



The Role of Partnerships in NASA's Research into Tropical Cyclones

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Overview: Type of Partnerships

■ Opportunities for Partnerships

- Satellite Missions
 - Missions in Operation
 - Missions in Development
- Field Campaigns
- Ground Networks
- Modeling and Analysis

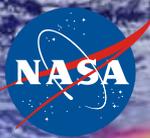
■ Types of Partnerships

- Interagency
- International
- Intra-agency
- With implementing communities (e.g., academia, industry)

NASA Earth Observing Satellite Fleet - 2012

- Launch-CY2011
- Launch-CY2012
- Launch-CY2013





Suomi-NPP Mission – launched 10/28/2011*

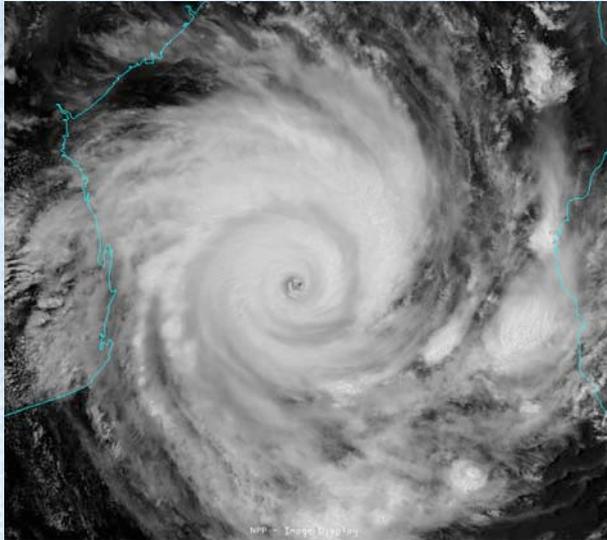


* Partnership is in its name

Tropical Cyclone Funso

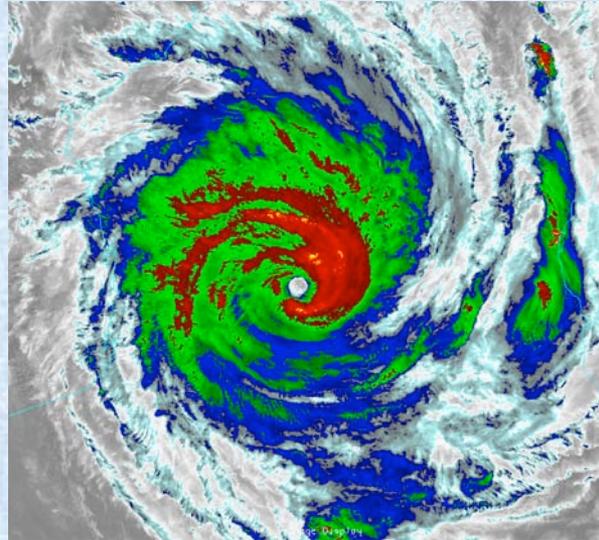
Tropical Cyclone Funso brought flooding rain to the coastal regions of Mozambique.

VIIRS Visible



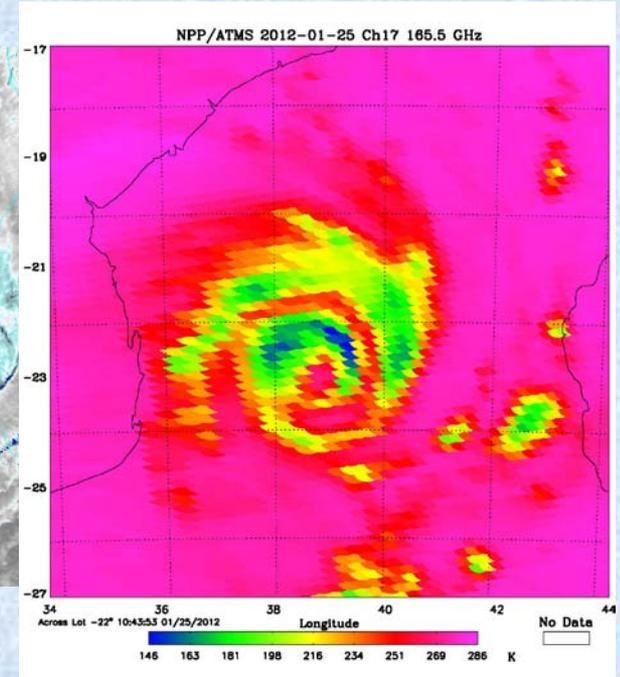
The coasts can be seen on either side of the storm. This VIIRS visible image of Tropical Cyclone Funso from January 25 2012 at 1043 UTC.

VIIRS Infrared



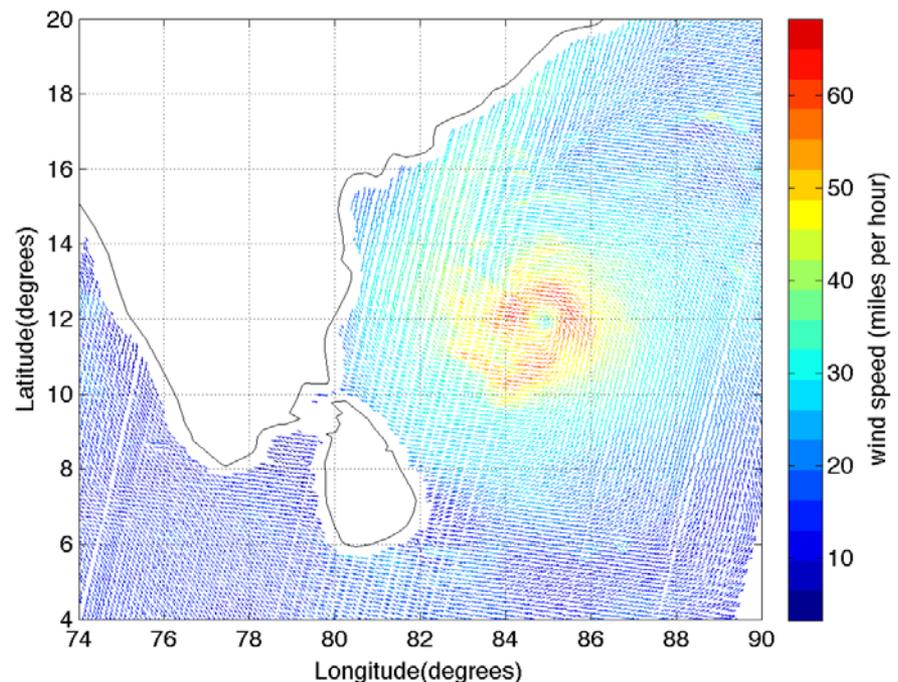
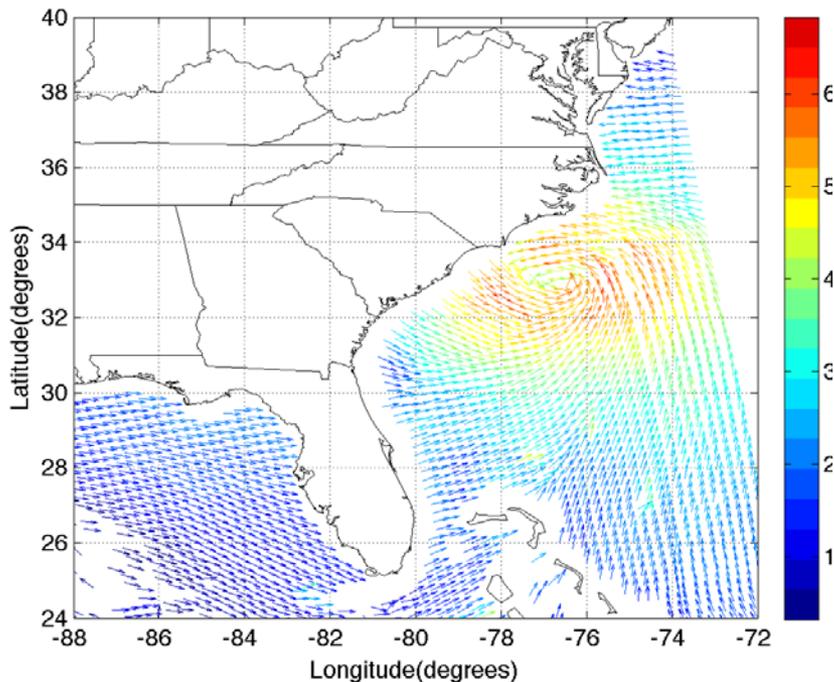
The clear eye and symmetric nature of the storm are indications that it's quite strong and well-organized. This VIIRS infrared view of Tropical Cyclone Funso on January 25 at 1043 UTC.

ATMS microwave



In all the ATMS Images, yellows, Greens, and blue indicate progressively Colder brightness Temperatures in the 165.5 GHz channel, Corresponding to Hydrometeors in the Towering cloud features Within the cyclone. In these images, these features are clearly Seen forming the circular bands Characteristic of cyclones.

OceanSAT-2 Tropical Cyclone Winds



- OceanSAT-2 flyover of Hurricane Irene, Aug 27, 2011.
- Radar backscatter produced by ISRO using initial calibration.
- Winds retrieved by NASA/JPL at 25 km resolution.
- No winds are retrieved in areas of low wind speed (e.g. southeast corner of image).

- OceanSAT-2 flyover of Cyclone Thane, Dec 28, 2011.
- Radar backscatter produced by ISRO using updated calibration.
- Winds retrieved by NASA/JPL at 12.5 km resolution, making use of improved calibration of high resolution “slice” backscatter measurements.
- Low wind areas improved.



GPM Constellation of Satellites

**GPM
Core Observatory
(NASA/JAXA)
2014**

**Suomi NPP
(NASA/NOAA)**

**MetOp B/C
(EUMETSAT)**

**Megha-Tropiques
(CNES/ISRO)**

**JPSS-1
(NOAA)**

**NOAA 19
(NOAA)**

**DMSP F19/F20
(DOD)**

**GCOM-W1
(JAXA, 2012)**



Next-Generation Unified Global Precipitation Products Using GPM Core Observatory as Reference

International Science Collaboration

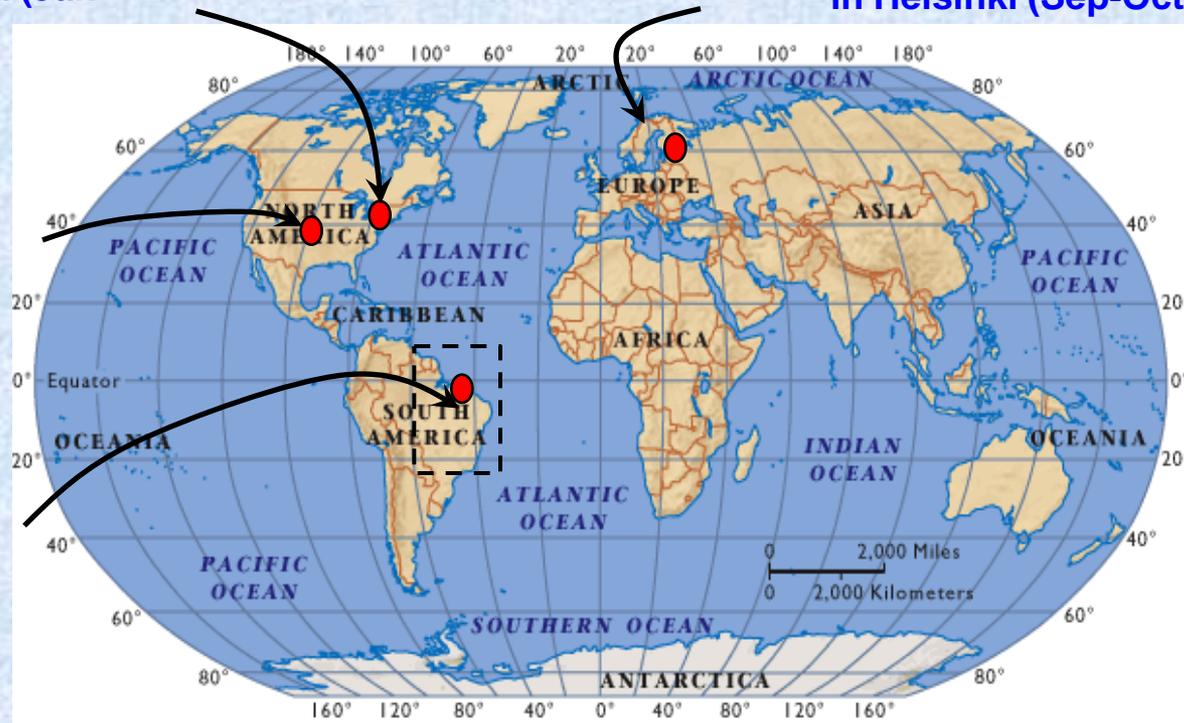
NASA has 21 active research projects with investigators from 19 countries to support satellite algorithm improvement and data evaluation including:

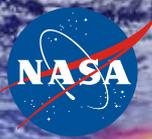
Joint Cold season snowfall field campaign with Environment Canada (Jan-Feb 2012)

Joint campaign with Finland and NASA's CloudSat mission on light rain in Helsinki (Sep-Oct 2010)

Joint campaign with U.S. Department of Energy on convective rain over land in Oklahoma, USA (Apr-Jun 2011)

Joint campaign with Brazil targeting warm rain in Alcântara, Brazil (Mar 2010)





NASA Hurricane Field Experiments

Field programs coordinated with other Federal Agencies

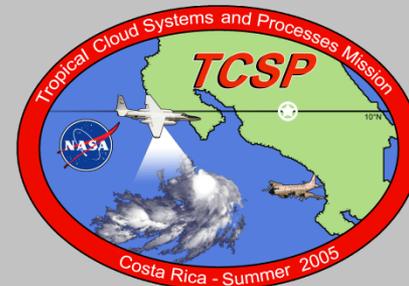
1998



2001



2005



2006



2010 GRIP



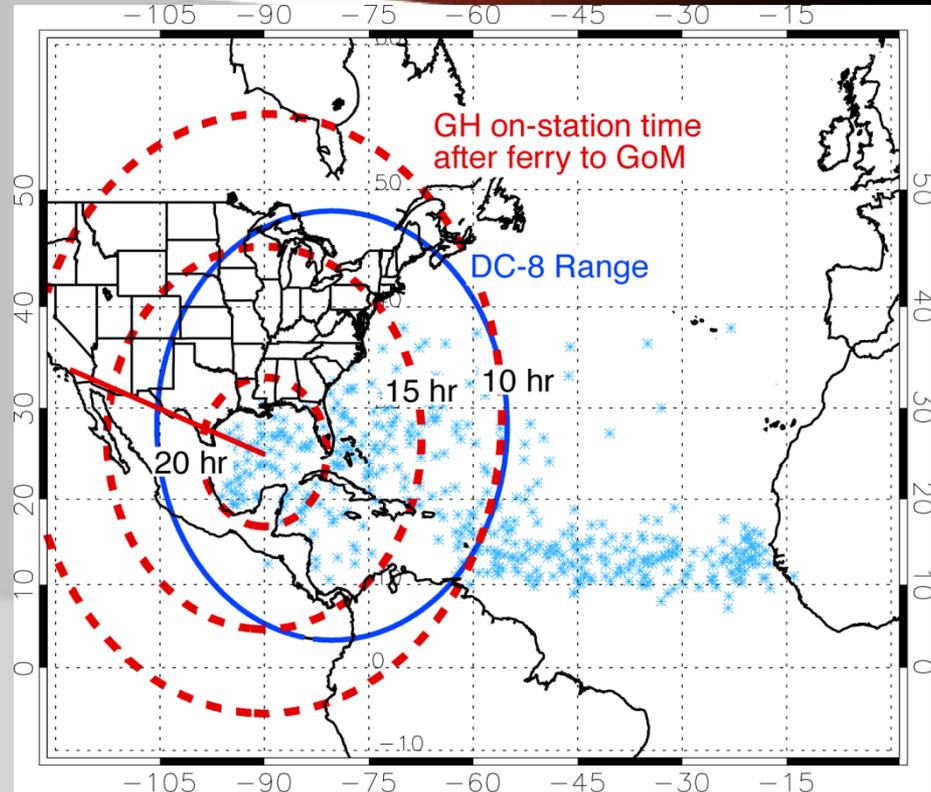
- **NASA sponsored field campaigns have helped us develop a better understanding of many hurricane properties including inner core dynamics, rapid intensification and genesis**



GRIP: (Hurricane) Genesis and Rapid Intensification Processes Field Experiment

- Global Hawk (UAV) (240 hours)
 - Radar (Heymsfield/GSFC), Microwave Radiometers (Lambrigtsen/JPL), Dropsondes (NOAA), Electric Field (Blakeslee/MSFC)
- Geosynchronous Orbit Simulation
- DC-8 four engine jet (120 hours)
 - Dual frequency precipitation radar (Durden/JPL)
 - Dropsondes (Halverson/UMBC), Variety of microphysics probes (Heymsfield/NCAR)
 - Lidars for 3-D Winds (Kavaya/LaRC) and for high vertical resolution measurements of aerosols and water vapor (Ismail/LaRC)
 - In-situ measurements of temperature, moisture and aerosols (Bui/ARC)
- WB-57 (60 hours, funded by NOAA)
 - Advanced Microwave Precipitation Radiometer
 - Hurricane Imaging Radiometer
- Six to Eight week deployment centered on September 1, 2010

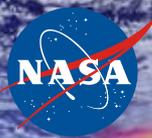
RED= IIP, GREEN= IIP+AITT



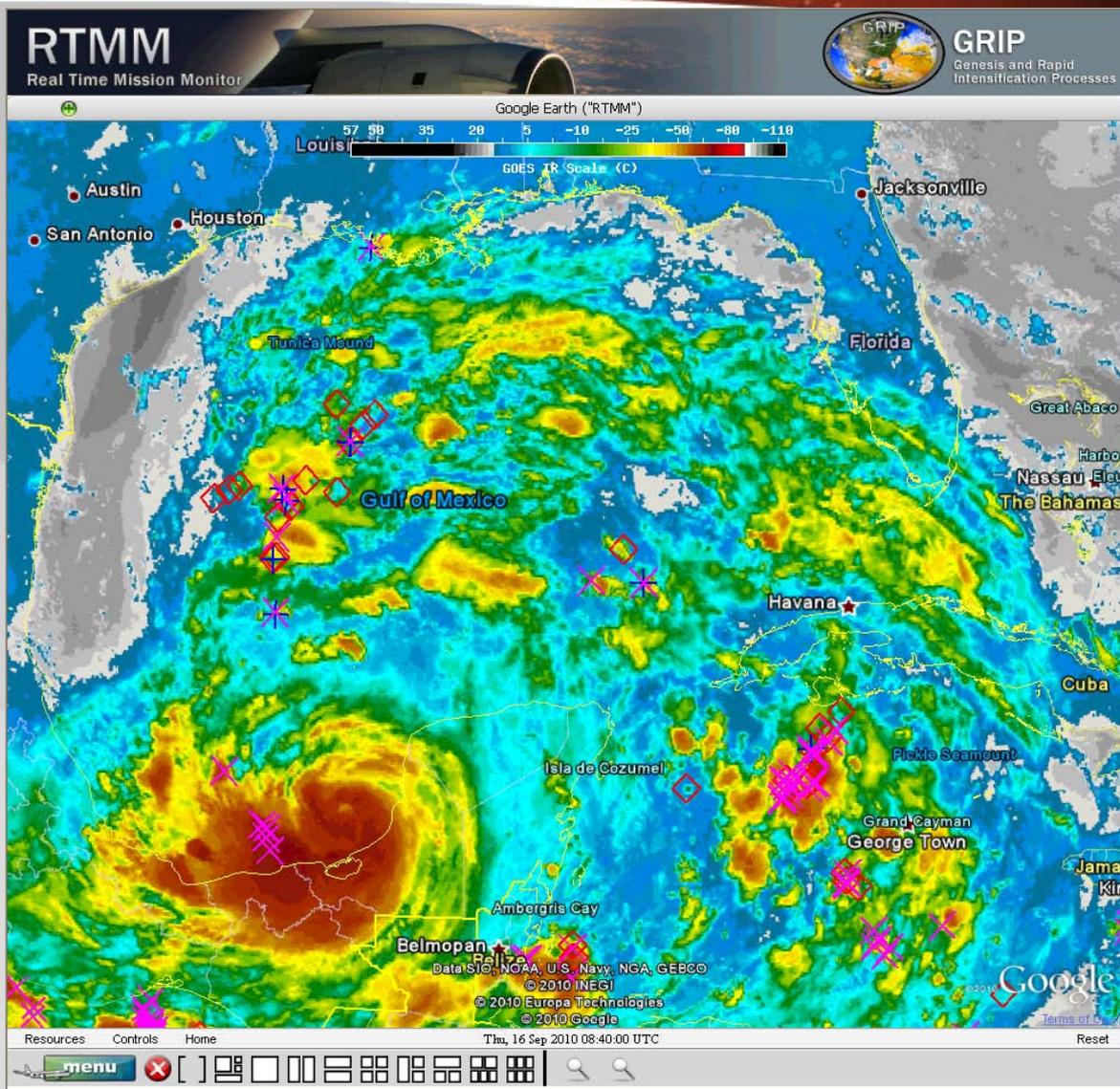
Blue line: DC-8 range for 12-h flight, 6 h on station

Red lines: GH range for 30-h flight with 10, 15 and 20 h on station

Light blue X: Genesis locations for 1940-2006



Integrated Airborne Observations of Hurricane Karl During GRIP



ESTO Technologies Providing Support to the 2010 GRIP Campaign



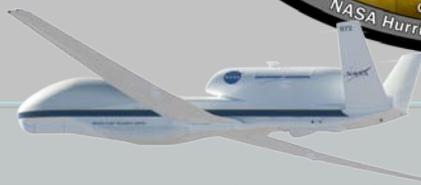
DC-8

- The Doppler Aerosol WiNd lidar (DAWN) is a 2-micron doppler lidar that can take vertical profiles of vectored horizontal winds. *(Principal Investigator: Michael Kavaya, NASA LaRC, IIP-04/IIP-07)*
- The Airborne Second Generation Precipitation Radar (APR-2) is an advanced radar system that obtained the first-ever simultaneous measurements of rain intensity and fall velocity profiles during the 4th Convection and Moisture Experiment (CAMEX-4) in 2001. *(Principal Investigator: Eastwood Im, JPL, IIP-98)*



WB-57

- The Hurricane Imaging Radiometer (HIRAD) instrument on board the WB-57 includes an ESTO-funded Agile Digital Detector (ADD) for Radio Frequency Interference (RFI) Detection and Mitigation system that can produce clearer microwave measurements, particularly over populated areas where wireless communications can crowd the spectrum. *(Principal Investigator: Chris Ruf, University of Michigan, IIP-04)*



Global Hawk

- The High-Altitude MMIC Sounding Radiometer (HAMSR) is a microwave atmospheric sounder that provides measurements that can be used to infer the 3-D distribution of temperature, water vapor, and liquid water in the atmosphere, even in the presence of clouds. *(Principal Investigator: Bjorn Lambrigtsen, JPL, IIP-98)*
- The High-Altitude Imaging Wind and Rain Airborne Profiler (HIWRAP) is a dual-frequency doppler radar capable of measuring tropospheric winds within precipitation regions as well as ocean surface winds in rain-free to light rain regions. *(Principal Investigator: Gerald Heymsfield, NASA GSFC, IIP-07)*

Support

- The Real Time Mission Monitor (RTMM) is a situational awareness tool that integrates satellite, airborne and surface data sets; weather information; model and forecast outputs; and vehicle state data (e.g., aircraft navigation, satellite tracks and instrument field-of-views) for field experiment management. RTMM will optimize science and logistic decision-making during the GRIP campaign by presenting timely data, graphics and visualizations that improve real time situational awareness of the experiment's assets. *(Principal Investigator: Michael Goodman, MSFC, AIST-08)*





Hurricane and Severe Storm Sentinel (HS3)

Application of the Global Hawk for Hurricane Studies

PI: Scott A. Braun (GSFC)



Science Goal:

To understand hurricane genesis and intensification.

Key Science Questions:

- How do hurricanes form?
- What causes rapid intensity changes?
- What is the role of deep convective cores in intensification?
- What's the role of the Saharan Air Layer?

Deployment Details:

- Deployments during hurricane seasons of 2012-2014
- Based at NASA's Wallops Flight Facility in Virginia
- 275 science flight hours (~10-11 26-hour flights) per deployment

Two Global Hawk (GH) aircraft

Environment GH instrumentation

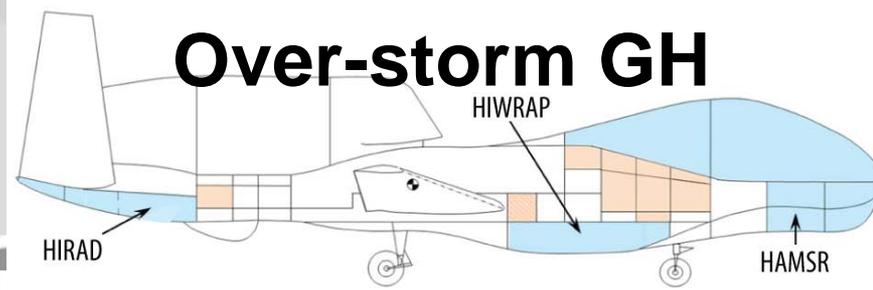
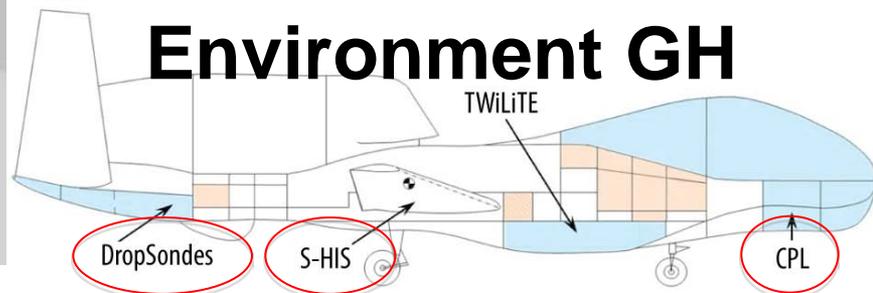
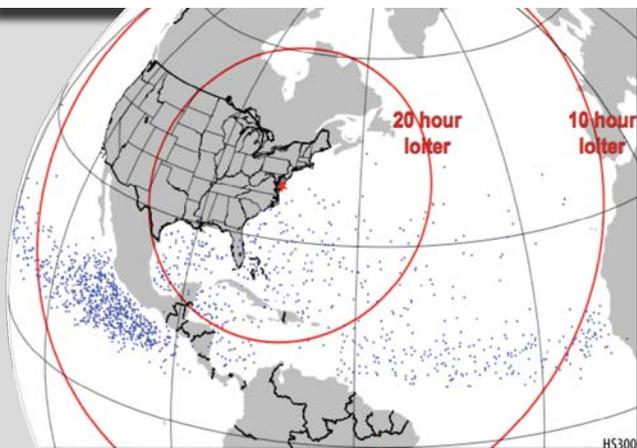
- TWiLiTE (direct detection wind lidar)
- CPL (cloud & aerosol lidar)
- Scanning HIS (T, RH)
- Dropsondes (wind, T, RH)

Sensors relevant to the A-Train

Over-storm GH instrumentation

- HIWRAP (3-D prep. + 3D winds + sfc winds)
- HIRAD (sfc winds and rain)
- HAMSR (T, RH, hydrometeor profiles)

Genesis Locations and Loiter Times



International GV Science Collaboration

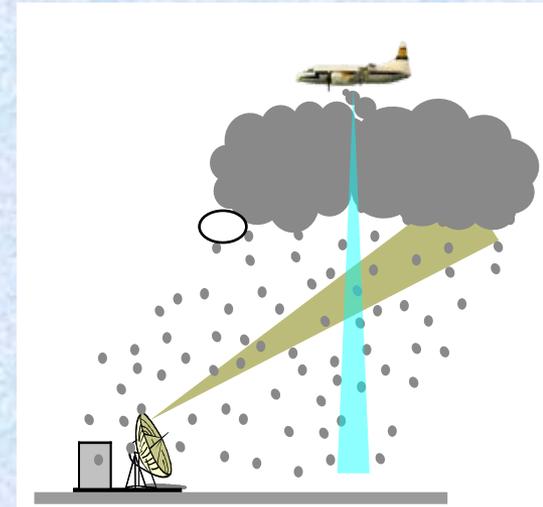
- *Direct statistical validation (surface)*
- *Precipitation physics validation (vertical column)*
- *Integrated science validation (4-dimensional)*

Active Projects

- Argentina (U. Buenos Aires)
 - Australia (BOM)
 - Brazil (INPE)
 - Canada (EC)
 - Ethiopia (AAU)
 - Finland (FMI)
 - France (CNRS)
 - India (ISRO)
 - Germany (U. Bonn)
- Israel (Hebrew U. Jerusalem)
 - Italy (CNR-ISAC)
- Italy (Sapienza U. Rome)
 - South Korea (KMA)
 - Spain (UCLM)
 - United Kingdom (U. Birmingham)

Proposals in Development

- Cyprus (CMS)
- Germany (MPI)
- Spain (Barcelona)
 - Taiwan



Through No-Cost Proposals to NASA
PMM Science Program

Finnish Meteorological Institute hosted the 4th International GPM GV Workshop on June 21-23 2010 in Helsinki



Modeling, Analysis, and Utilization

Coupling **A**dvanced Multi-Scale **M**odeling and Concurrent **V**isualization (CAMVis) weather prediction tool is developed to achieve the following goals by seamlessly integrating NASA technologies (including advanced multiscale modeling visualizations and supercomputing):

1. to inter-compare satellite observations (e.g., TRMM precipitation and QuikSCAT winds), field campaigns (e.g. Grip, HS3) and model simulations at fine resolution, aimed at improving understanding of consistency of satellite-derived fields;
2. to improve the insightful understanding of the roles of atmospheric moist thermodynamic processes and cloud-radiation-aerosol interactions with high temporal and spatial-resolution 3D visualizations;
3. to improve real-time prediction of high-impact tropical weather at different scales.

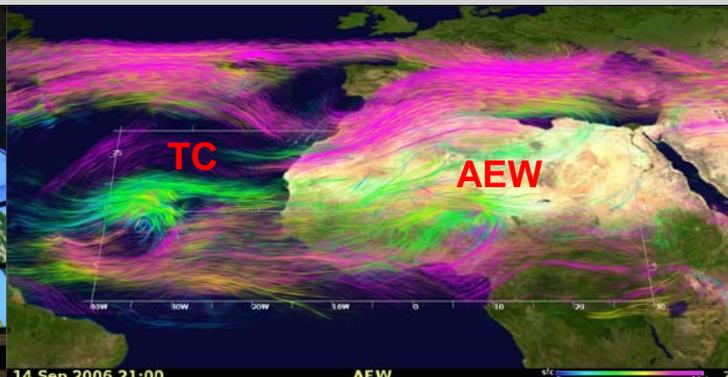
Project CAMVis has the potential for supporting the following NRC Decadal Survey Earth Science missions: ACE, XOVWM, PATH, SMAP, 3D-Winds.



Supercomputing

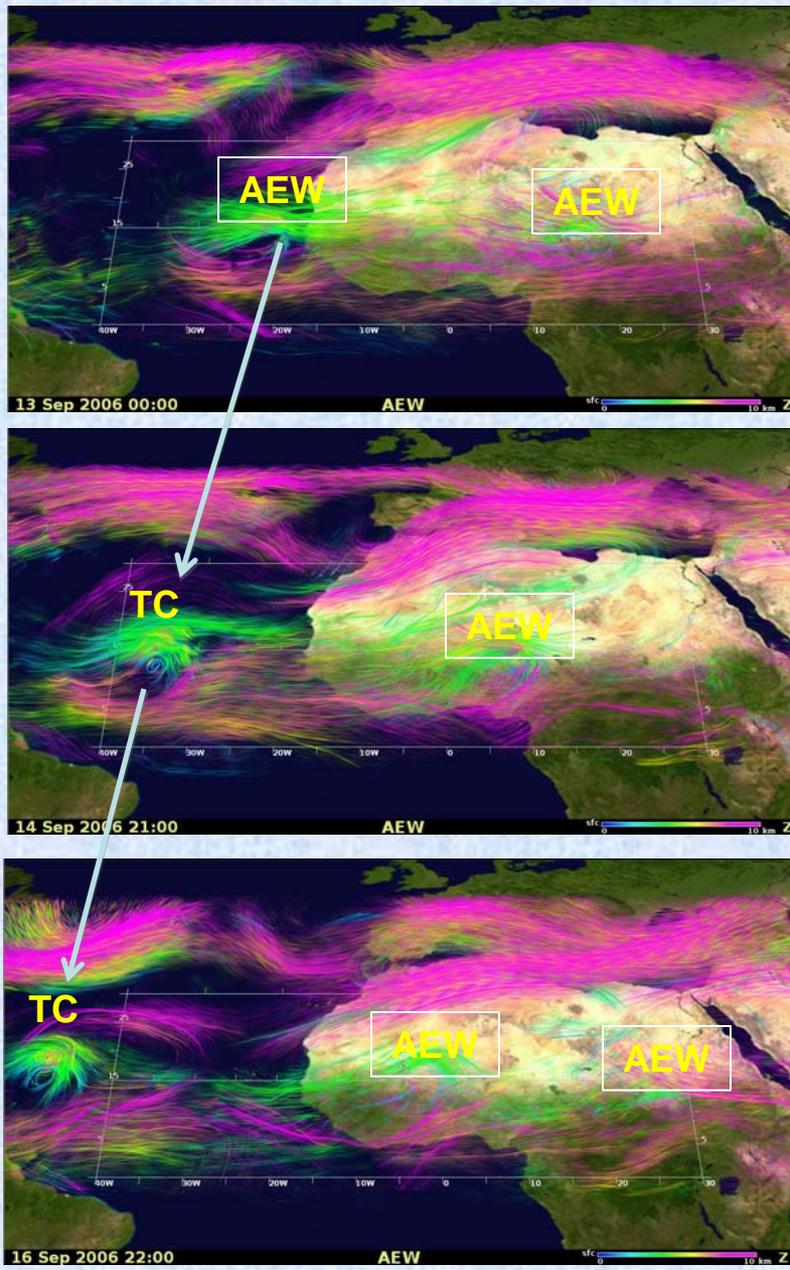


Visualization



Modeling and Analysis

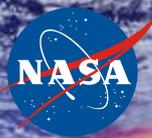
Modeled formation of Hurricane Helene



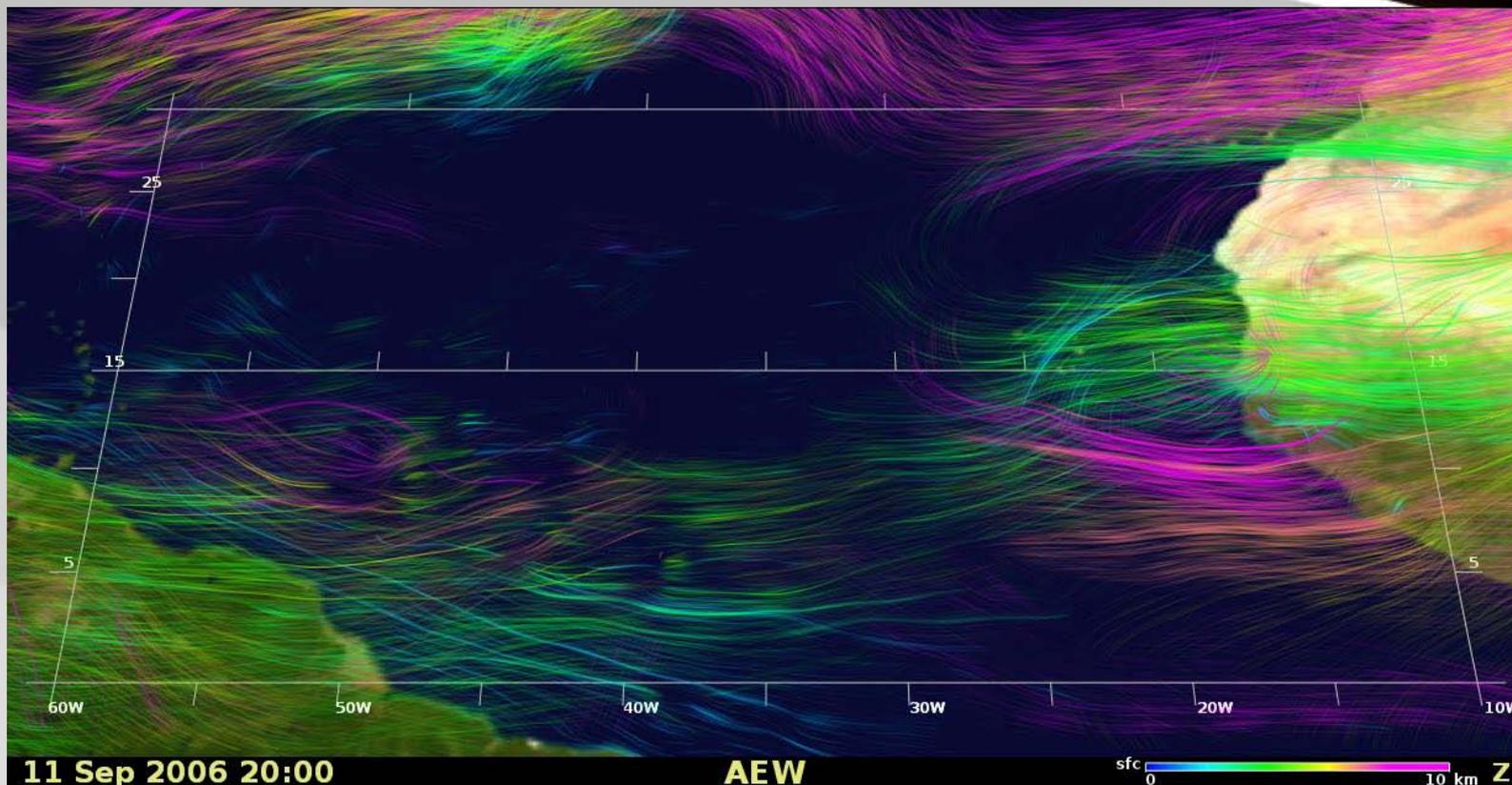
- Upper-level winds in pink
- Middle-level winds in green
- Low-level winds in blue

Left Figure: Formation of Hurricane Helene (2006) and its association with the intensification of an African Easterly Wave (AEW) in a 30-day run initialized at 0000 UTC August 22, 2006. Upper-level winds are in pink, middle-level winds in green and low-level winds in blue. (a) Initial formation of Helene as the AEW moves into the ocean, validated at 0000 UTC Sep. 13 (day 22); (b) initial intensification associated with intensified low-level inflow with counter clockwise circulation, validated at 2100 UTC Sep. 14; (c) further intensification with an enhanced outflow with clockwise circulation (indicated in pink), validated at 2200 UTC Sep. 16. An animation can be found:

<http://tiny.cc/i9uI9>



NAMMA significantly improved our understanding in Hurricane Genesis. What Can We Expect in the next 10 years?



- Theory on scale interactions during hurricane genesis is established: Shen, B.-W. W.-K. Tao and M.-L. Wu, 2010b: African Easterly Waves in 30-day High-resolution Global Simulations: A Case Study during the 2006 NAMMA Period. Geophys. Res. Lett., L18803
 - The theory dramatically increases the predictability in hurricane forecast.



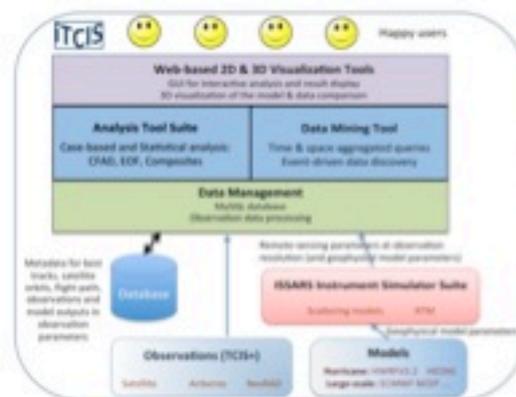
Fusion of hurricane models and observations: Developing the technology to improve the forecasts

PI: Svetla Hristova-Veleva / JPL

Objective

To develop the technology to provide the fusion of observations and operational model simulations to help improve the understanding and forecasting of the hurricane processes. Specifically,

- To develop processing techniques to enable multi-source data fusion across hurricane forecast models, satellite data, and *in-situ* sensors,
- To develop tools to manage the validation and assessment of model comparisons to more easily evaluate the performance of different numerical models,
- To develop interactive visualization techniques to enable analysis of highly complex systems.



Existing Google Earth API-based Integrated Data Analysis System

Approach:

Integration of the ISSARS instrument simulator with operational hurricane forecast models and incorporation of simulated satellite observables into the existing database of satellite and airborne observations

Development of a set of advanced analysis tools

Development of data immersion to enable real-time interaction with the models, and visualization of highly complex systems

CoIs: P. Li, B. Knosp, J. Turk, S. Tanelli, B. Lambrigtsen, Q. Vu (JPL); R. Rogers, S. Gopalakrishnan, F. Marks, T. Vukicevic, V. Tallapragada (NOAA)

Key Milestones

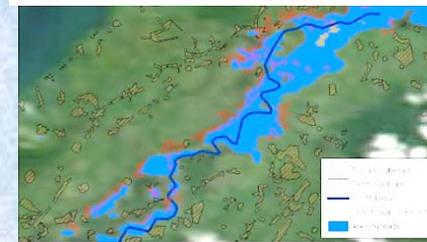
- | | |
|-------------------------------------|---------|
| • ISSARS - readers for models | 10/2012 |
| • Visualization of airborne data | 04/2013 |
| • Inclusion of all satellite data | 04/2014 |
| • Database finalized | 10/2014 |
| • Analysis tools finalized | 04/2015 |
| • Completion of technology infusion | 04/2016 |

TRL_{in} = 3

Number of direct hurricane and tropical storm strikes per municipality in Central America



Flooded areas due to Tropical Storm Agatha, May 2010

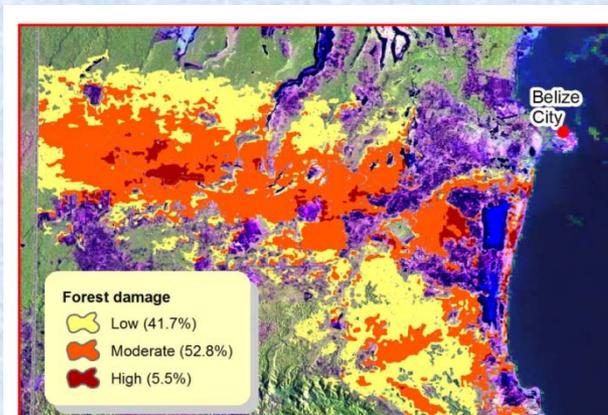


before

**MODIS images
Izabal,
Guatemala**

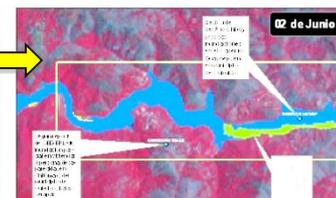
after

Estimated forest damage caused by Hurricane Richard, October 2010



Combination of ALOS PALSAR radar images with optical images from NASA's MODIS sensor, *Central Belize*

ASTER images, *Rio Chixoy, Guatemala*



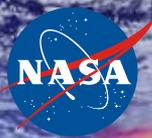
before

after



Summary

- Partnerships are central to NASA's efforts in advancing the science associated with tropical cyclones
- Partnerships cross organizational boundaries within NASA, across agencies (domestically and internationally), and with partners in program implementation
- Partnerships include those associated with satellites, field campaigns, surface-measurement networks, and modeling/analysis/utilization
- NASA's involvement in relevant partnerships is expected to continue into the future



Backup

■ XXX

GRIP Accomplishments

Scientific Accomplishments

Tropical Cyclone Genesis

- Tropical Storm Gaston— a “null” case for development
- Hurricane Karl— unprecedented multiday coverage from first detection through genesis

Rapid Intensification

- Hurricane Earl— documentation of rapid intensification as well as weakening of a large Category 5 storm
- Hurricane Karl— observations of rapid intensification from storm stage to Category 3 and landfall

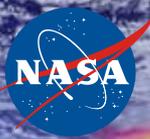
Technical Accomplishments

Hurricane Earl

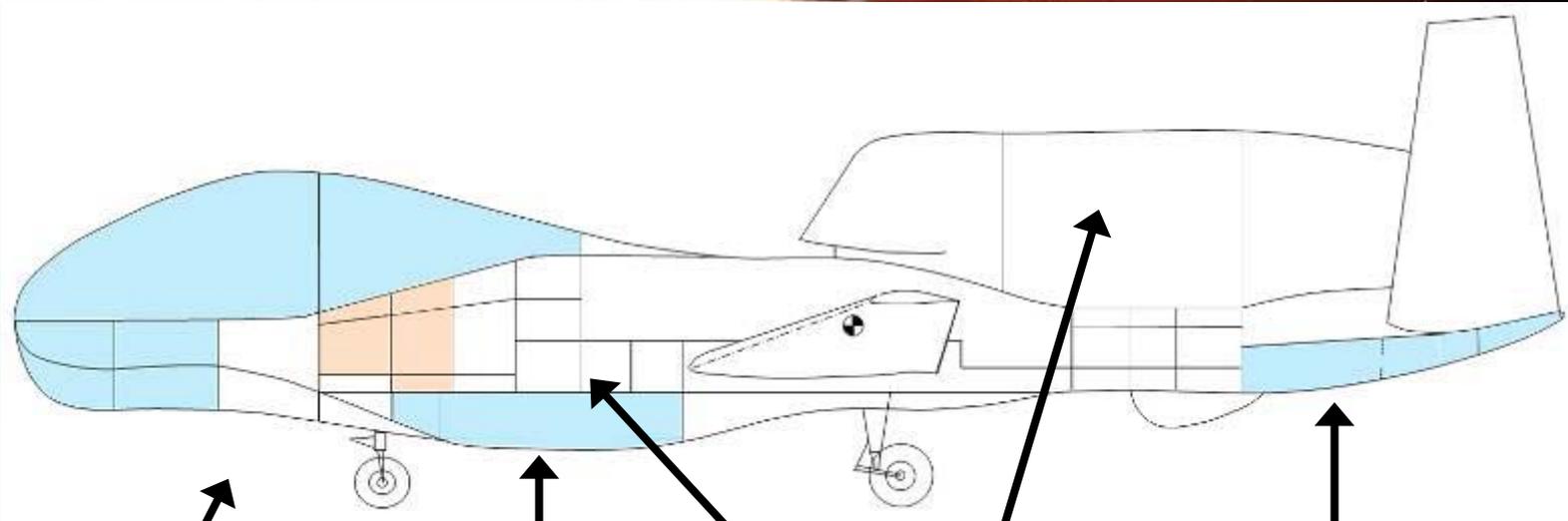
- First Global Hawk flight over a hurricane

Hurricane Karl

- 20 crossings of eye of Hurricane Karl by Global Hawk
- Close flight coordination of:
 - Global Hawk
 - DC-8
 - WB-57
 - NOAA G-IV & P-3's
 - NCAR G-V, and
 - Air Force C-130J's



GRIP GH Payload



HAMSR

High Altitude MMIC
Sounding Radiometer
(Temp, H₂O_v, Cloud liquid
& ice distribution)

HIWRAP

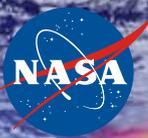
High Altitude Imaging
Wind and Rain Profiler
(Horizontal wind
vectors and ocean
surface winds)

LIP

Lightning Instrument
Package
(Lightning and
Electrical Storm
observation)

Driftsondes

High Altitude Lightweight
Dropsonde
(Vertical profiles of temp,
humidity, pressure &
winds)



GRIP DC-8 Payload



Dropsondes
(Vertical Profiles of
Temp, Press,
Humidity and Winds)

CAPS, CVI, PIP
(Cloud Particle Size
distributions, Precip
Rate, Rain & Ice water
content)

LASE
Lidar Atmospheric
Sensing
Experiment
(H₂O_v, Aerosol
profiles and Cloud
distributions)

DAWN
Doppler Aerosol
Wind Lidar
(Vertical Profiles of
Vectored Horizontal
Winds)

APR-2
Airborne Precipitation
Radar Dual Frequency
(Vertical Structure Rain
Reflectivity and Cross
Winds)

MMS
Meteorological
Measurement System
(Insitu Press, Temp, 3D
Winds and Turbulence)



OceanSAT-2 Tropical Cyclone Winds

- OceanSAT-2 is a 13.4 GHz ocean wind scatterometer operated by the Indian Space Research Organization (ISRO).
- For the past two years ISRO has been collaborating with NASA/JPL and NOAA to refine the calibration of the OceanSAT-2 backscatter data.
- The goal of the collaboration is to extend the Ku-band scatterometer wind data record initiated by QuikSCAT.
- A crucial element of this effort has been the repointing of the QuikSCAT instrument to match the OceanSAT-2 viewing geometry.
- Although QuikSCAT ceased nominal operations in November 2009, its precisely calibrated backscatter measurements remain useful for cross-platform calibration.
- To date the ISRO/NASA/NOAA collaboration has resulted in:
 - More robust wind retrieval in low wind areas.
 - Absolute backscatter calibration tuned to match QuikSCAT data within 0.1 dB.
 - Improved wind accuracy as compared to numerical wind products and buoys.
 - Ongoing monitoring of calibration drift by comparison between QuikSCAT and OceanSAT-2 backscatter values.
- The fruitfulness of the collaboration is further illustrated by the tropical cyclone winds on the next slide.
 - The OceanSAT-2 operational wind product is binned at 50 km with a conservative land mask employed to insure accurate winds.
 - JPL has retrieved winds at higher resolutions and closer to the coast.
 - Cases are shown before and after calibration improvements.

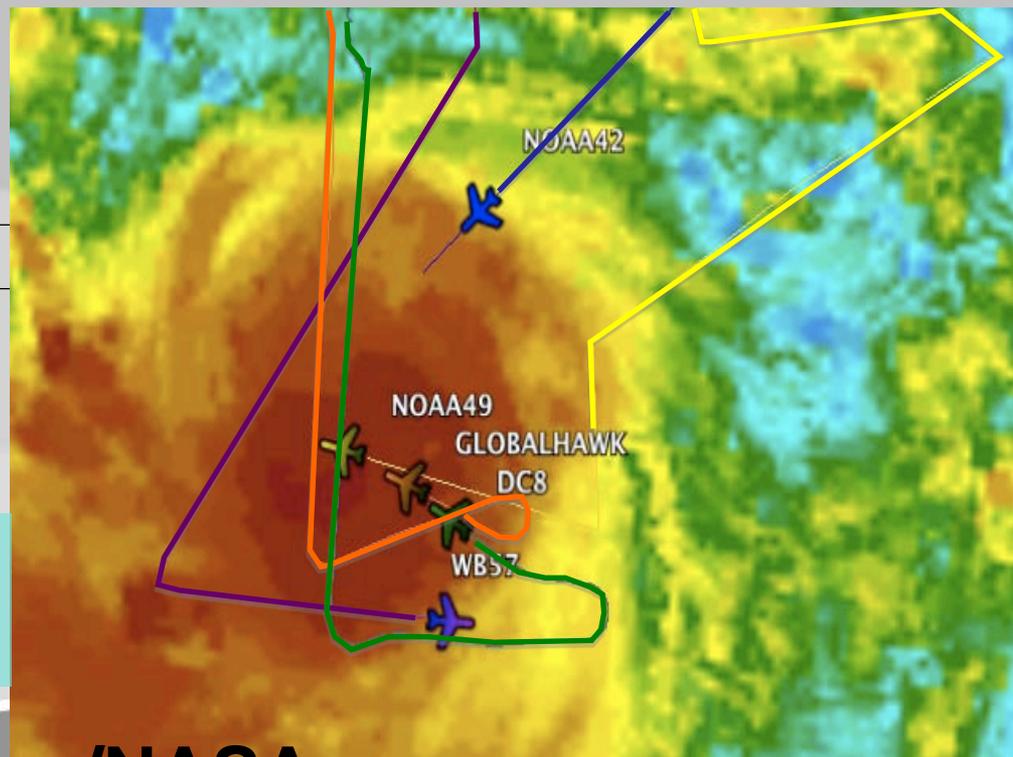


NASA Aircraft Hours and GRIP Coordination



WB-

Storm	GH	DC-8	57	NOAA	NSF	AF
Frank	15.3	0	0	N	N	N
Earl	24.2	39.3	10.9	Y	Y	Y
Gaston	0	14.5	0	N	Y	N
Karl	48.5	40.2	17.5	Y	Y	Y
Matthew	25.1	17.8	0	Y	Y	Y
Other Sci	0	12.2	0			
Transit/test flights	8.6	14.9	0			
TOTAL	121.7	138.9	28.4			



Coordination of a combined 5 NASA and NOAA aircraft in Hurricane Karl on 16 September 2010 at ~1955 UTC



Integration of the NASA CAMVis and Multiscale Analysis Package (CAMVis-MAP) For Tropical Cyclone Climate Study

PI: **Bo-Wen Shen (UMD/ESSIC)**

Objective

CAMVis-MAP is a scalable multiscale analysis tool that will be developed to achieve the following goals by integrating the CAMVis (coupled advanced multiscale modeling and visualization systems), satellite data modules, and data analysis algorithm on NASA supercomputing facilities:

- to understand the tropical cyclone (TC) *genesis processes, accompanying downscaling (by large-scale events) and upscaling processes (by small-scale events), and their subsequent non-linear interactions;*
- *to increase our confidence in extended-range TC prediction and thus TC climate projection by discovering hidden predictive relationships between meteorological and climatological events.*

Project CAMVis-MAP has the potential for supporting the following NRC Decadal Survey Earth Science missions, including ACE, PATH, SMAP, XOWWM, and 3D-Winds.

Approach

Our approach is to

- (1) develop a scalable Multiscale Analysis Package (MAP) that includes the NASA state-of-the-art Hilbert-Huang Transform (HHT) and improved multi-dimensional ensemble empiric mode decomposition (EEMD, e.g., Wu and Huang, 2009);
- (2) integrate the MAP with the models and satellite data modules (e.g., TRMM and QuikSCAT) of the CAMVis (CAMVis-MAP);
- (3) apply the coupled system to conducting multiscale time-frequency and/or space-wavenumber analysis on long-term satellite and/or model data with the aim of studying TC climate.

Co-I's/Partners

- Co-I's: Zhaohua Wu (FSU, CO-PI), Piyush Mehrotra (ARC, CO-I), Jui-Lin Li (JPL, CO-I), Samson Cheung (ARC, CO-I), Wei-Kuo Tao (GSFC, CO-I).

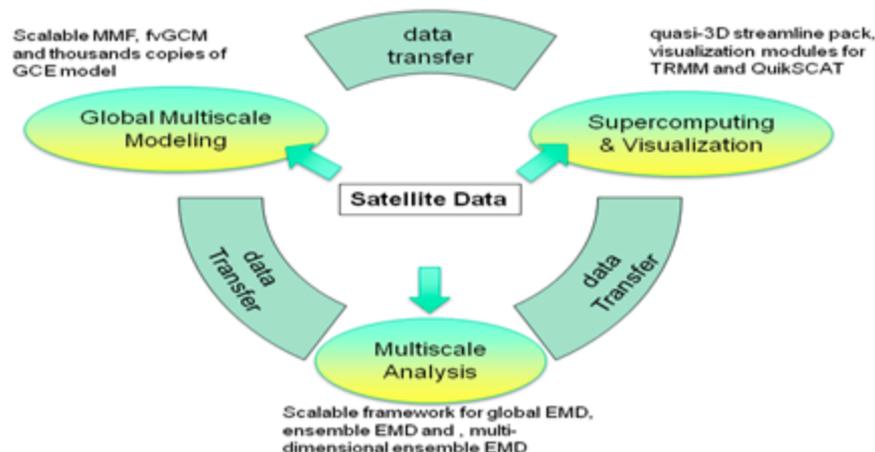


Figure: A diagram of the integrated CAMVis (top two components) and Multiscale Analysis Package (MAP, bottom). The MAP will be developed for performing multiscale analysis with satellite and model data.

Key Milestones

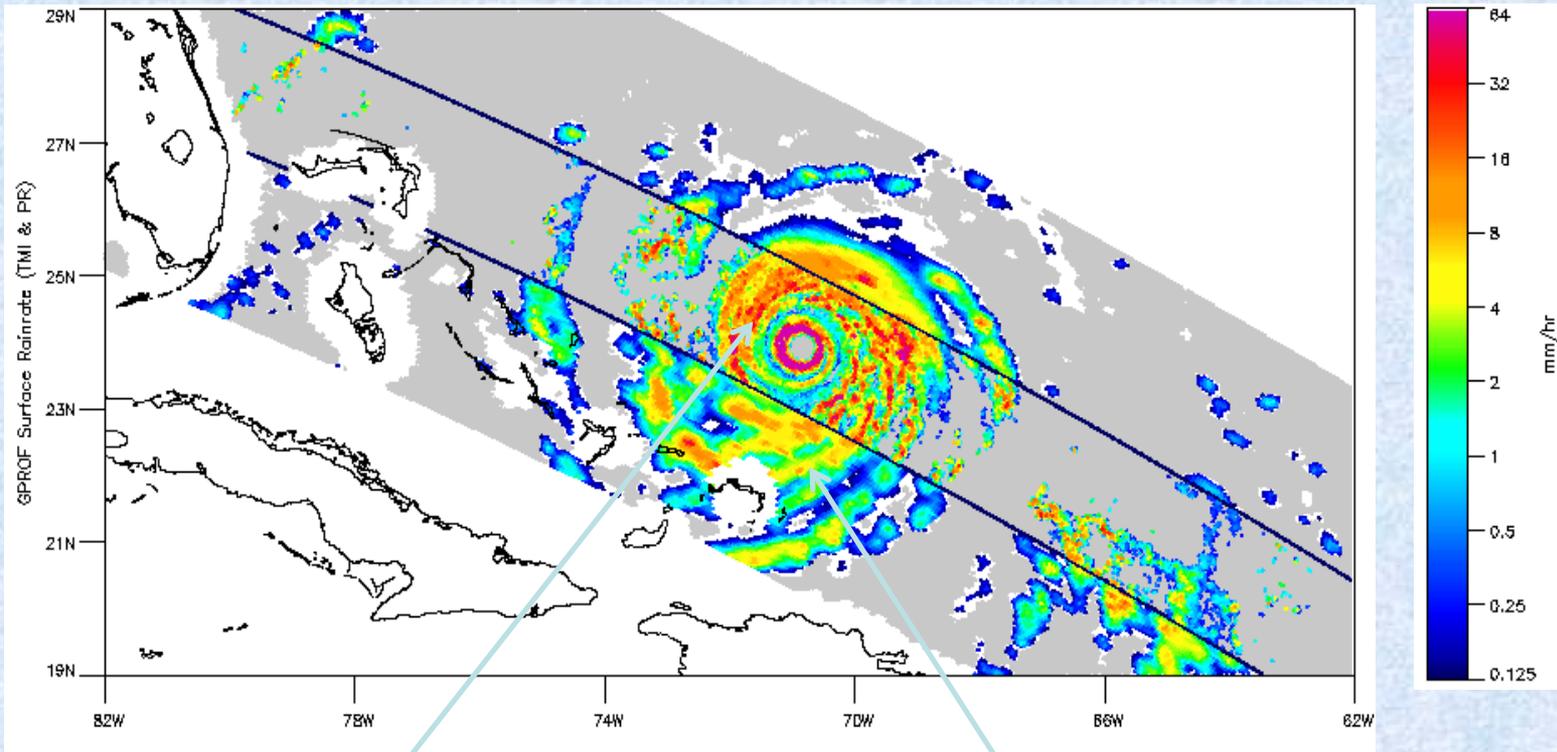
- Port and test EEMD codes on NASA supercomputers; **09/2012**
- Conduct preliminary multiscale analysis with selected TC events
- Develop a scalable MAP with two-level parallelism for performing EEMDs; Improve the MAP to be geolocation aware; **03/2013**
- Implement a third-level parallelism in the geolocation-aware MAP;
- Improve the MAP with a target parallel efficiency of 2,000~3000 cores;
- Design the layout of visualizations for multi-dimensional time-frequency and space-wavenumber diagrams with Matlab;
- Integrate the MAP and satellite data modules; Integrate other packages such as hurricane tracking codes for TC studies; **03/2014**
- Streamline data flow for production runs; test the CAMVis-MAP system
- Conduct multiscale analysis with multi-year data from global reanalysis, model simulations and satellite data **03/2015**

TRL_{in} = 3, TRL_{final} = 7



GPM Core: Reference Standard for Constellation Radiometers
GPM Unified Constellation Radiometer Retrieval
Prototype GPM radiometer rain retrieval:

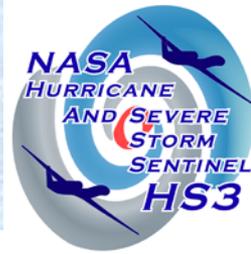
Proof-of-Concept Demonstration using TRMM PR and TMI



**Radar Rain Retrieval
(Inner Swath)**

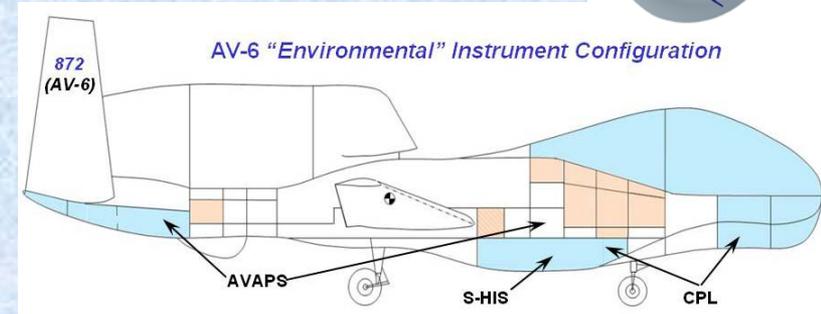
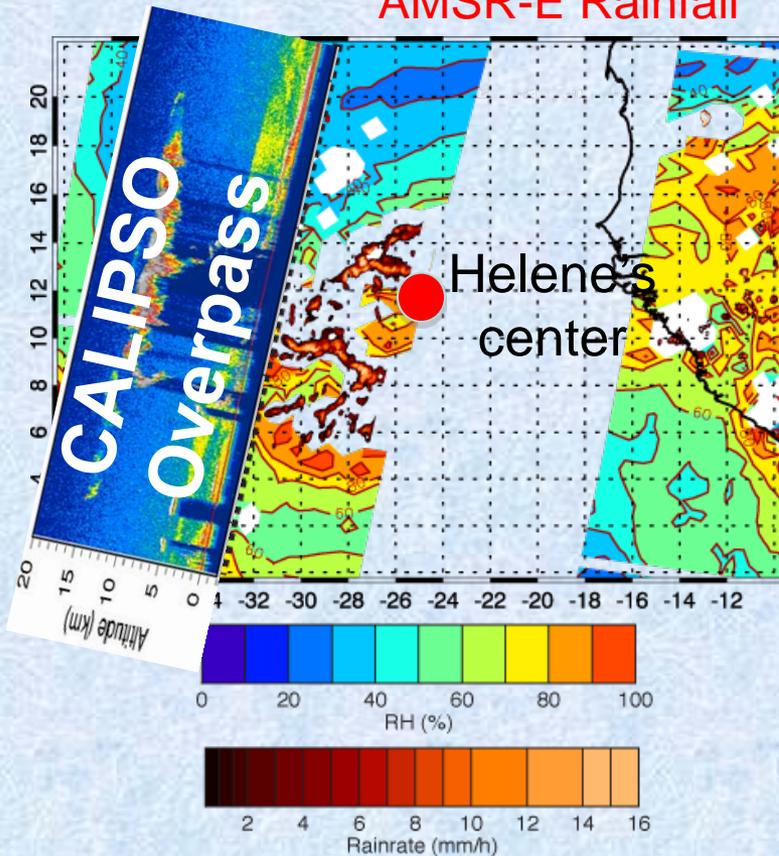
**Radiometer Retrieval Using a Retrieval
Database Constrained by PR+TMI Data
(Outer Swath)**

HS3 and the A-Train



Early stages of Hurricane Helene (2006)

AIRS 850-700 hPa RH
AMSR-E Rainfall



HS3's environmental sensor suite

- CPL: high-resolution aerosol backscatter data similar to CALIPSO
- S-HIS: temp, humidity data in clear air with high horiz. resolution, AIRS-like vertical resolution
- Dropsonde: validation data for S-HIS plus high vertical resolution T, RH, winds
- Data critical for tracking features seen, at best, twice per day by A-Train satellites