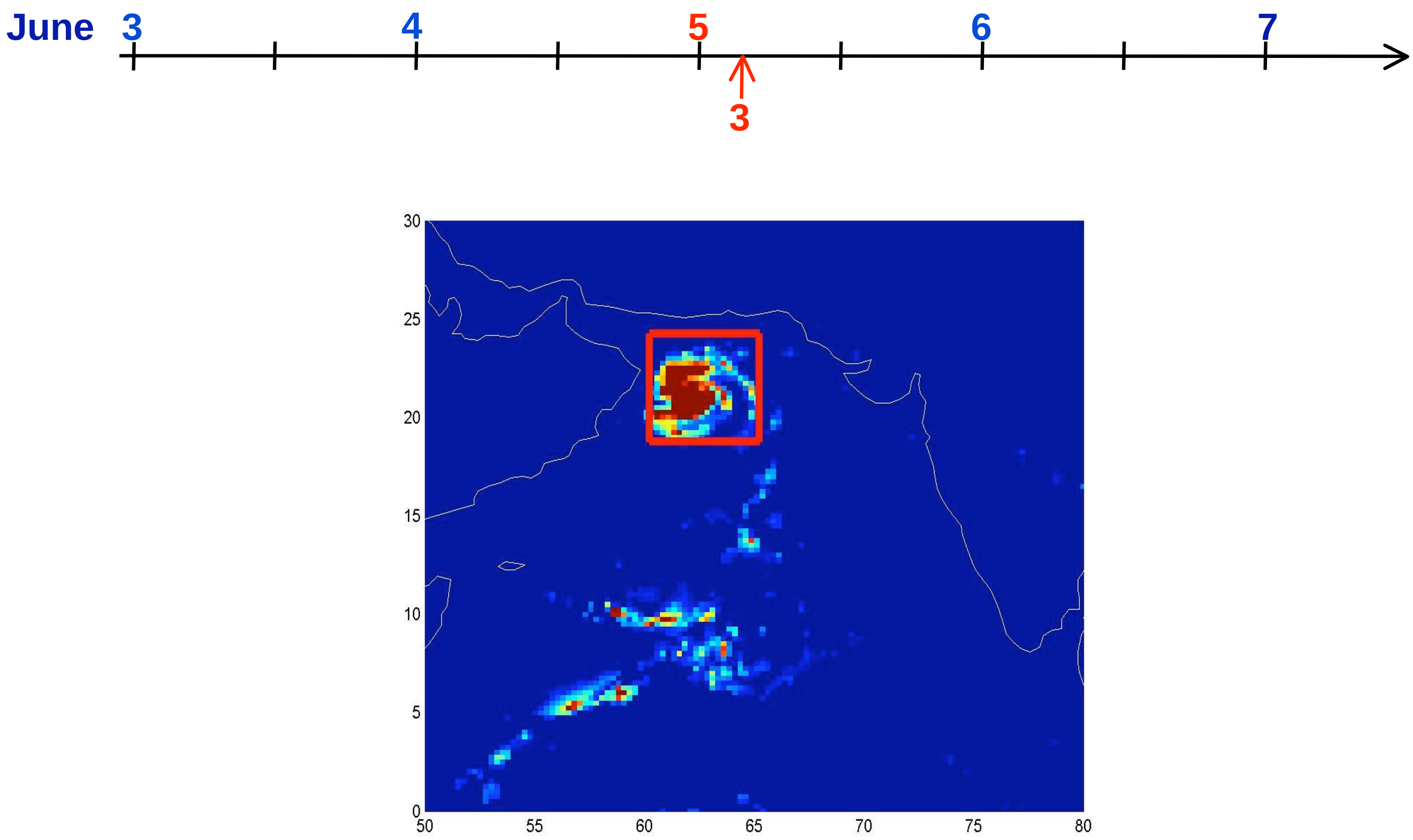
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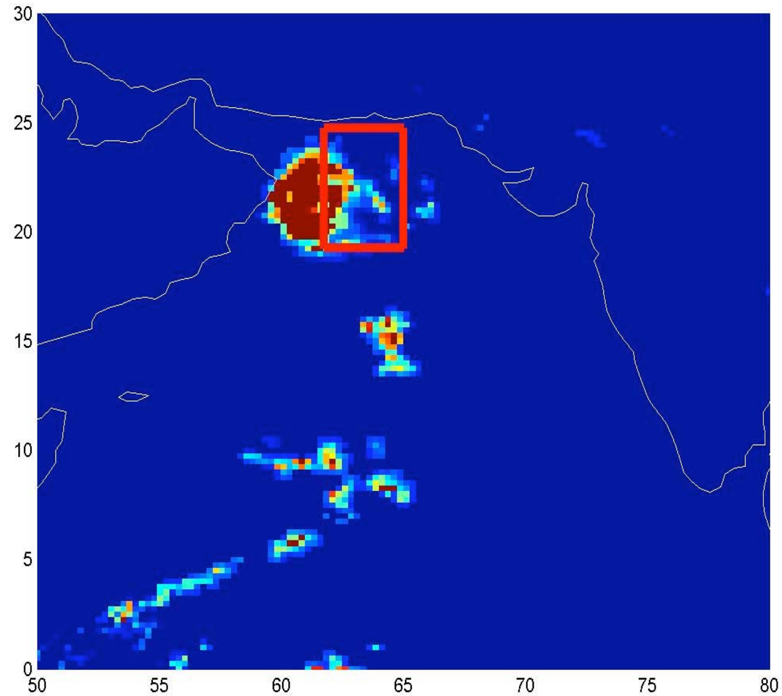

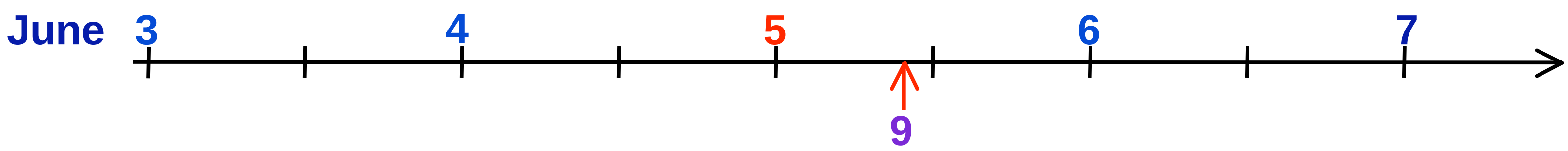
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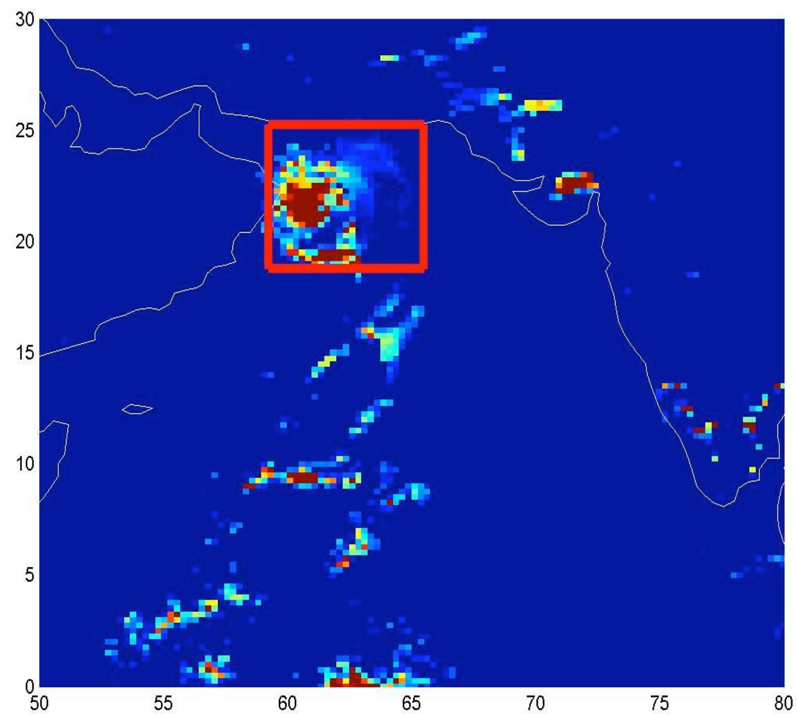
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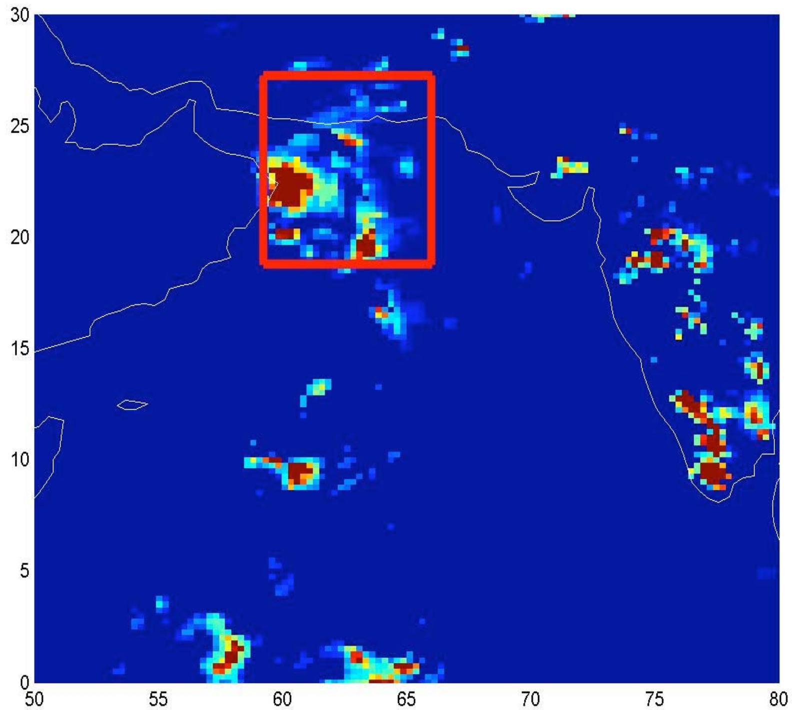

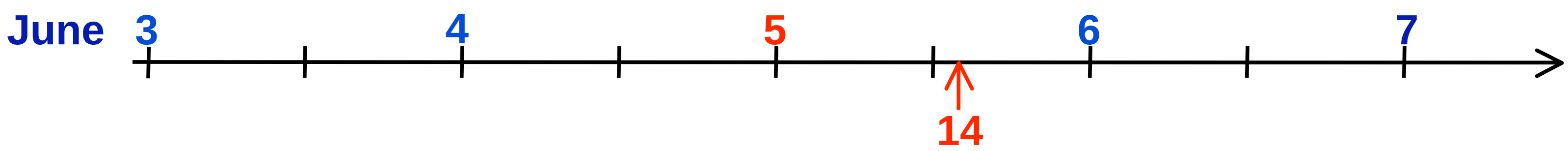
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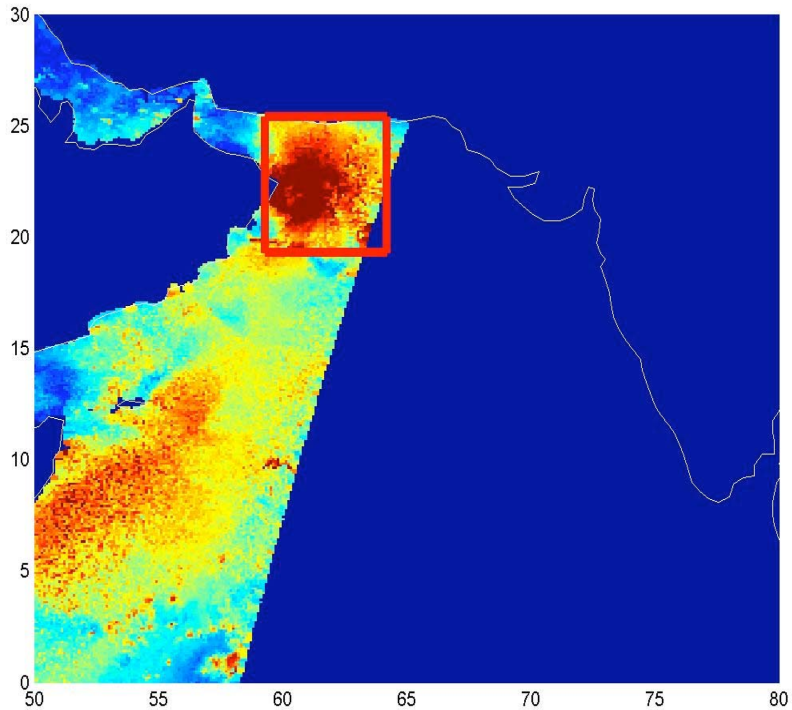
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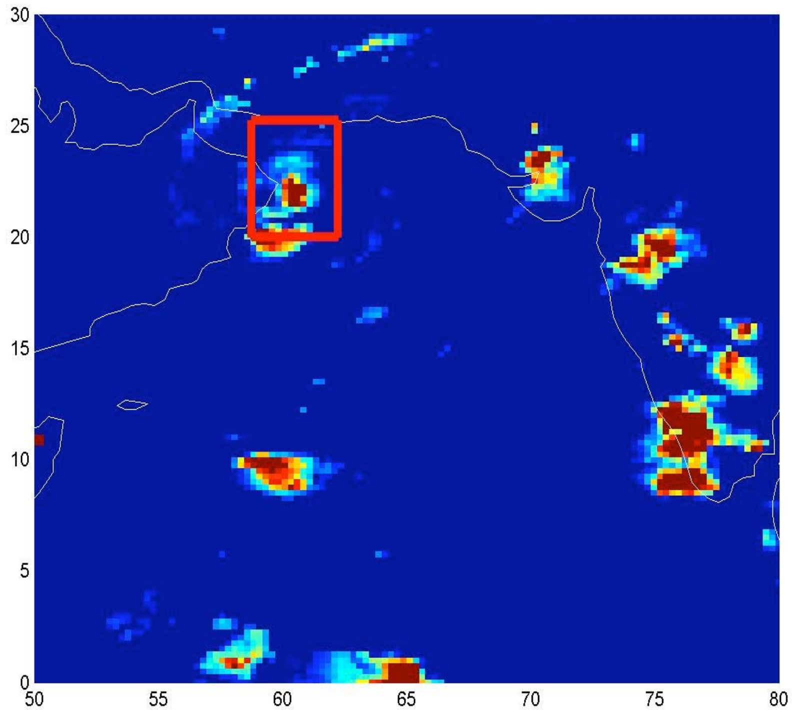

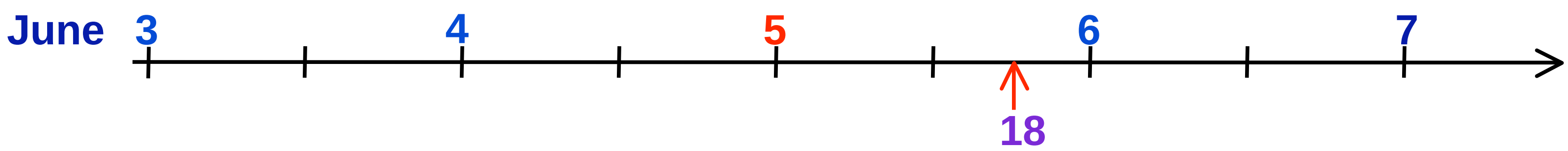
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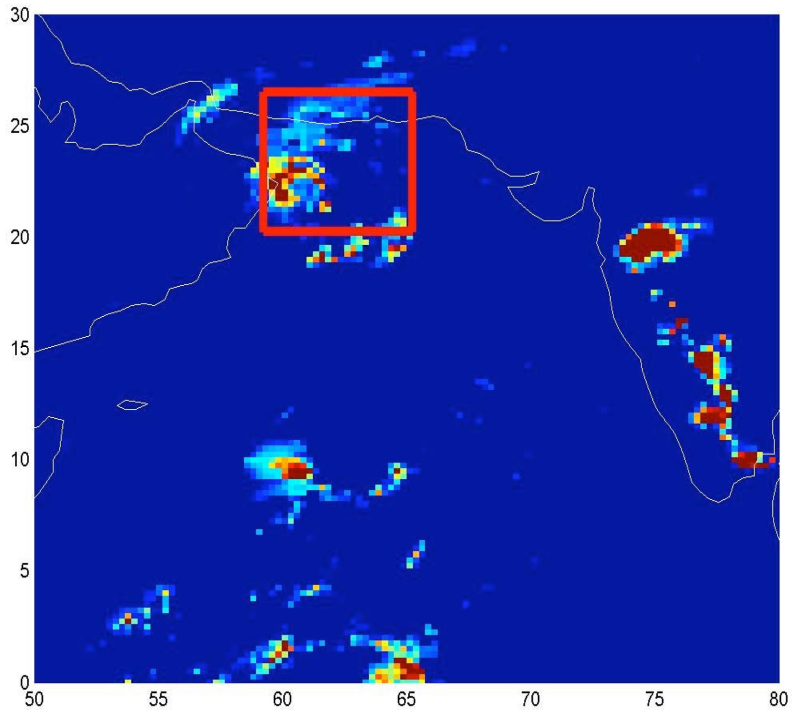
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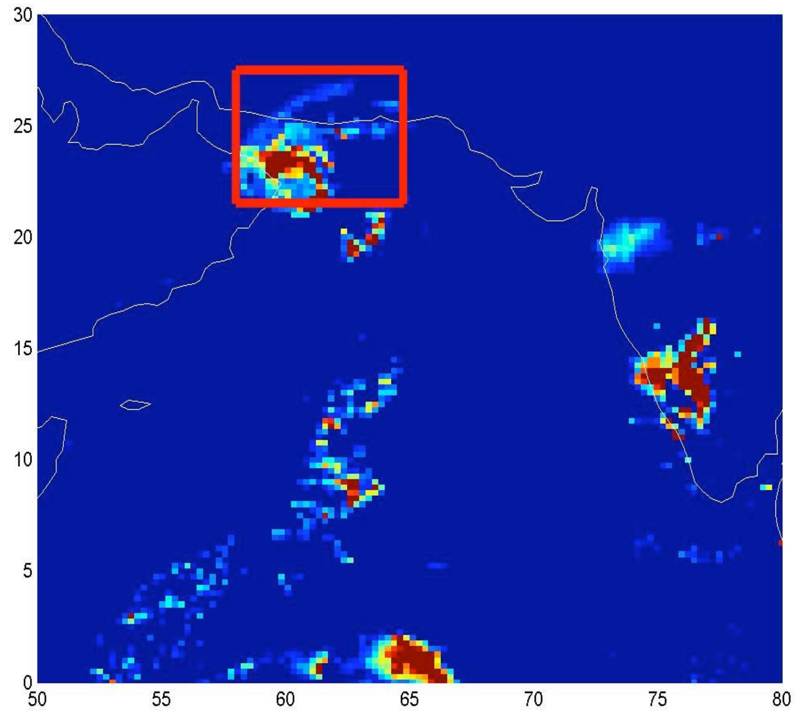

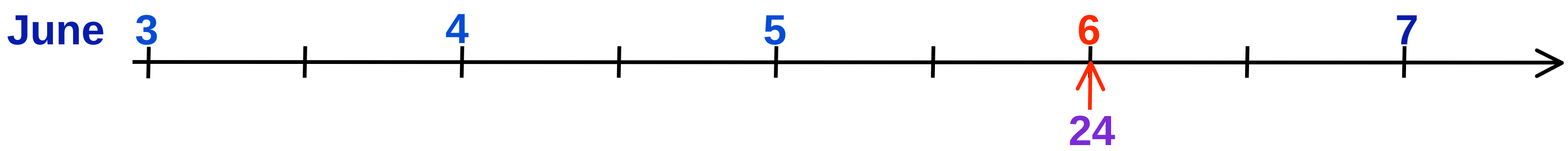

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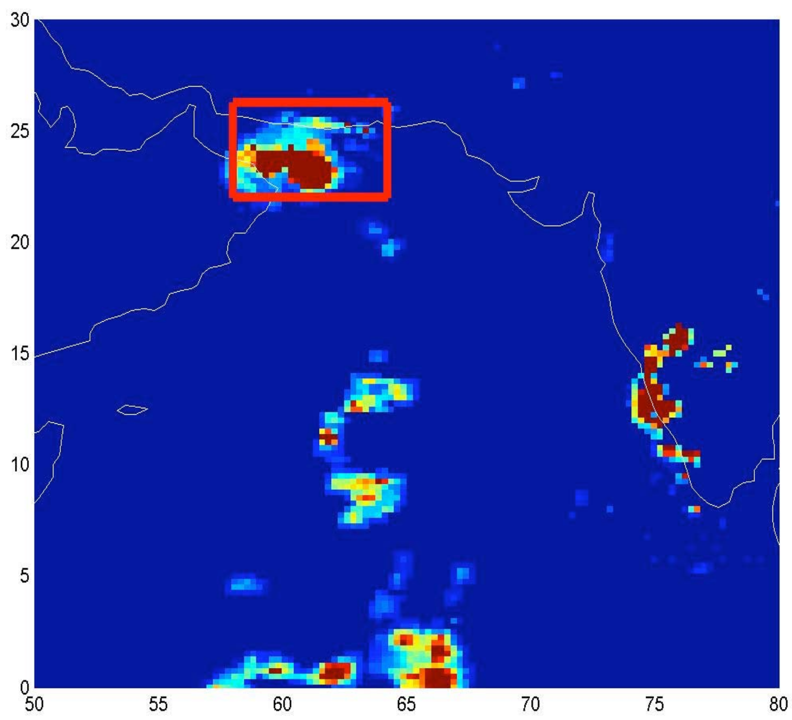

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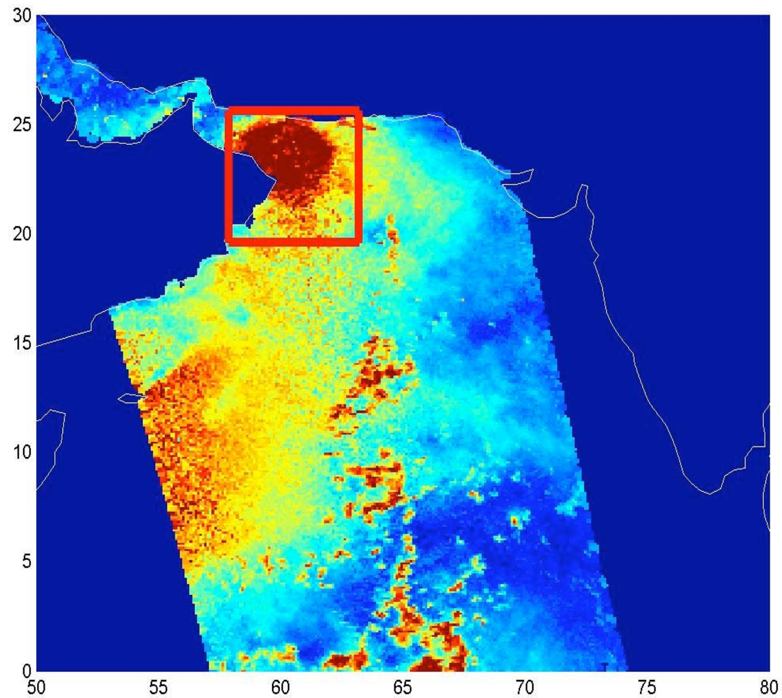

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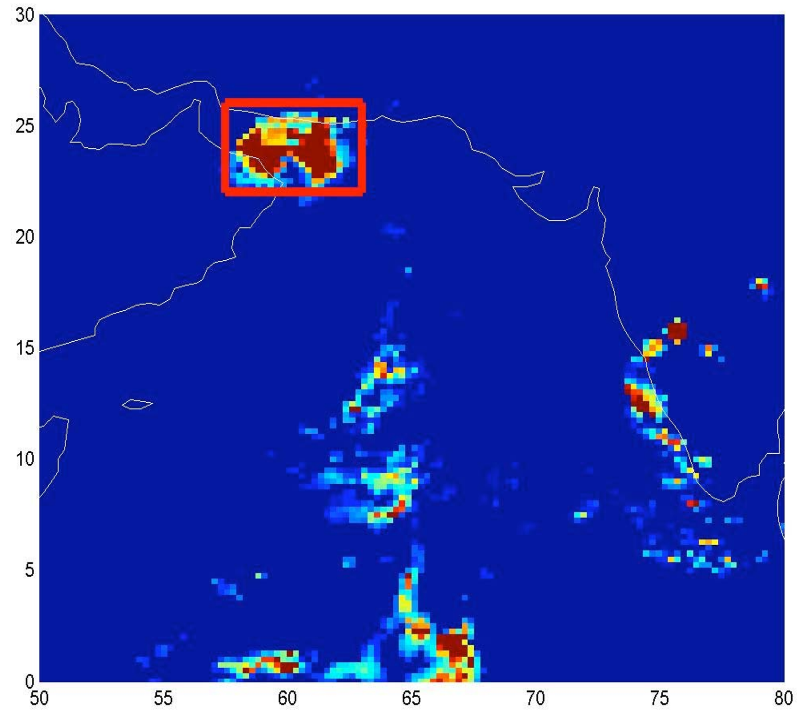

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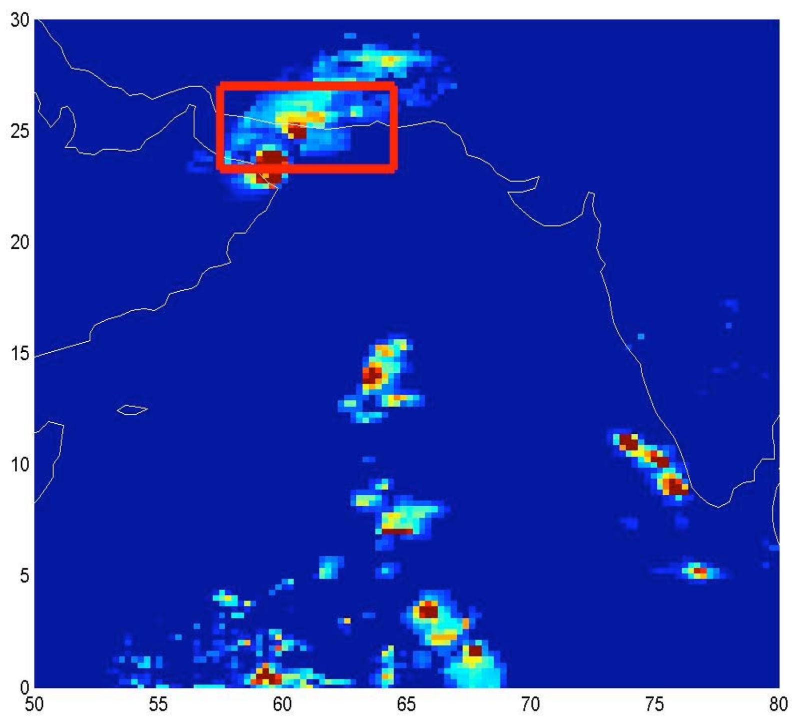

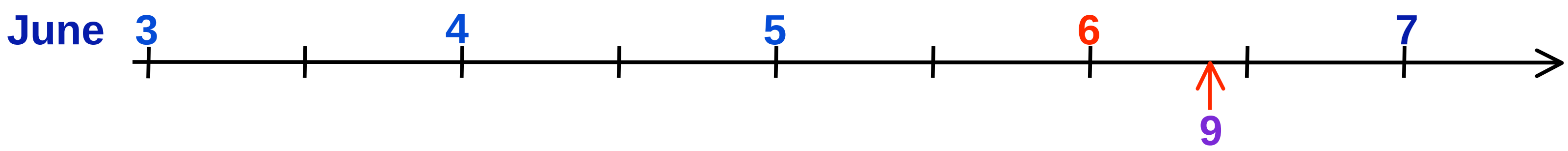
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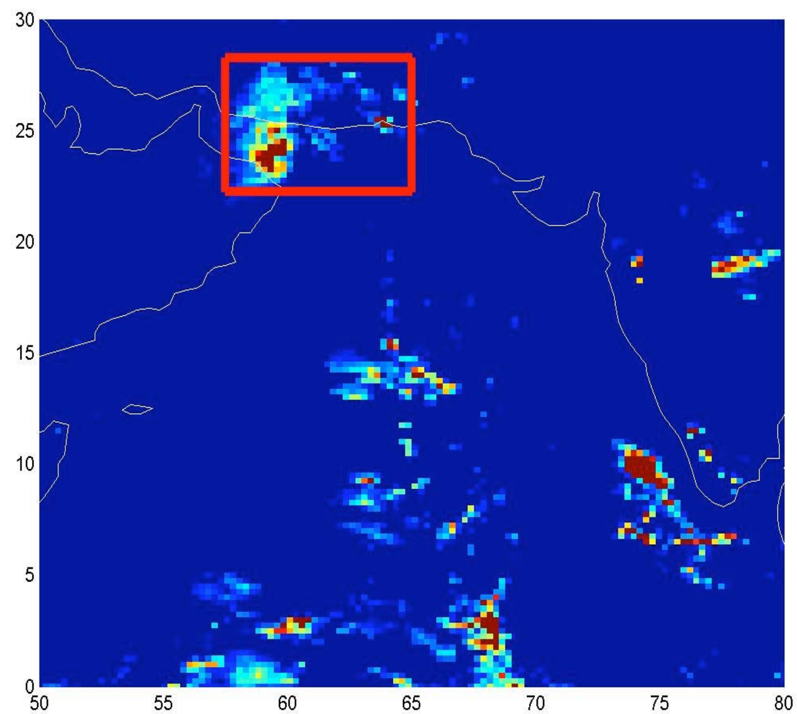
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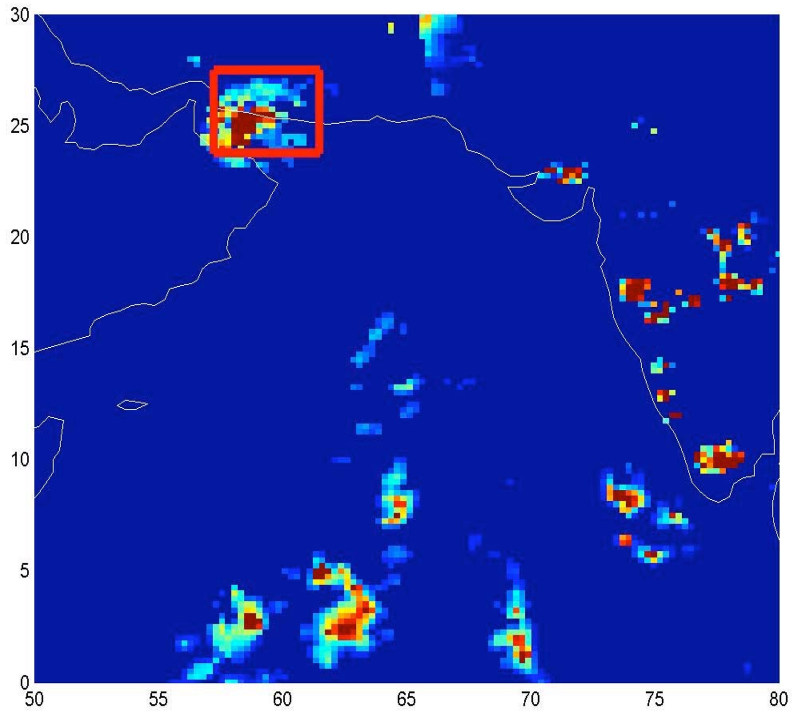

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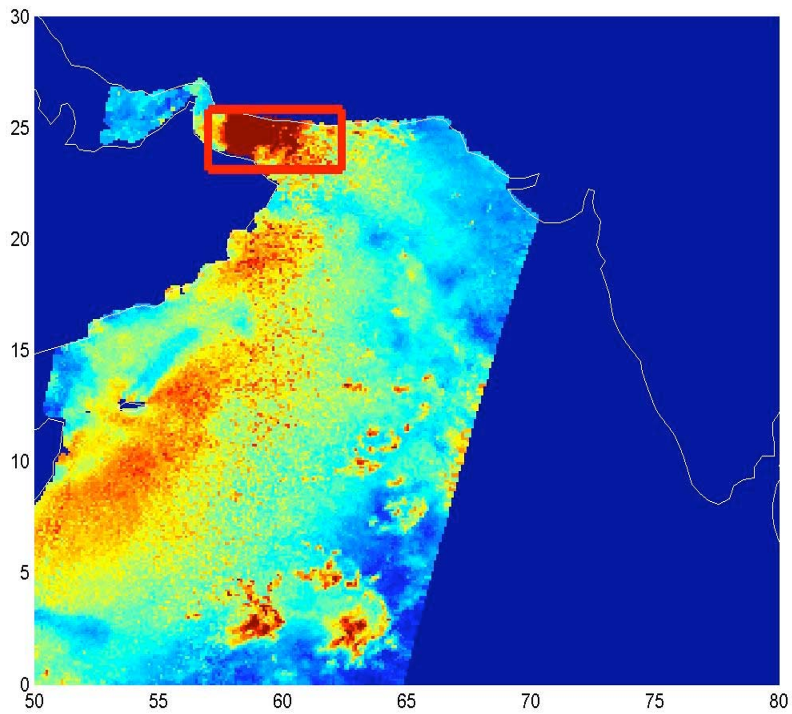

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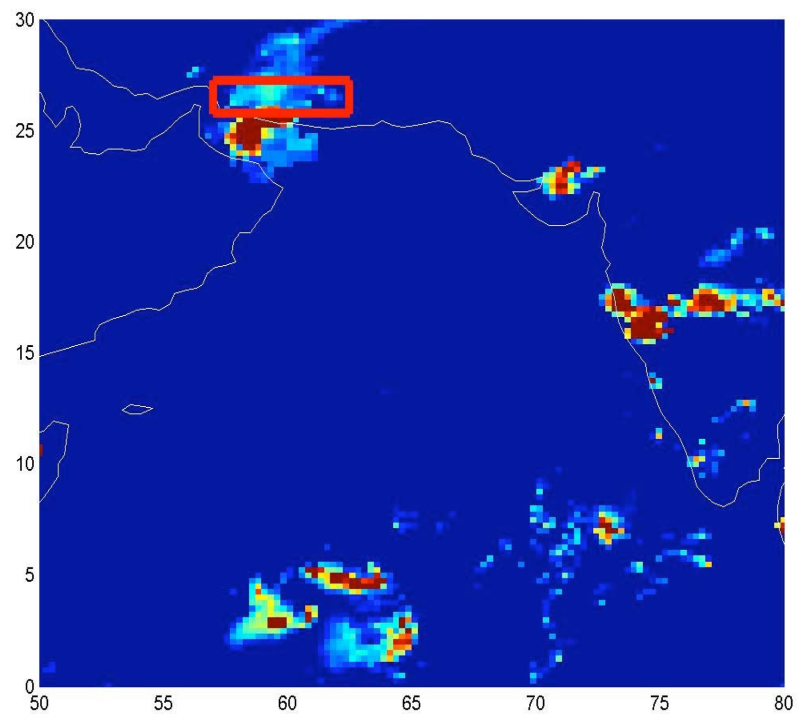

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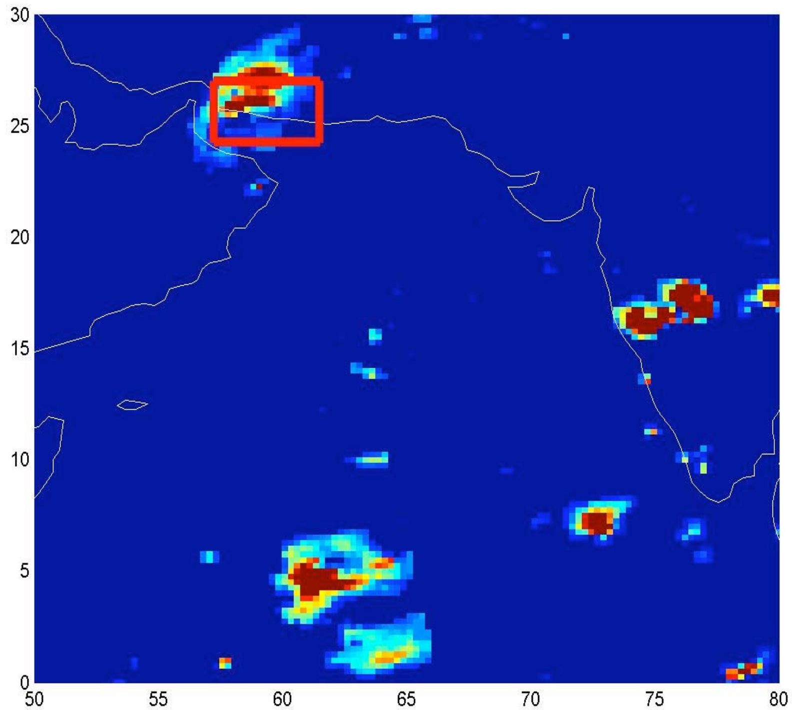

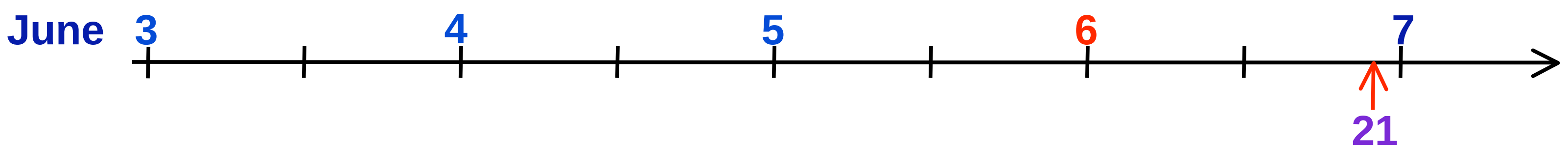
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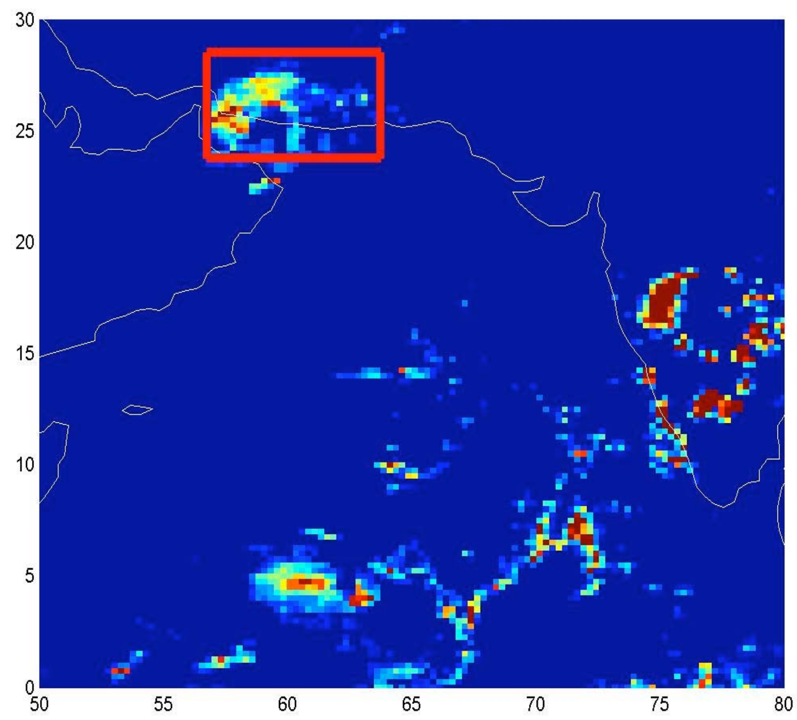
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GLYDER For Tropical Cyclogenesis Studies: Case Study

- Generally agreed requirements for cyclones to born and develop in tropics is:
  - Over warm water (SST>26^{o} C through an ocean depth of 60m or more) with sufficient ocean heat content to sustain hurricane's circulation through latent heat release;
  - Far enough from the Equator (~ > 4^{o} latitude) with a significant Coriolis effect so that the influence of the Earth's rotation be strong enough to initiate a cyclonic circulation;
  - Weak verticle wind shear (over the depth of troposphere is less than 10-15 m/s);
  - Preexisting cyclonic relative vorticity in the lower troposphere (e.g. easterly waves, the monsoon trough)

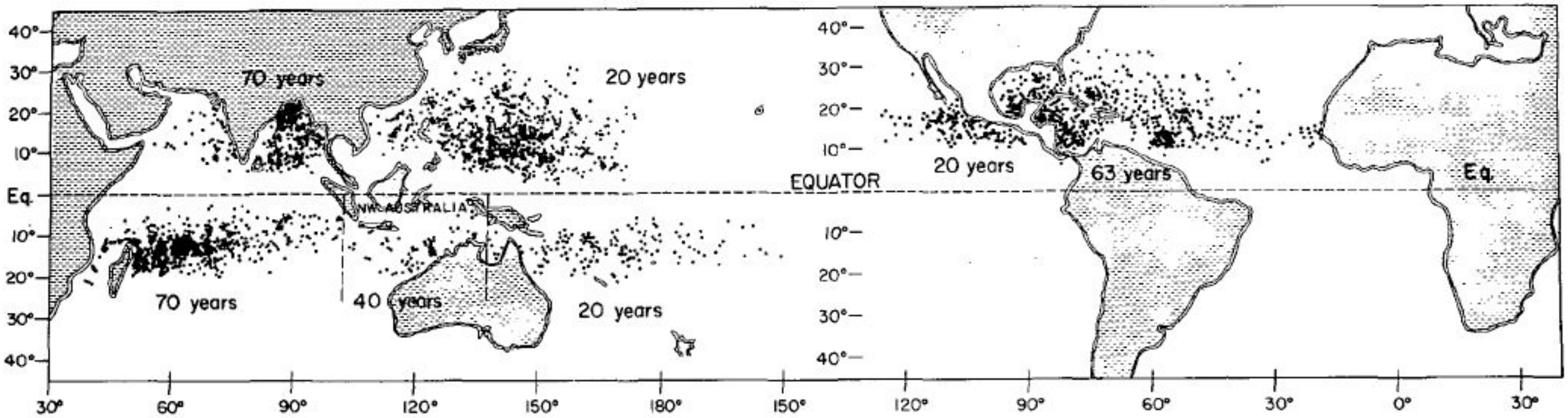

FIGURE 1.—Location points of first detection of disturbances which later became tropical storms.

Although tropical disturbances or mesoscale convective systems (MCS) occur frequently over tropical oceans, only a small percentage evolve into full-blown hurricanes. The mechanisms that either inhibit or favor development are still poorly understood

Significant Results and Events

- **Perl and Shell script automation of satellite data acquisition from remote servers**
  - **Earlier data extraction involved manually intensive process**
- **Validation of single sensor cyclone detection algorithm on full year (2005)**
- **Overall Results:**
  - **All 26 tropical cyclones reported by NHC are detected.**
  - **1 post-season NHC identified subtropical storm detected.**
  - **2 out of 3 tropical depressions (that did not develop further) reported by NHC are detected.**
  - **2 tropical cyclones detected 3 days before NHC reports**

Ongoing and Future Work

- Testing our implementation over longer time scale in a region that have multiple cyclone occurrences
- Assimilate information from other measurements (e.g. AVHRR, GOES)
- Statistical tracker for “reverse storm tracking” (cyclogenesis)
  - Yields multiple possible evolution paths of pre-storms and MCS when tracks are “weaker”
- Include TRMM 2B25 swath data to construct a vertical profile of reflectivity for cyclone detection
- Include TRMM 3B40RT gridded data with an hourly temporal resolution to improve quality and accuracy of cyclone tracking
- Explore “transfer learning” for cyclone detection
- Active learning for improved classifier design
- Integration with near real-time data streams
- Possible dissemination to wider science community
  - Beta-Test toolkit for cyclogenesis and early evolution of cyclones

Additional References

For additional reading, please refer to:

- Publications –
  - IEEE Aerospace Conference 2008 conference
  - Knowledge and Data Mining Conference 2008 – Industrial Track
  - AAAI Transfer Learning Workshop

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