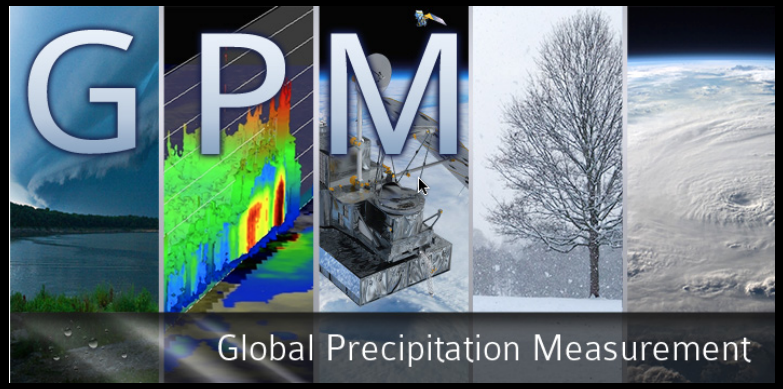

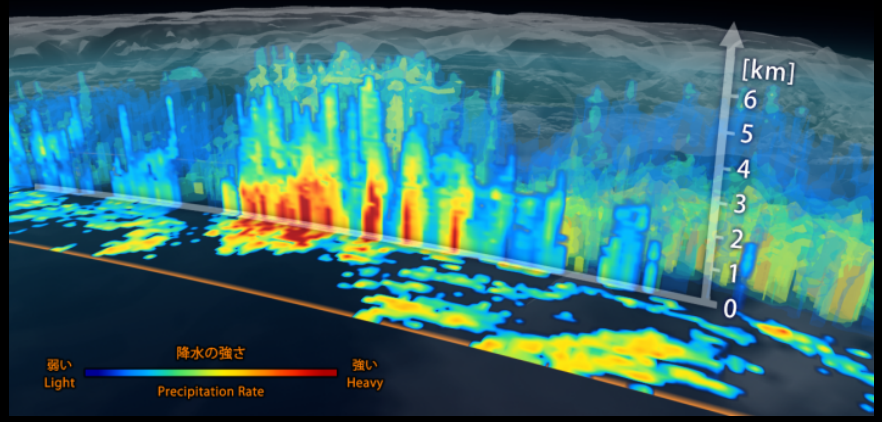

The Global Precipitation Measurement (GPM) Mission After Three Years in Orbit

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Radar Science and Engineering
Pasadena, CA jturk@jpl.nasa.gov

18 May 2017, *NRL-Monterey, CA*

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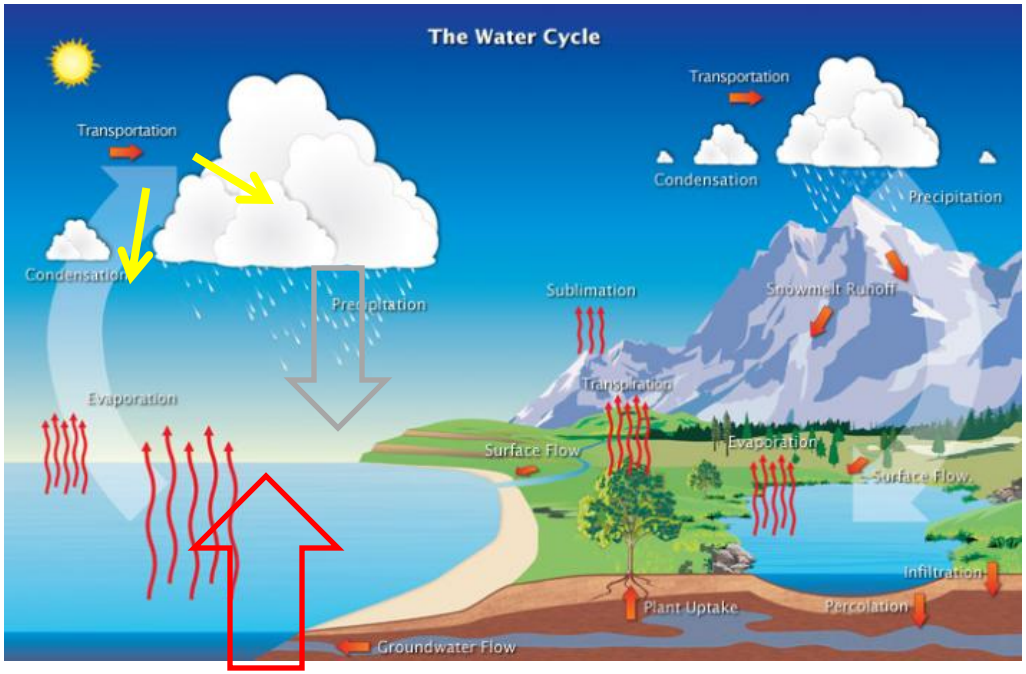
Precipitation as an Energy Balancer

*Only about **one fourth** of the energy needed to drive the global atmospheric circulation comes from direct solar energy. The other **three-fourths** of the energy is transferred to the atmosphere by evaporating water.*

- As the water vapor rises, it carries energy needed to turn liquid into water vapor (*Latent Heat of Evaporation*). This energy is released into the atmosphere in huge cloud clusters near the equator.
  - Latent heat energy contained in clouds ***cannot*** be seen or measured directly but rainfall, a product of this energy release, ***can*** be measured

We need to better define the **amount** of rainfall and the energy released when rain occurs in order to improve climate models, understand the global water and energy budget, and monitor our vital water resources.



Courtesy G. Skofronick-Jackson, GSFC

Characteristics of Precipitation

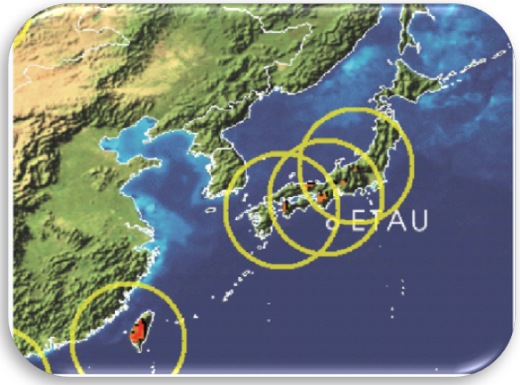
- **Wide variability in space, time, and intensity**
- – Discontinuous; range of extremes; intermittent
- – Controlled across scales from microscale (microphysics), mesoscale (e.g., sea breezes), synoptic (fronts), terrain, environmental conditions
- – Frozen state: Covers 30% of land (Snow melt is the main source of fresh water for 60 million Americans)

- **Spaceborne measurement of precipitation**:
- – Constrained by observing system limitations (orbit, resolution, coverage..)
- – Used by an increasingly broad and diverse user community
- – Not straightforward to validate

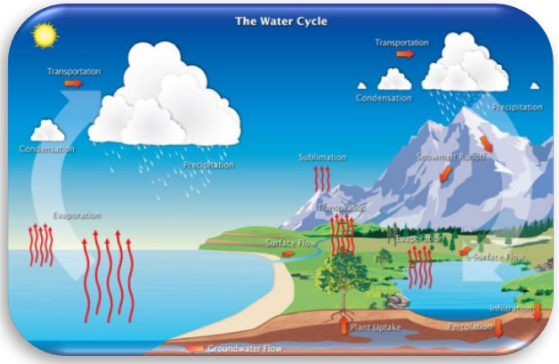
Science With Integrated Application Goals

Flooding

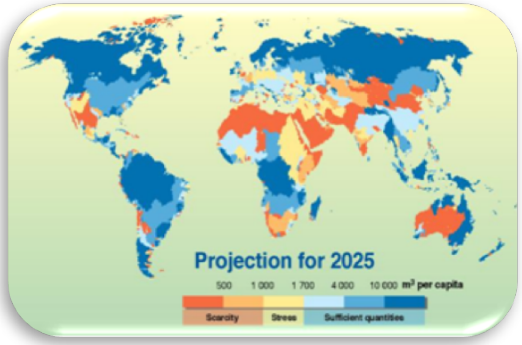
Landslides



Land surface and climate modeling



Freshwater Availability

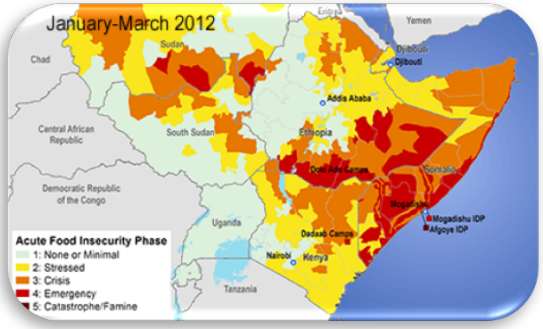


GPM Science Objectives:

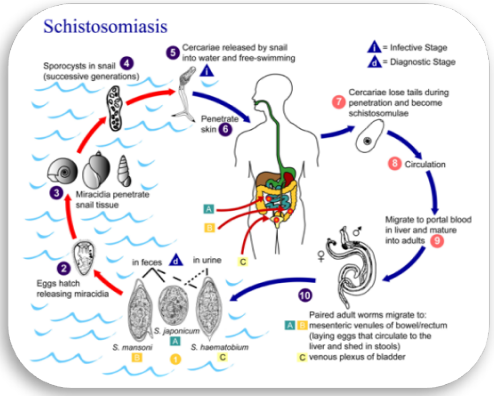
- **New reference standards for precipitation measurements from space**
- **Improved knowledge of water cycle variability and freshwater availability**
- **Improved numerical weather prediction skills**
- **Improved climate prediction capabilities**
- **Improved predictions for floods, landslides, and freshwater resources**

Extreme Events

Agriculture/Famine Early Warning

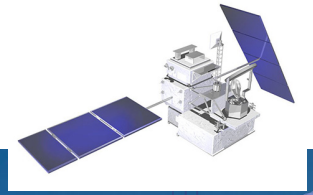


World Health



Complementary Nature of Space- and Ground-Based Radar

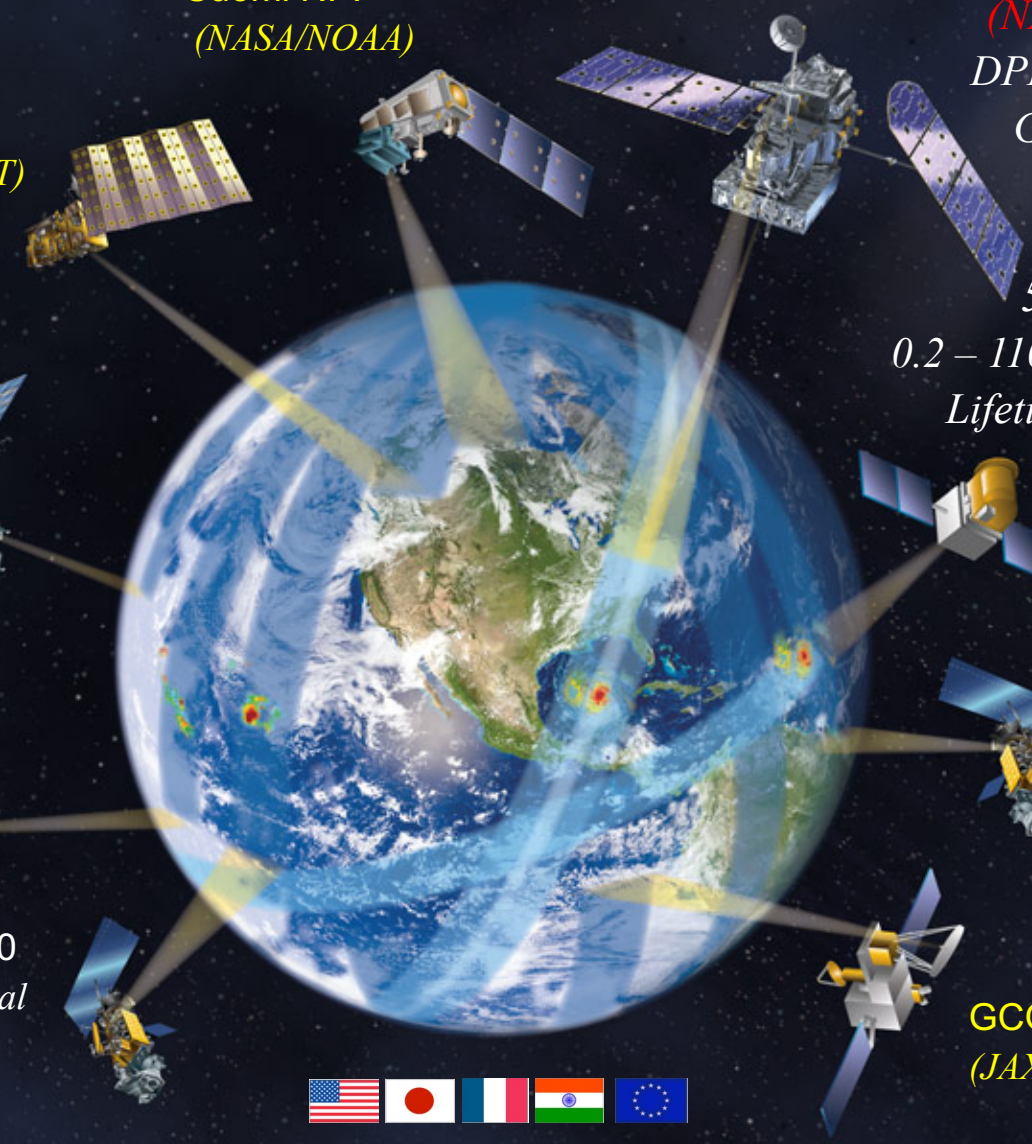
Space:
Infrequent revisit
Limited coverage
Not yet Doppler (air motion)
Captures vertical cloud structure
Global



Ground:
Frequent update (e.g., 5-min)
3-D scanning
Doppler/polarization-agile
Misses top or bottom of cloud structure, depending upon range
Localized

(not to scale)

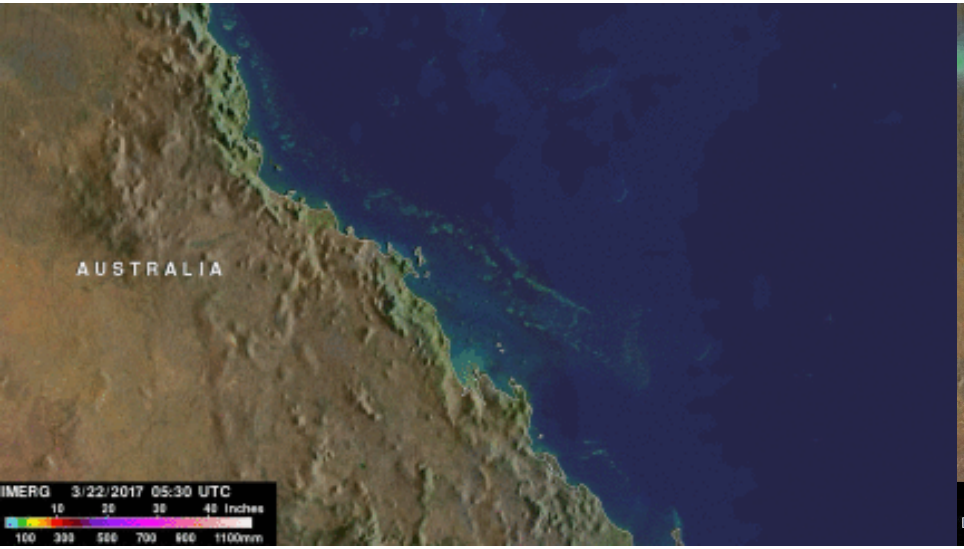
GPM Constellation Concept

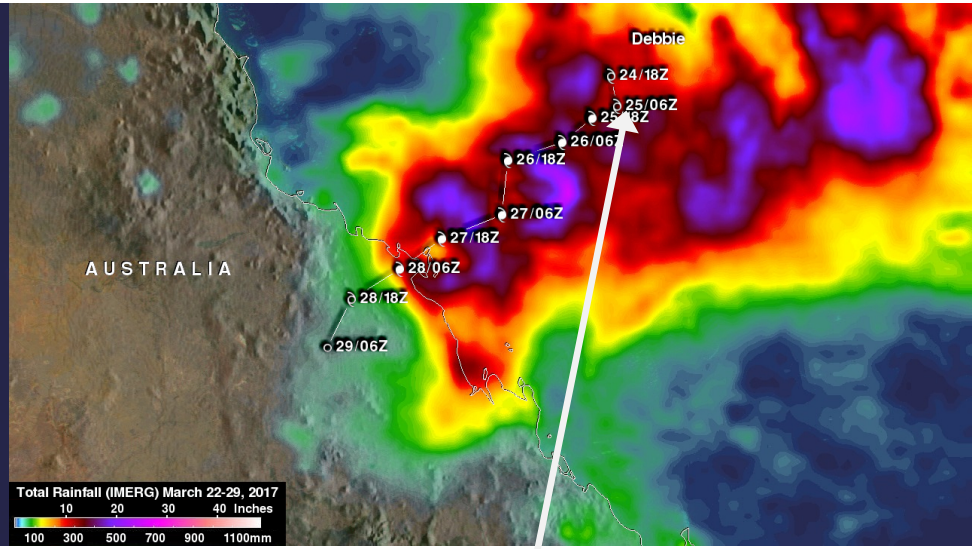


GPM Core Observatory
(NASA/JAXA, 2014)
DPR (Ku & Ka band)
GMI (10-183 GHz)
65° Inclination
407 km altitude
5 km best footprint
0.2 – 110 mm/hr and snow
Lifetime: 3, 5, 15 years

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

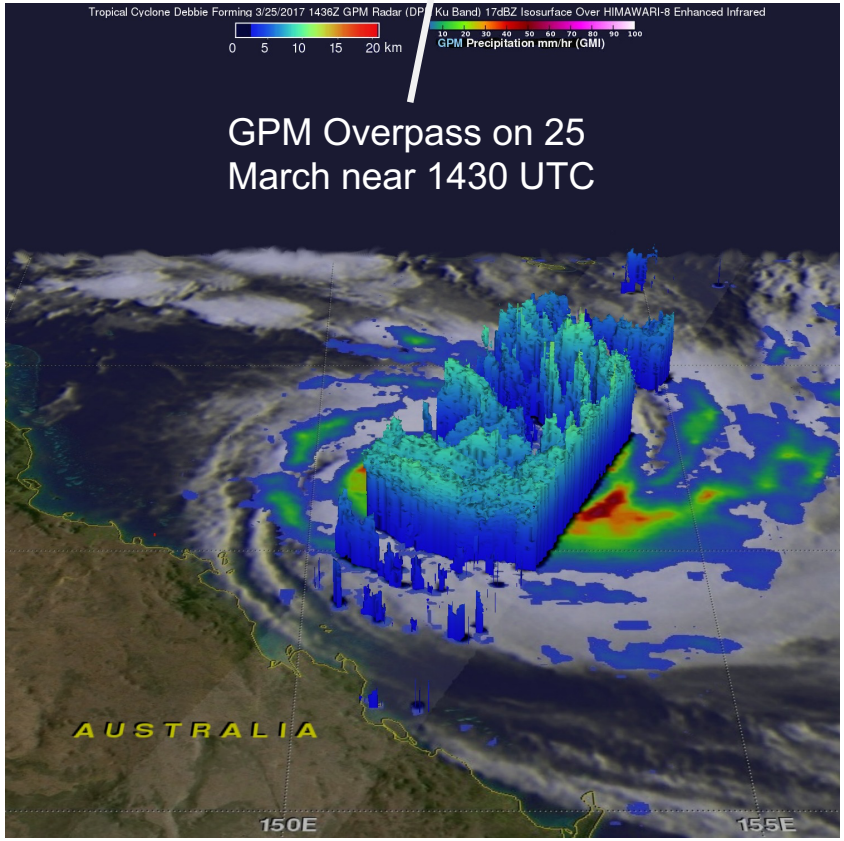
Precipitation rates everywhere in the world every three hours



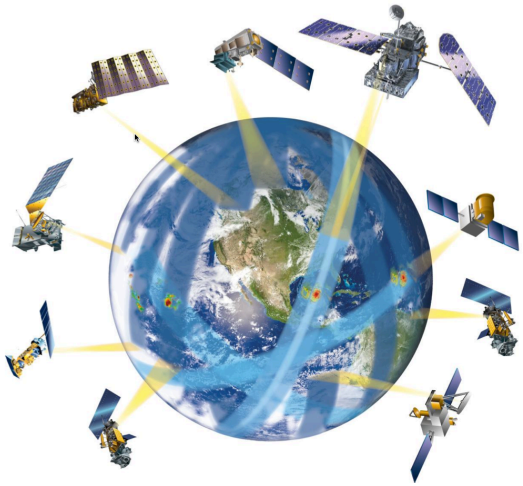


IMERG Accumulations, March 22-29, 2017

TC Debbie: NE Australia last week



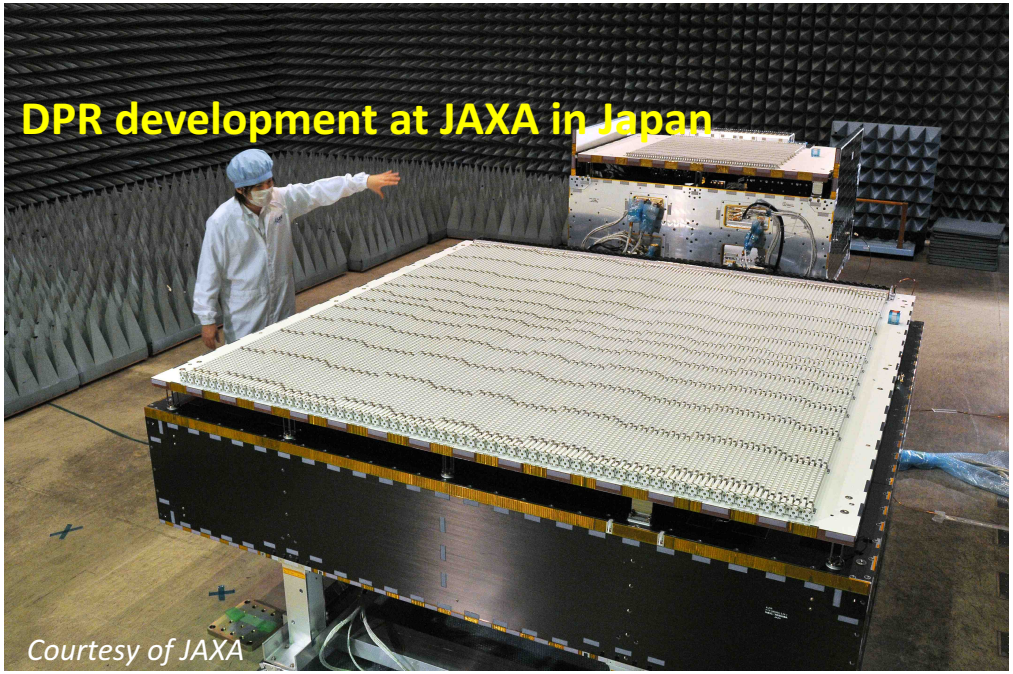
NASA's Space-Based Atmospheric Radar Systems

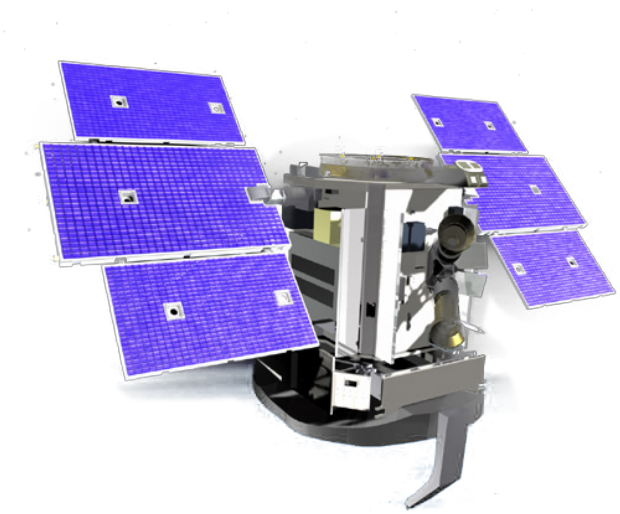


- **TRMM: Tropical Rainfall Measuring Mission (11/97-early 2015)**
  - single satellite mission (26% of observations are over land)
  - First precipitation radar in space
  - science oriented, for climate scale (monthly, 5-degree)
- **GPM: Global Precipitation Measurement (3/2014-current)**
  - "core" satellite anchors a constellation (44% observations over land)
  - Like TRMM but with dual-frequency radar
  - science and operations/applications in scope
- **CloudSat (6/2006-current):**
  - 94-GHz cloud radar: 30x higher frequency than the NWS 3-GHz NEXRAD ground radars
  - Part of NASA's "A-Train" sequence of satellite systems

Dual-frequency Precipitation Radar (DPR)

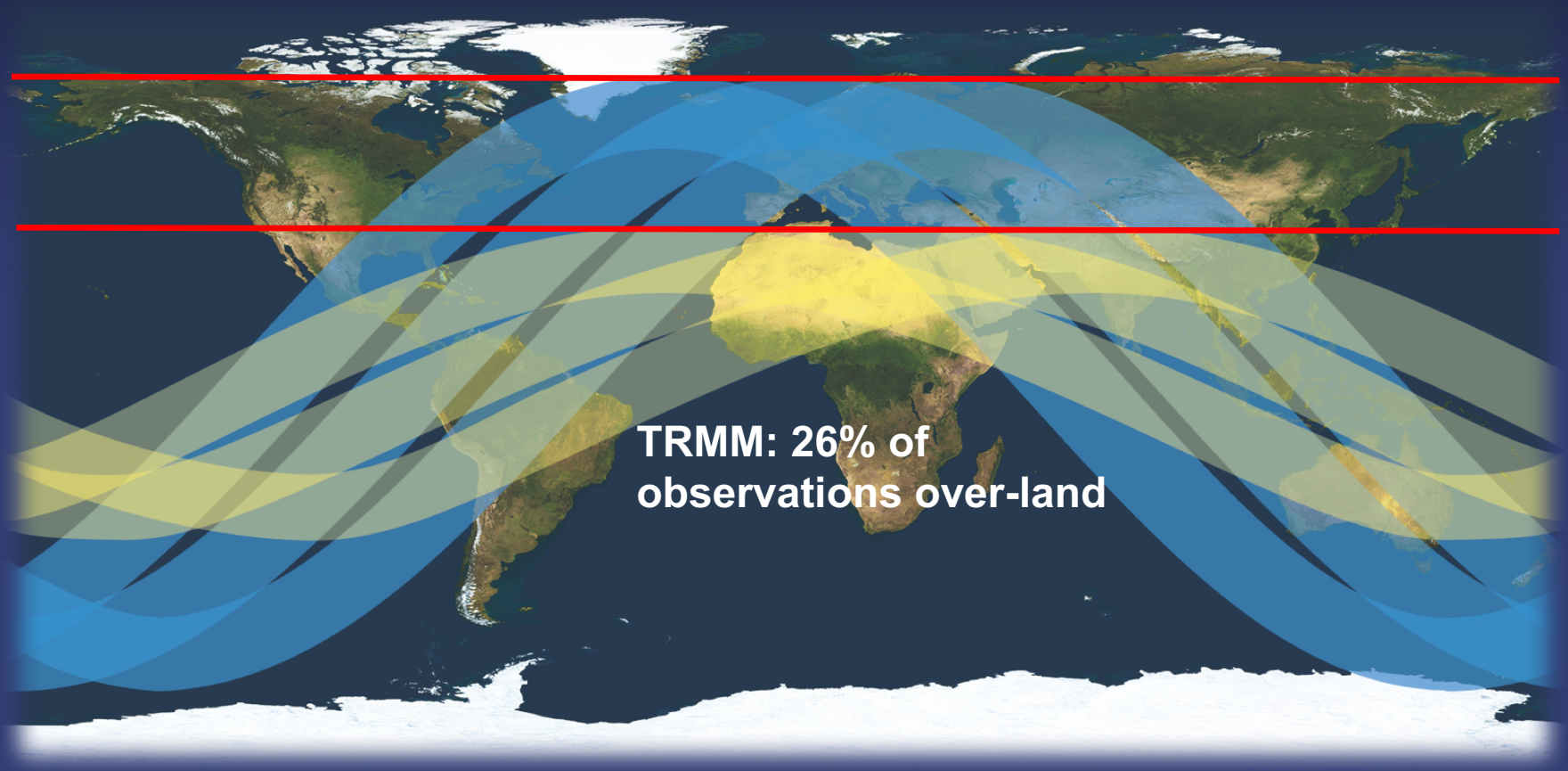
- The DPR sends out two different pulses of energy at 35 GHz and 13.6 GHz to determine the size and distribution of rain and snow particles in the cloud
- Resolution: 5-7 km horizontally, 250-500 m vertically





CloudSat Profiling Radar

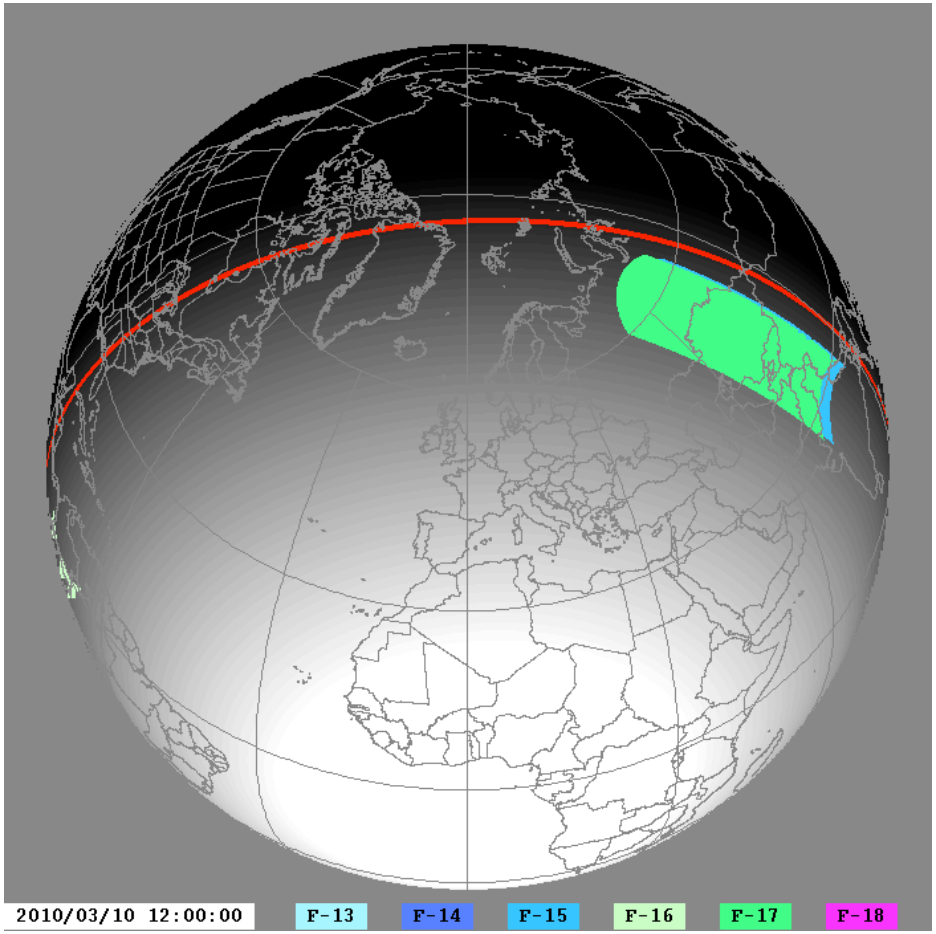
- CloudSat operates at 94 GHz (3-mm wavelength), much more sensitive to cloud drop sizes, but greatly attenuated by precipitation
- Resolution: 1-km horizontally, 250-m vertically (does not scan)
- Part of NASA's A-Train formation



Blue: GPM's orbit path

Yellow: TRMM's orbit path

Factors Limiting the Ability to Quantify Precipitation from Space



Example from DMSP satellites on March 10, 2010

Solar zenith is indicated by the white shades and the red stripe indicates the day-night terminator. Note how each satellite follows the sun (nearly the same local time) each orbit

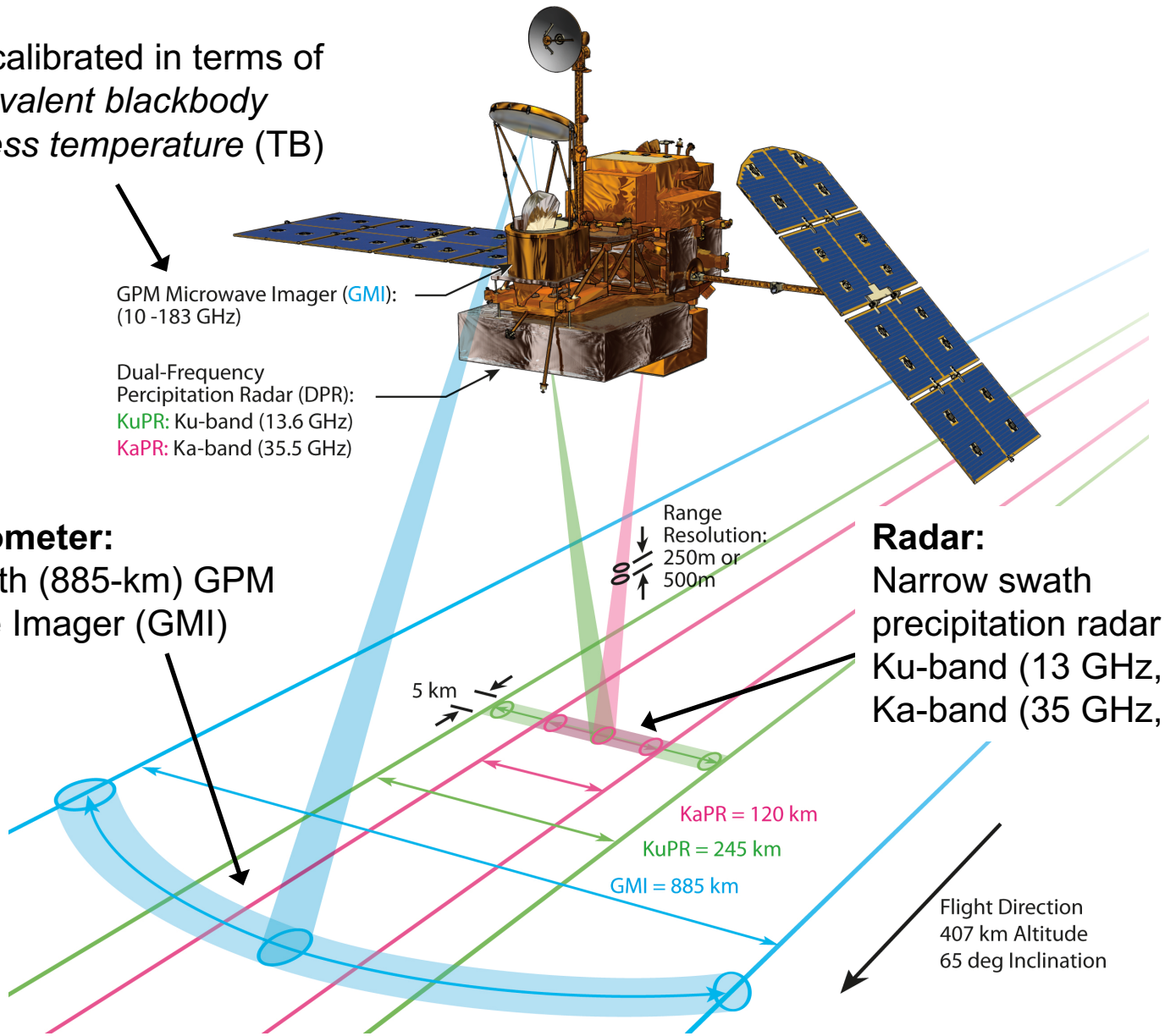
Revisit Time

A typical satellite orbits the Earth every 90 minutes and commonly observes at (nearly) the same local time

Non-Uniform Beamfilling

The structure of the underlying rainfall is finer than the sensor can resolve (think of a low-resolution digital camera)

Global Precipitation Measurement (GPM) core satellite

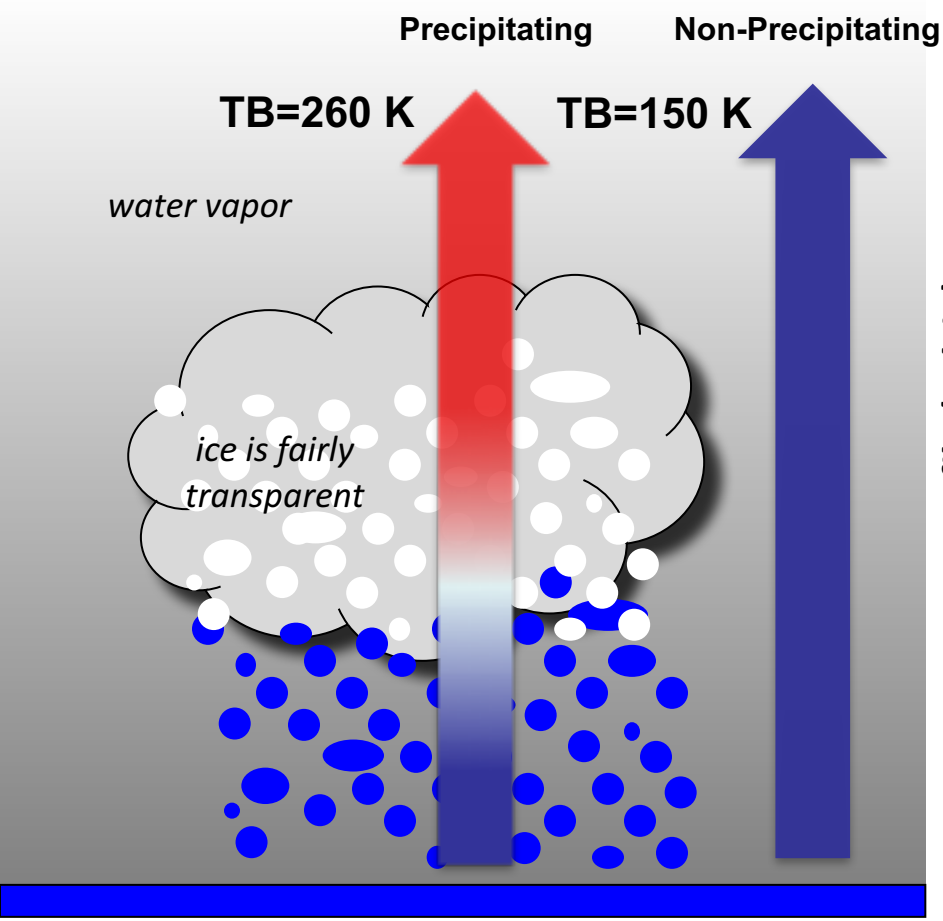


Courtesy G. Skofronick-Jackson, GSFC

Passive Microwave Radiometry: A Study in Contrast

Over Ocean

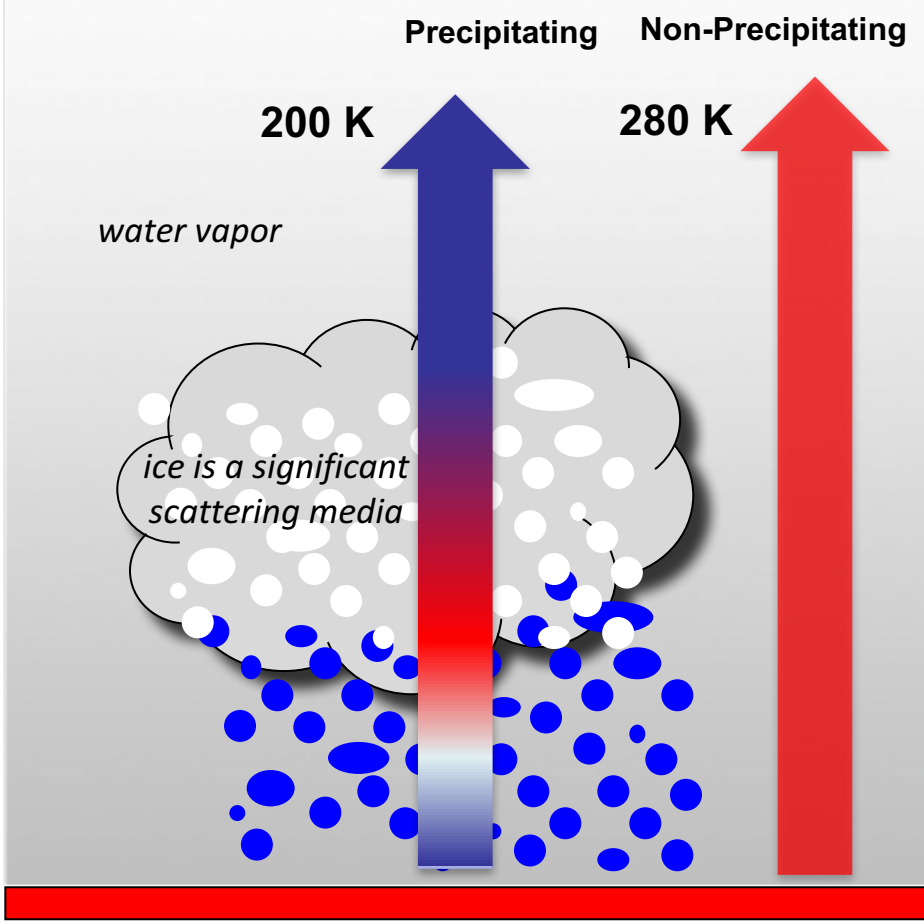
At 10 GHz, increasing precipitation shows radiometrically "warmer" brightness temperatures (TB) than the background



Radiometrically cold ocean surface

Over Land

At 85 GHz and above, increasing precipitation is radiometrically "colder" than the background



Radiometrically warm land surface

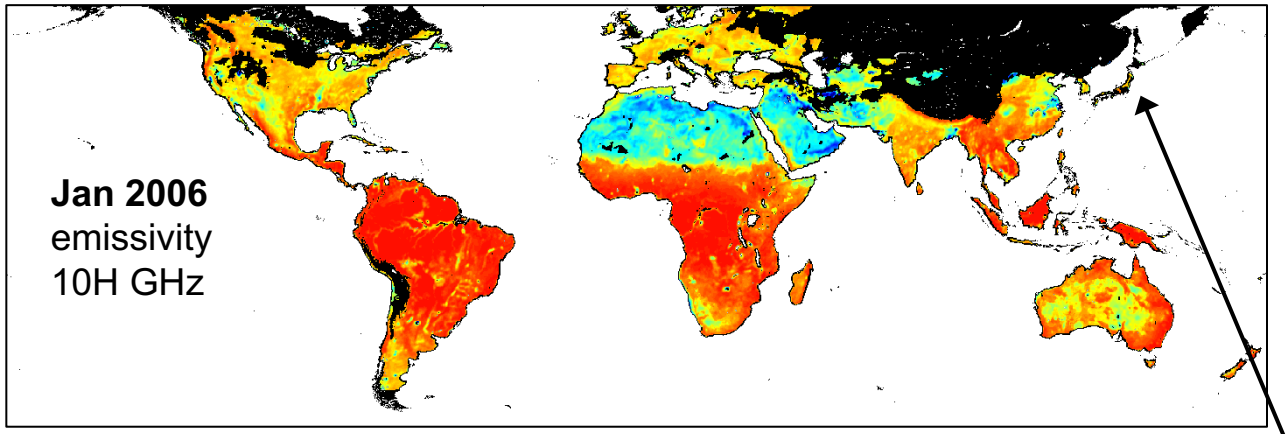
Temperature profile (Kelvin)

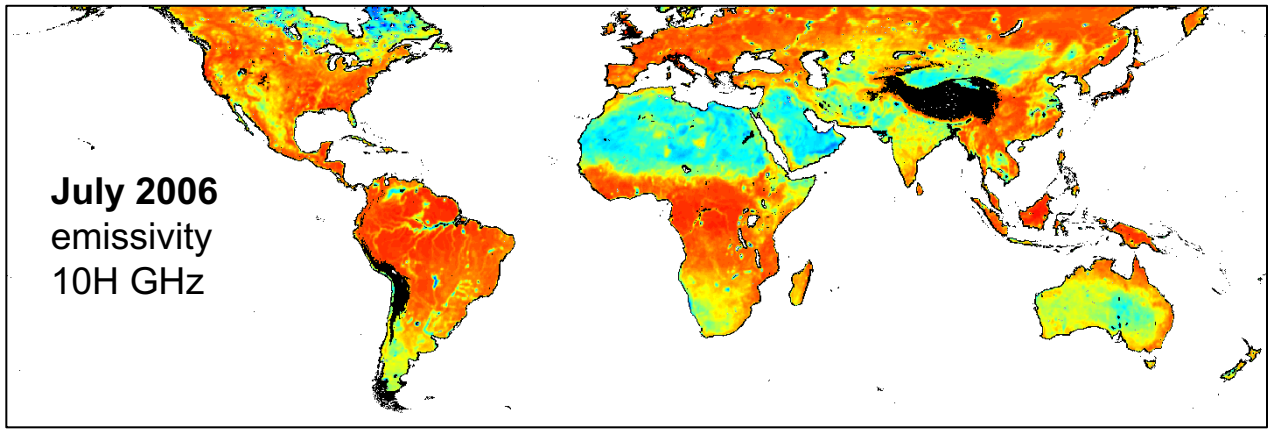
radiometrically cold *radiometrically warm*

Space-Based Over-Land Precipitation Estimation

The satellites have to contrast precipitation against a wide variety of land surfaces and terrain, that are dynamically changing (soil conditions, snowcover, temperature, vegetation)

In some conditions, a non-raining scene can “look like” a precipitation scene (false alarm)





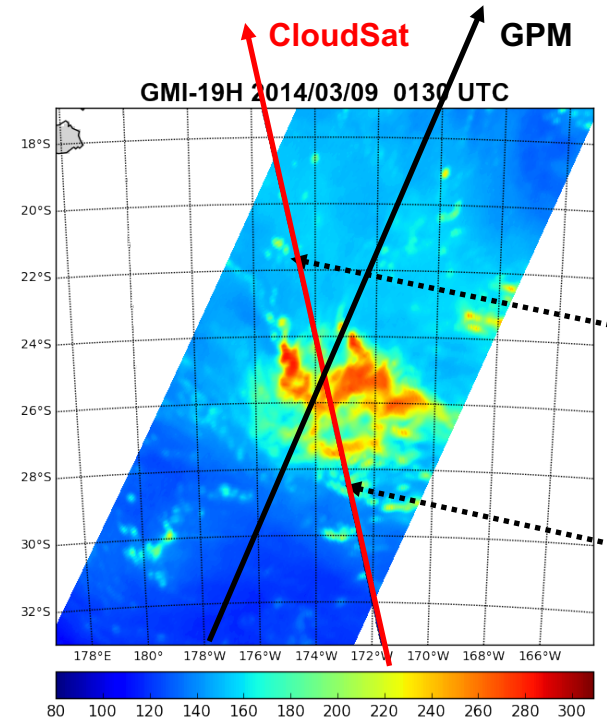
snow/ice cover and cold surface not shown

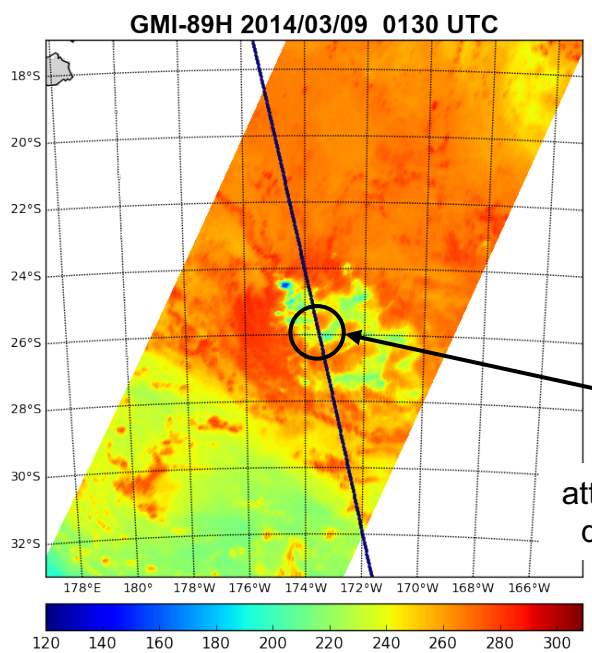
In general, dry surfaces exhibit higher 10 GHz emissivity

Range of Emissivity

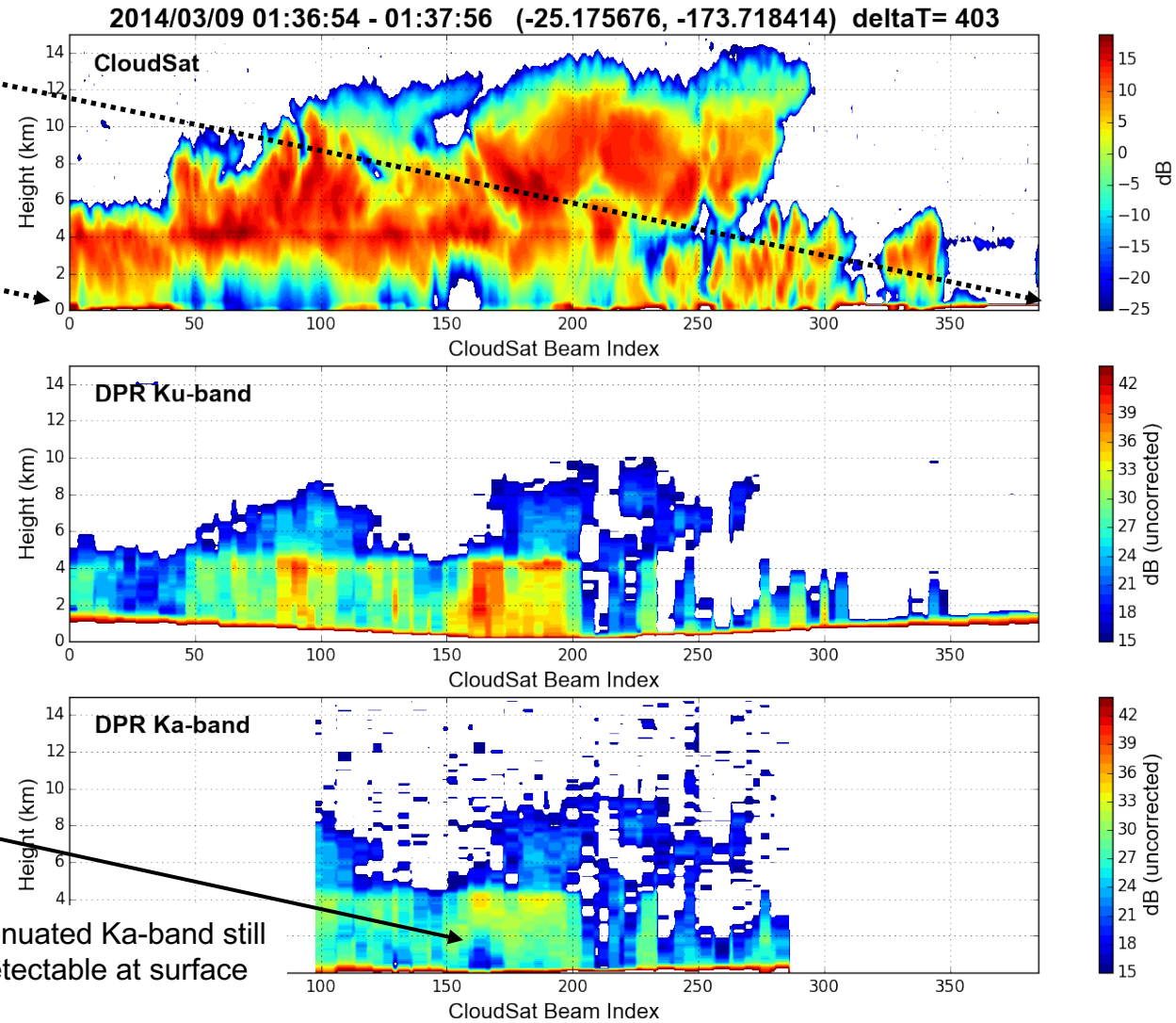
0.65 --> 0.99

What Types of Clouds Can GPM Sense?



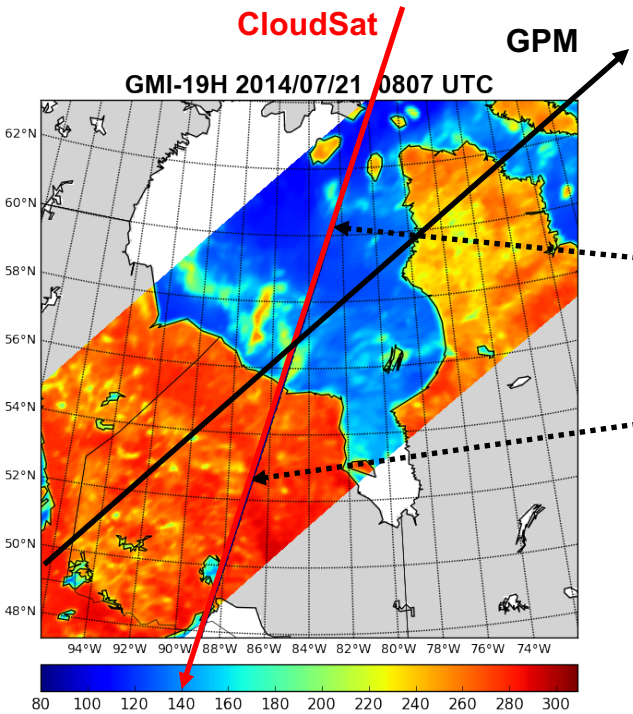


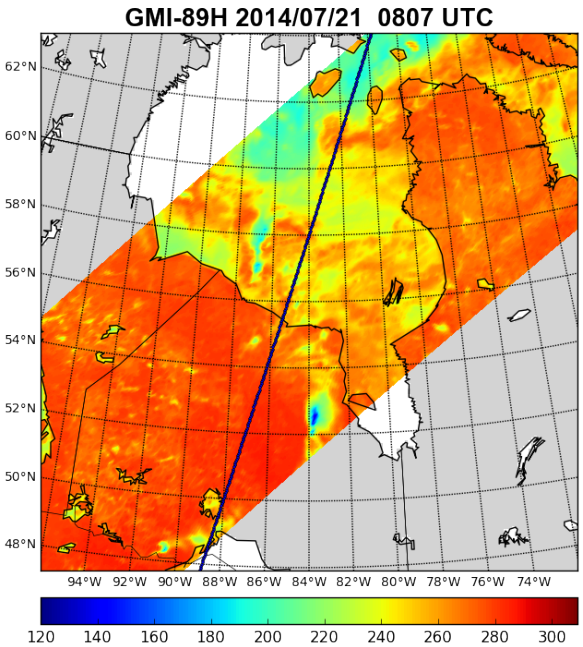
2014/03/09 0137 UTC
Southern Pacific Ocean: Deep Convection



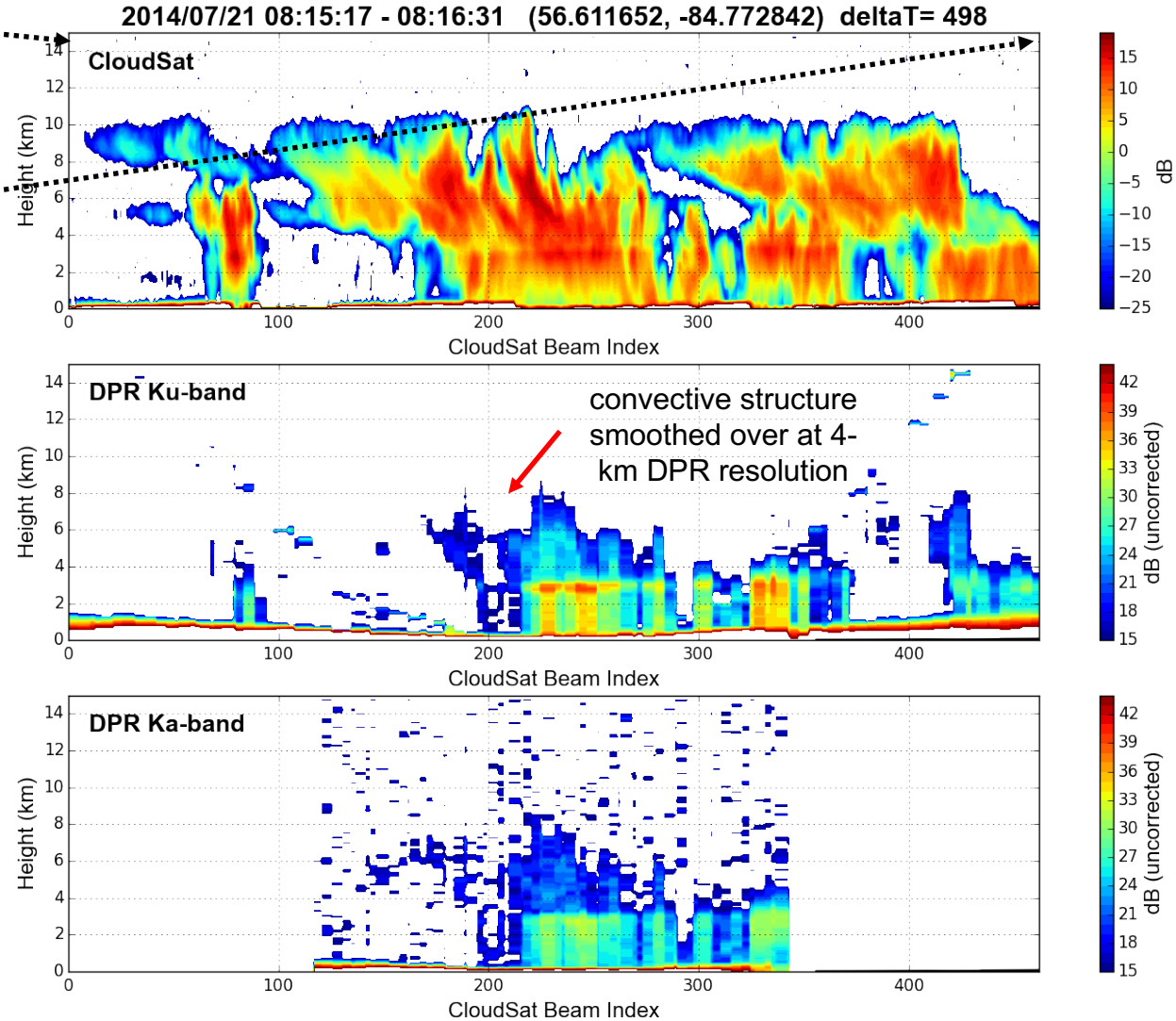
attenuated Ka-band still detectable at surface

What Types of Clouds Can GPM Sense?



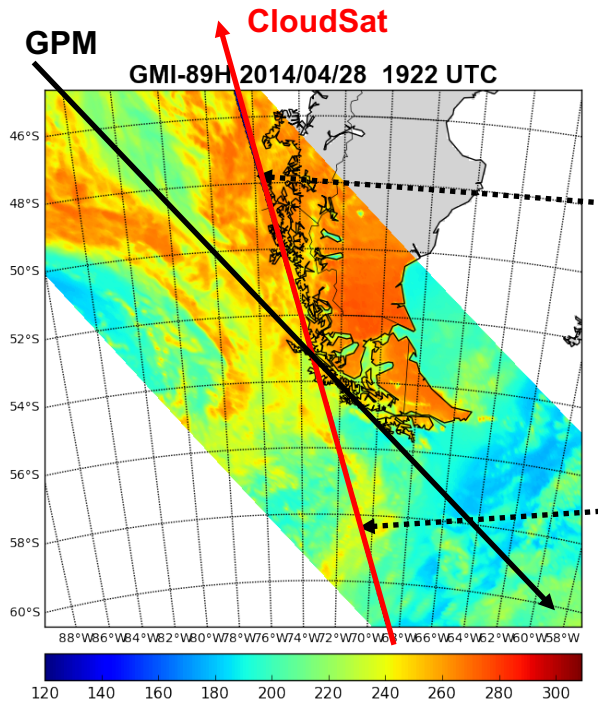


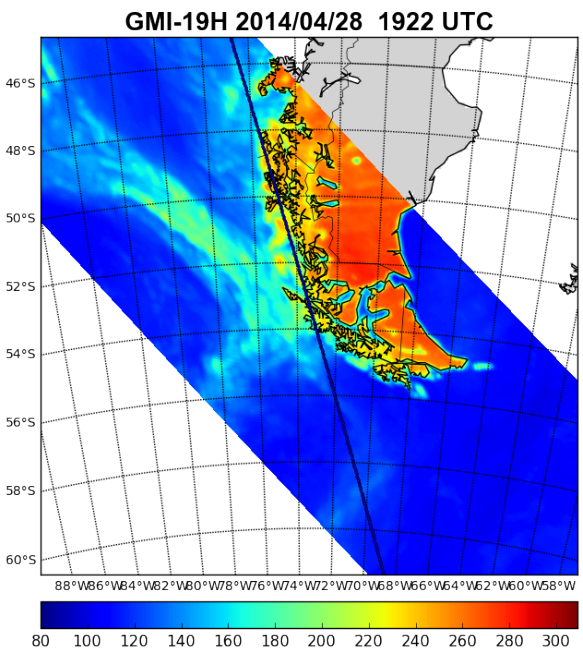
2014/07/21 0816 UTC
Hudson Bay, Canada, Mostly Convective

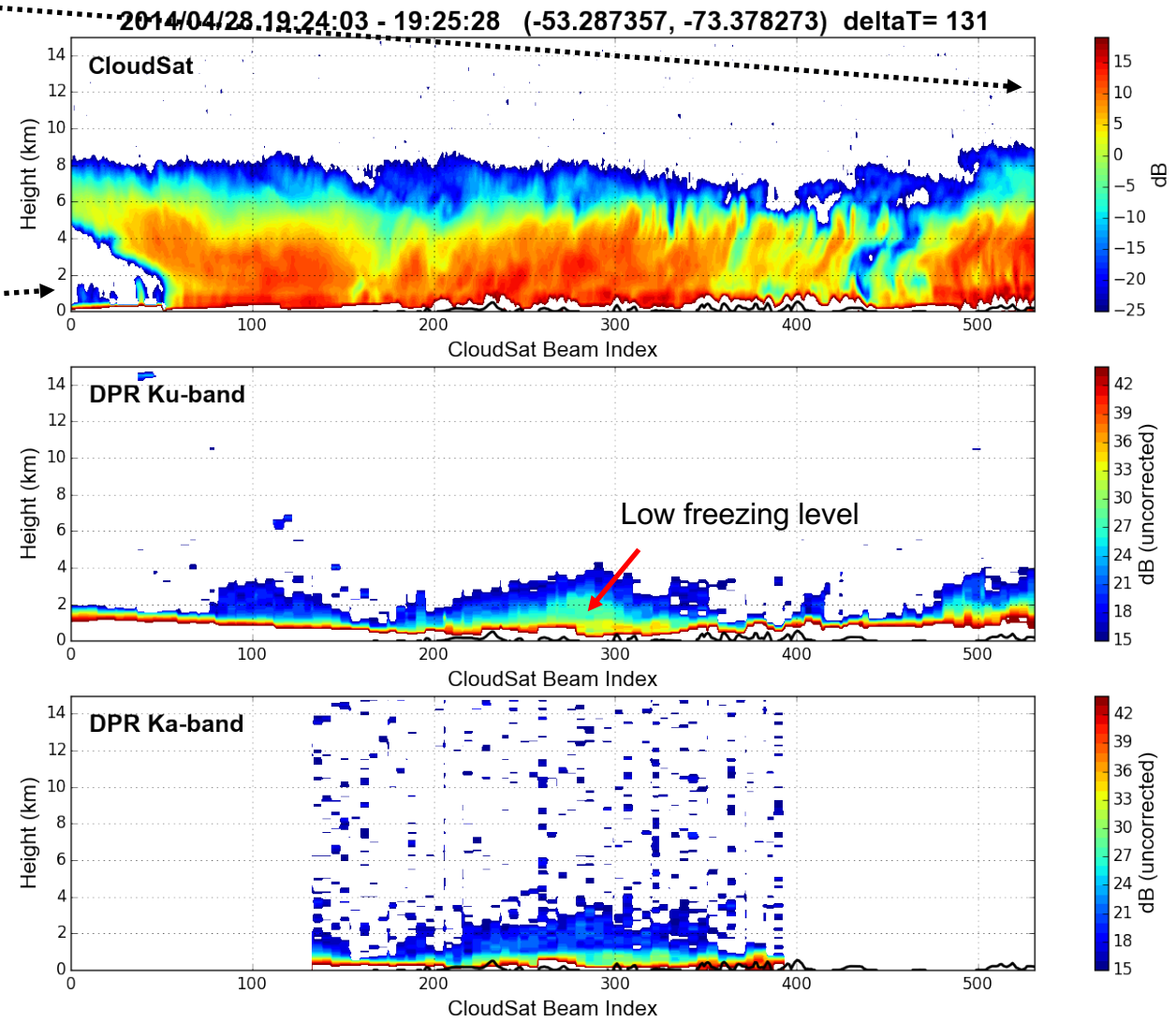


What Types of Clouds Can GPM Sense?

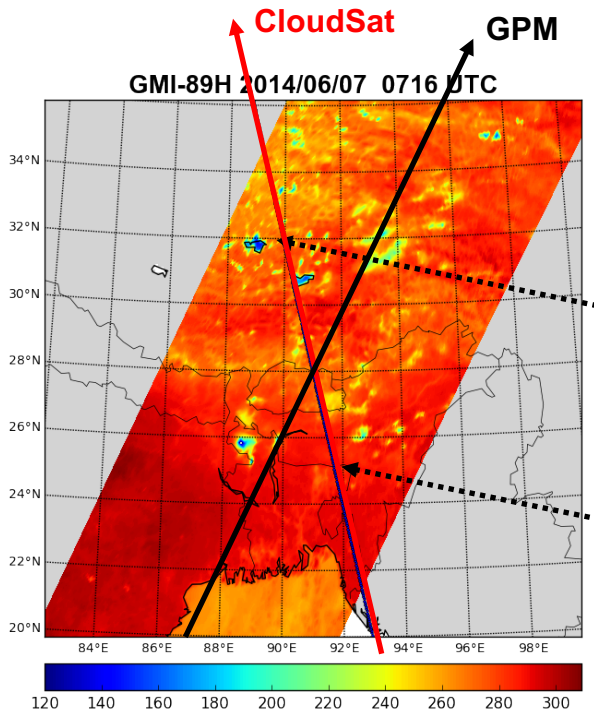
2014/04/28 1924 UTC
Edge of SW Chile Coast Cold Maritime Drizzle

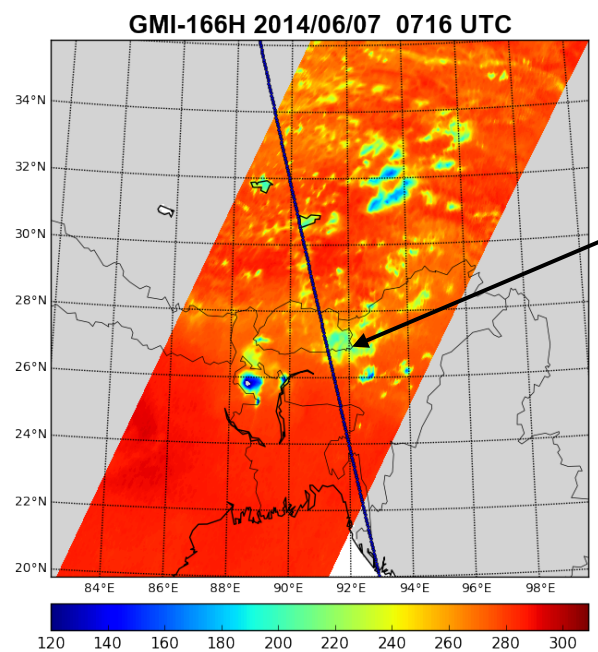






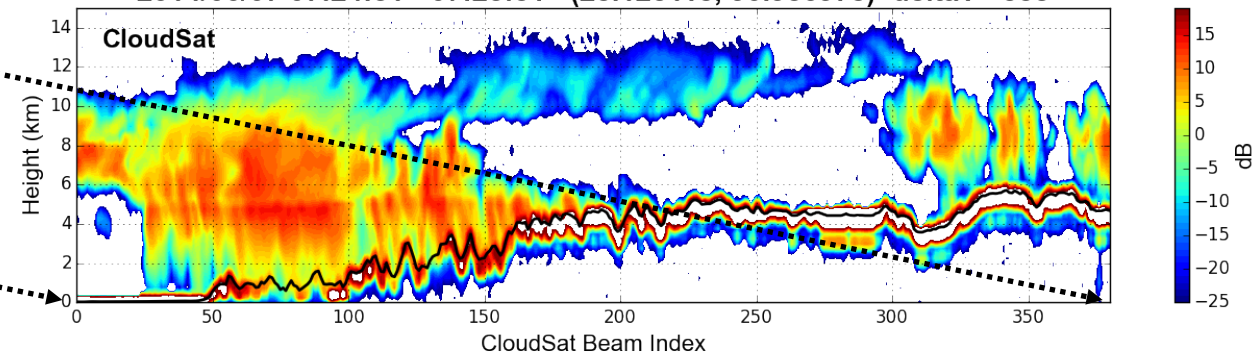
What Types of Clouds Can GPM Sense?

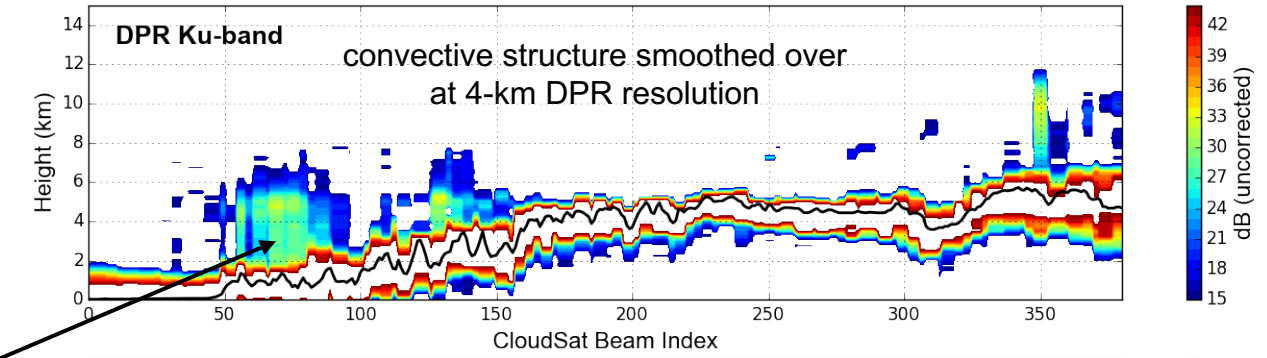


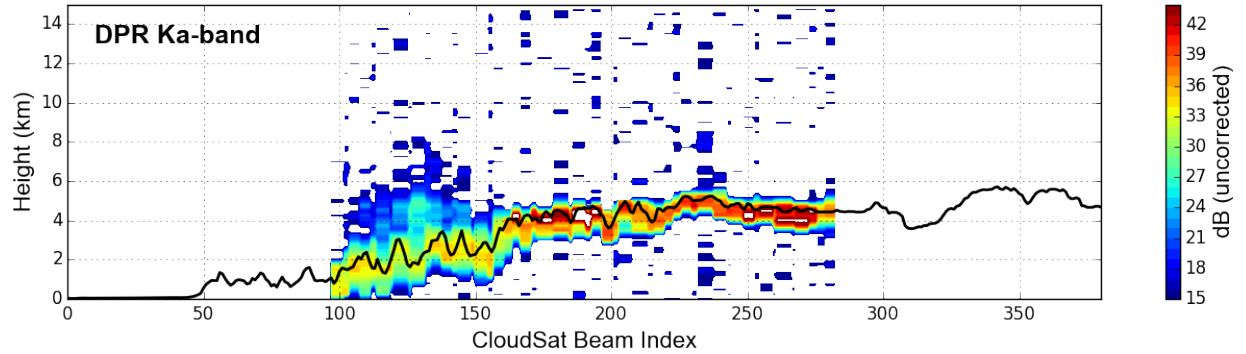


2014/06/07 0724 UTC
Bhutan Himalayas Orographic

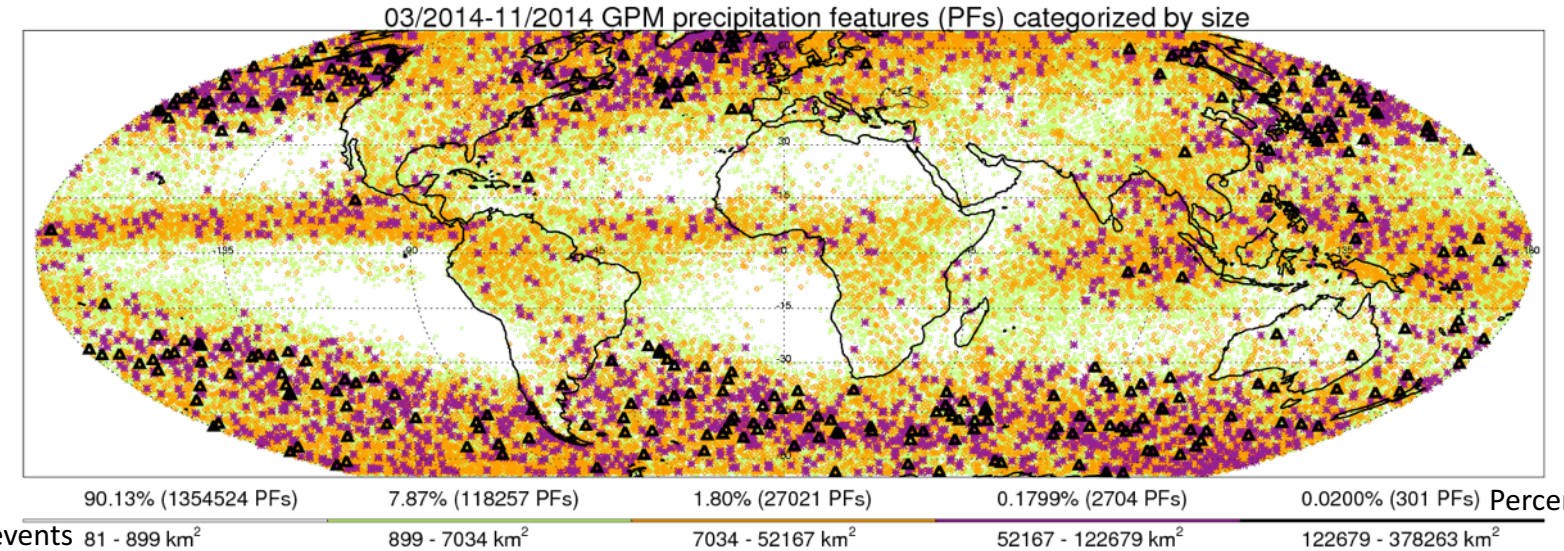
2014/06/07 07:24:51 - 07:25:51 (28.125118, 90.956978) deltaT= 558



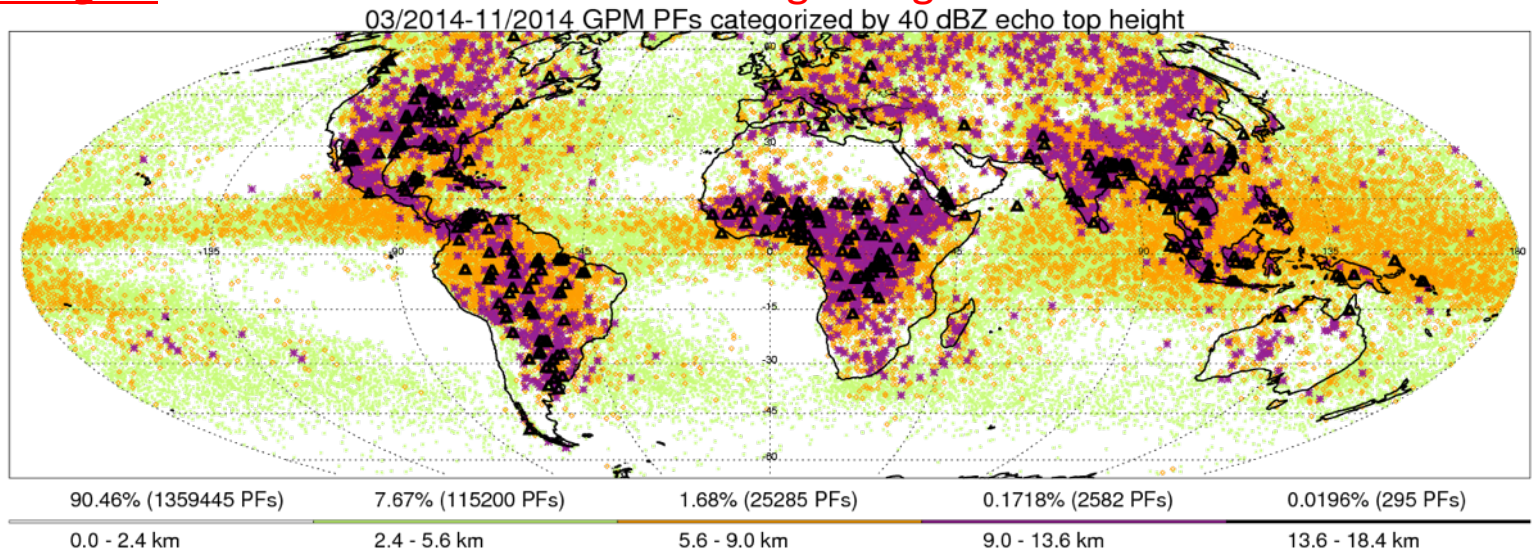




The most ***extensive*** precipitation systems are found over mid and high latitude ocean

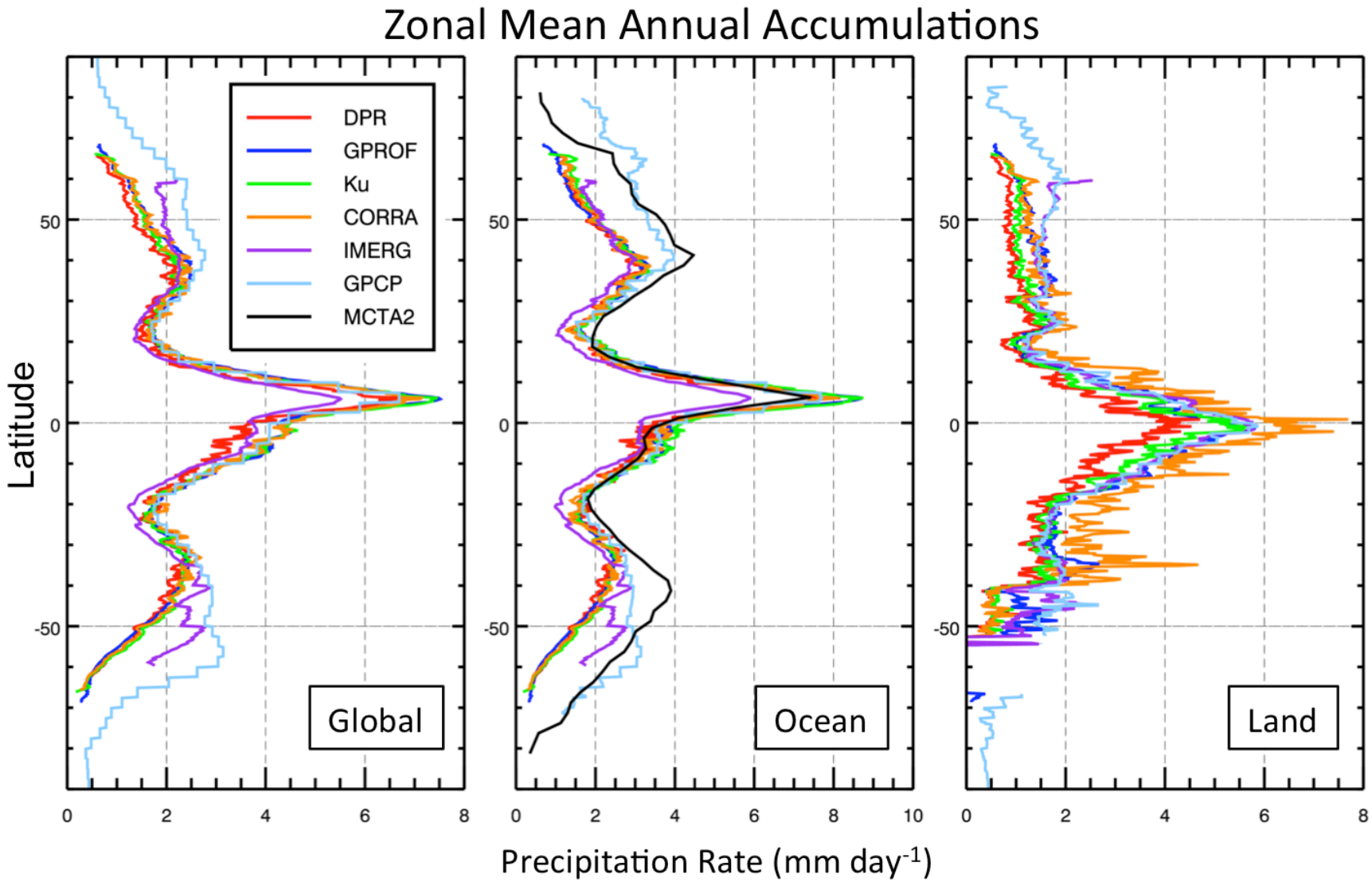


The ***strongest*** storms such as hailstorms and lightning storms are dominant over land



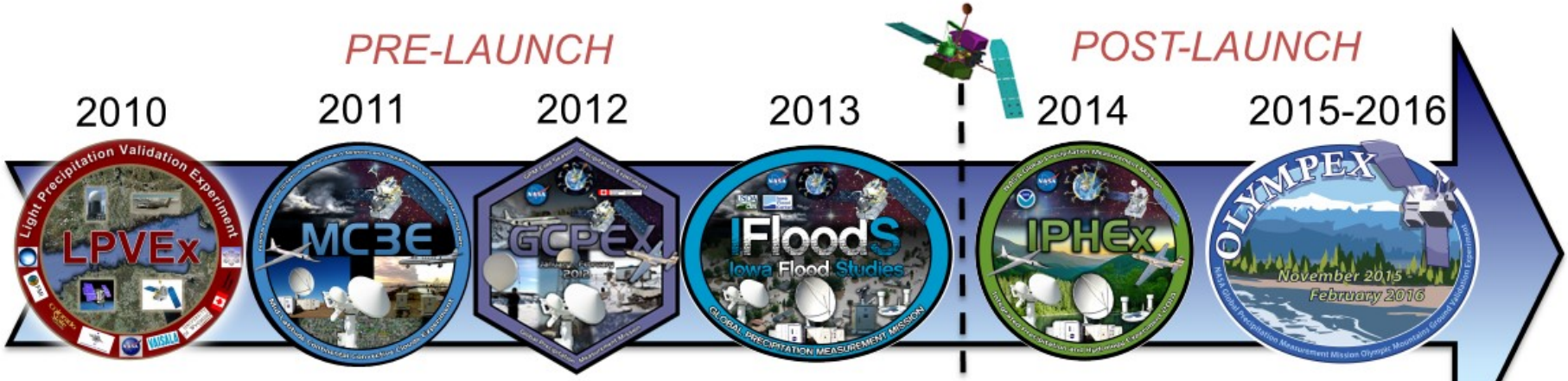
Credit: Chuntao Liu, Texas A&M – Corpus Christi

Zonal Means

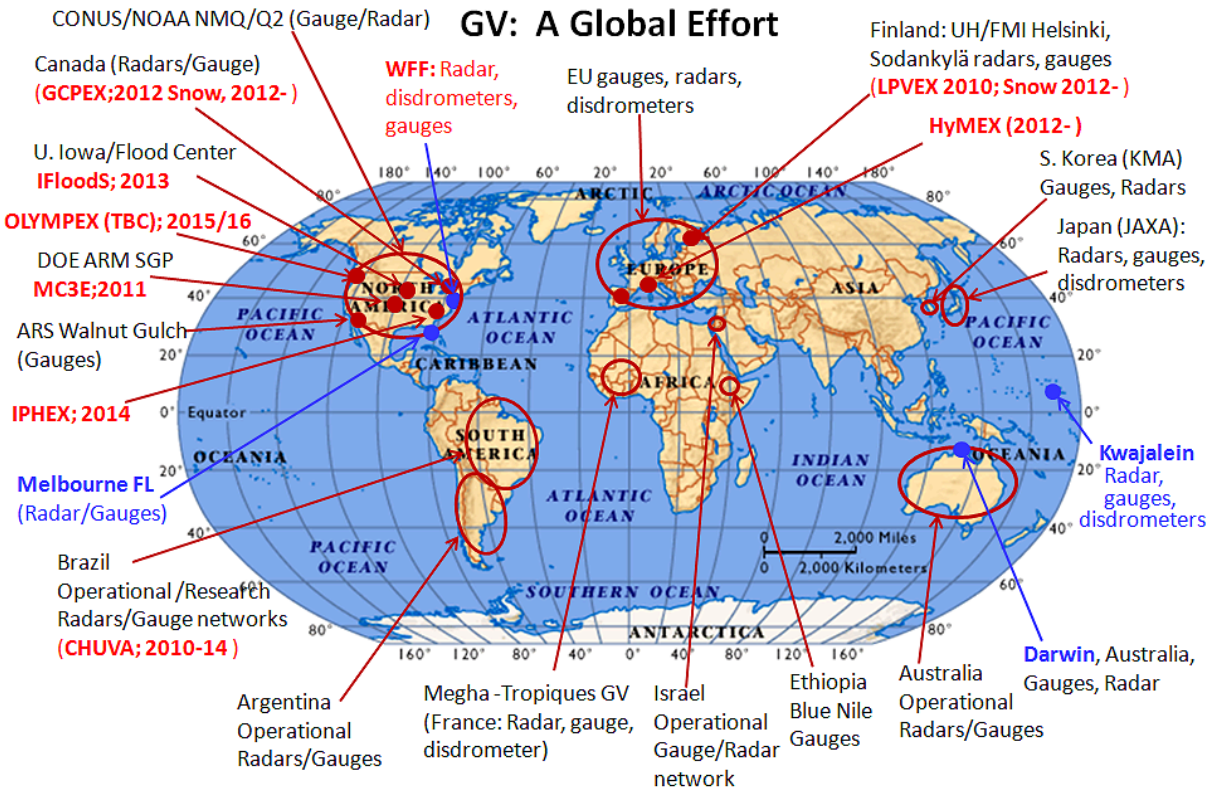


Zonal precipitation averages (in mm day^{-1}) for the full annual cycle in 2015.

Field Campaigns led or co-led by GPM:



GV: A Global Effort



Olympic Mountains Experiment (OLYMPEX) Nov-Dec 2015

PI's: Lynn McMurdie, Bob Houze
Univ. of Washington

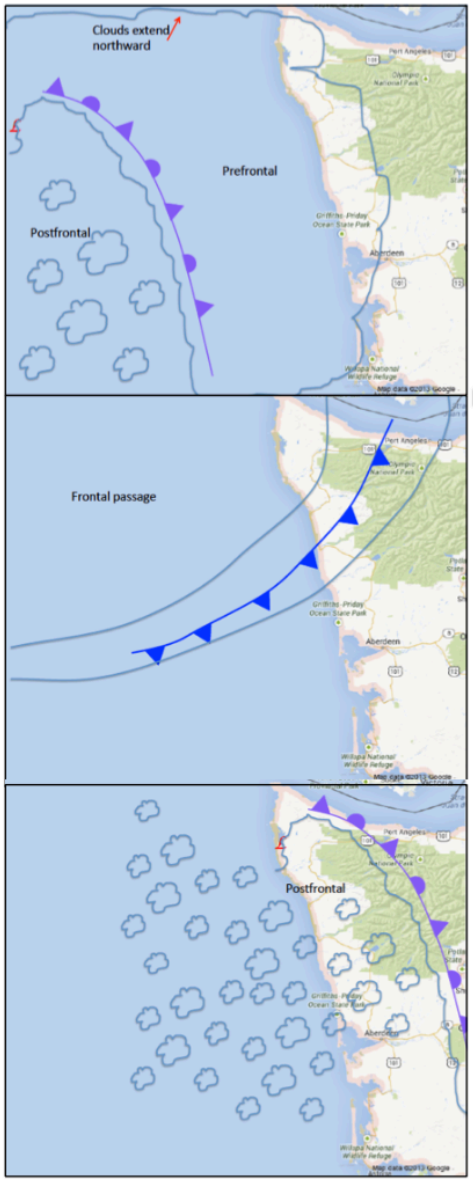
1) Physical validation of GPM satellite-based precipitation (rain and snow) estimation algorithms

2) Relation of mid-latitude frontal precipitation mechanisms and their modification by terrain to GPM rainfall estimation uncertainties

3) Quantifying the accuracy and uncertainty of the GPM precipitation data and impacts on hydrologic applications

4) Merger of numerical modeling and satellite observations to optimize precipitation estimation in hybrid weather monitoring systems of the future.

Doppler-on-Wheels



Pre-Frontal:
Warmer, steady rainfall

Frontal:
Transition from warmer to colder air mass,
less steady but more intense rainfall

Post-Frontal:
Cold air mass, showers and snow in mtns

Figure 6: Idealized depiction of the three sectors of a typical midlatitude cyclone. Cloud outlines as seen from satellite imagery shown in blue, standard frontal symbols shown in blue (cold front) and purple (occluded front): Prefrontal (top), Frontal (middle) and Post Frontal (bottom).

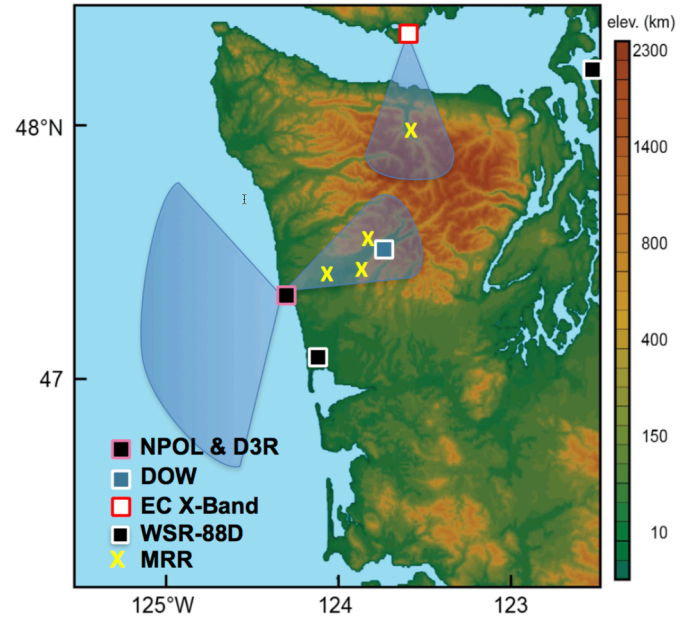
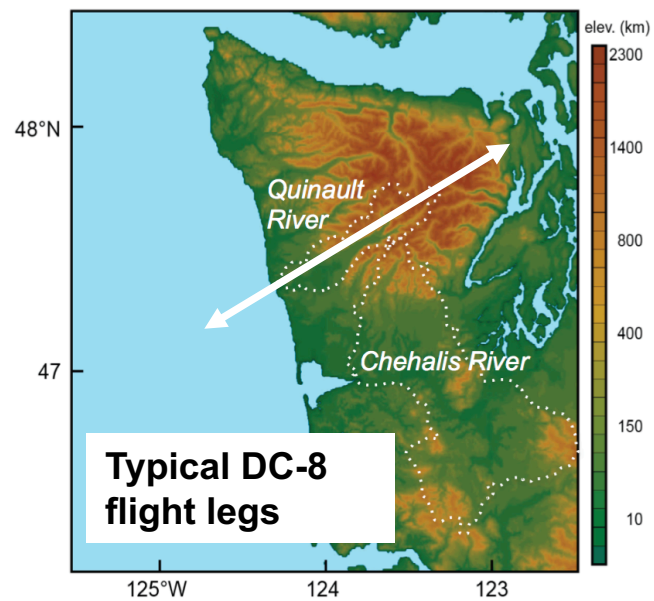


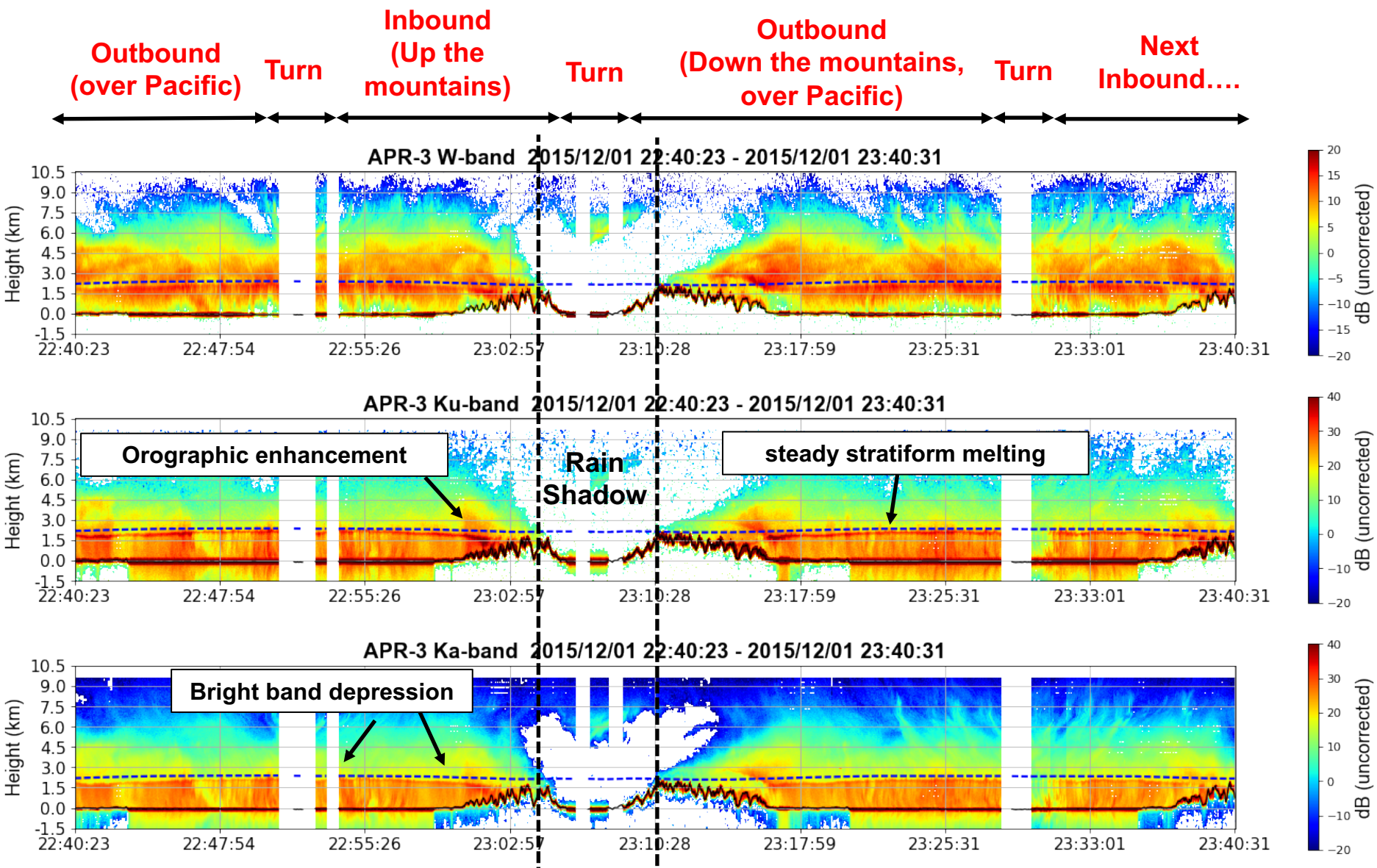
Figure 14: Locations of all the available ground radars for OLYMPEX and the RHI scanning regions for NPOL and EC X-band.



http://olympex.atmos.washington.edu

OLYMPEX APR-3 Radar onboard DC-8 Dec 1, 2015

APR-3 is the "airborne equivalent" of the GPM+CloudSat radars



blue dashed line is MERRA-2 freezing level ≈ 2.2-km

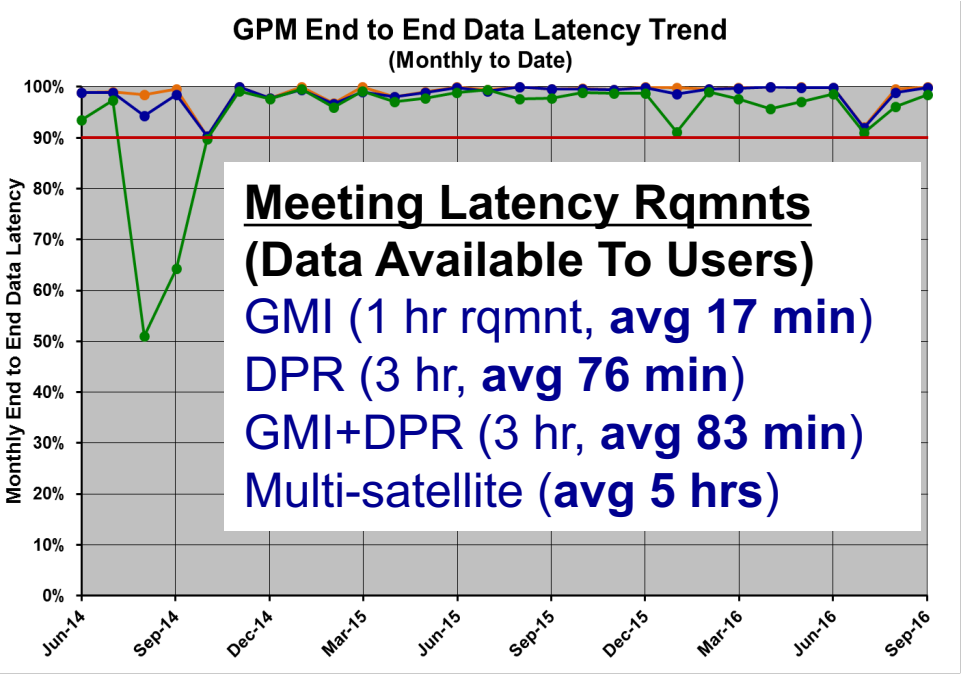
GPM Core Observatory & Data Summary

Spacecraft, Instrument, & Data Capture Status:

Green

Data Products:

- GPM Version 05 algorithms expected in 2017
- TRMM+GPM long-term record expected in 2018



GPM/TRMM data?

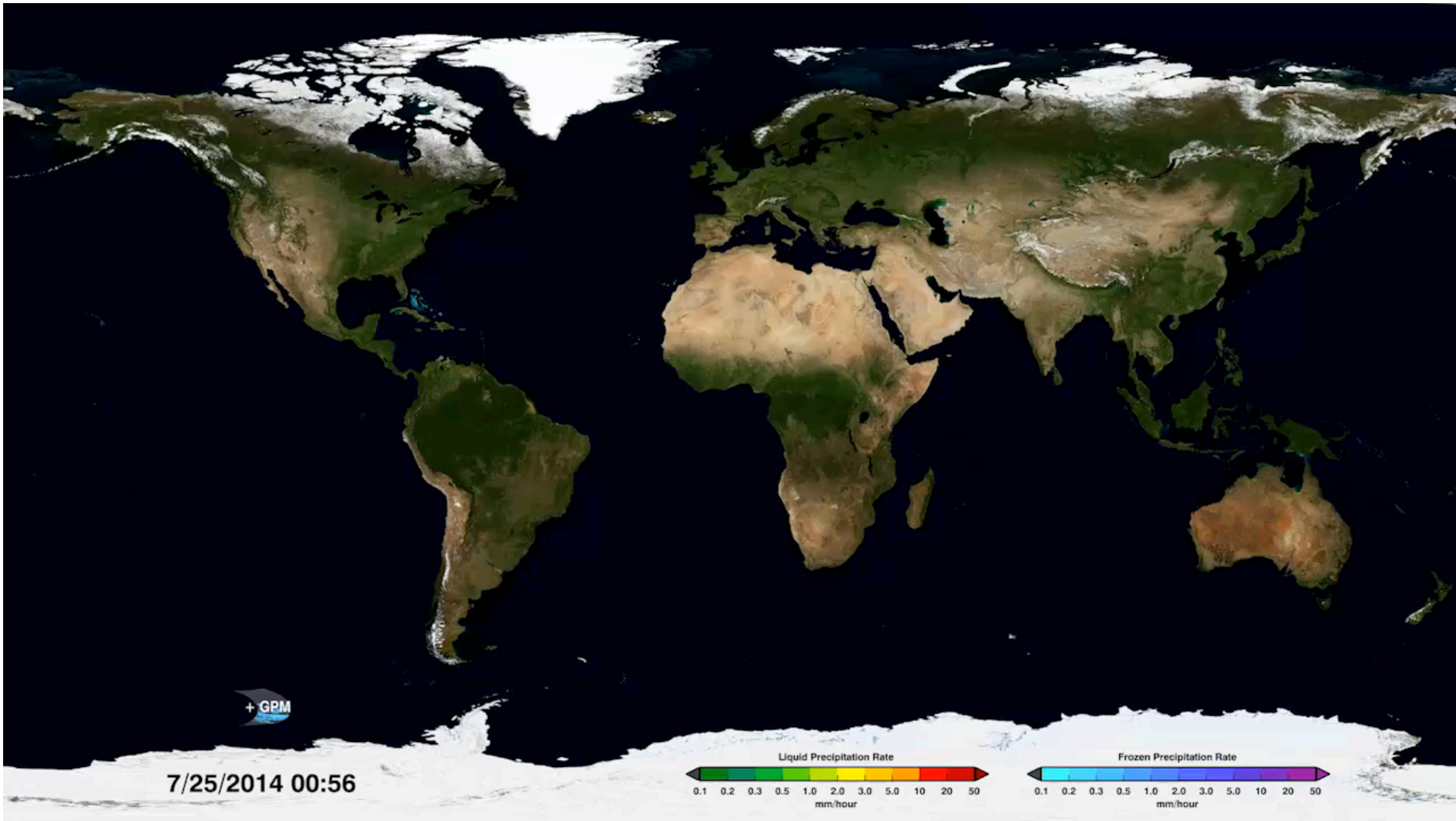
http://gpm.nasa.gov

Fuel Predictions (w/controlled re-entry)

Prediction	Plus/Early	Mean/Nominal	Minus/Late
Nov 2016	08/2029 (15 years)	04/2035 (21 years)	10/2038 (24 years)

Fuel is unlikely to be the limiting factor for GPM

Integrated Multi-satellitE Retrievals for GPM (IMERG)

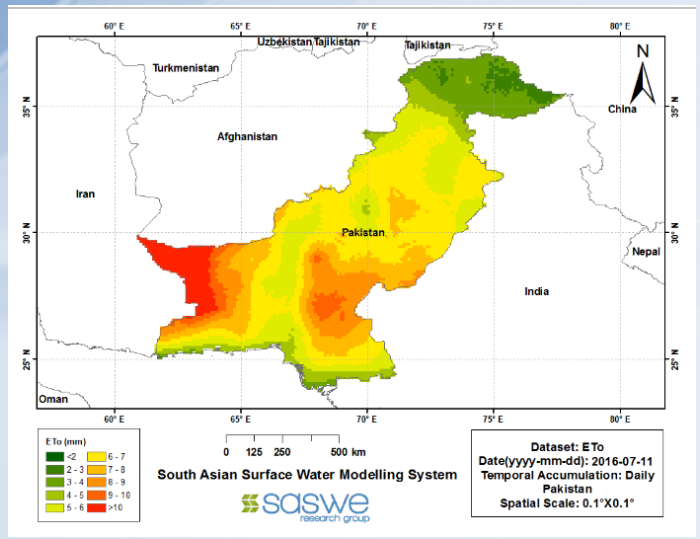


Integrated MultisatellitE (IMERG) Retrievals for GPM available (with a 4-5 hour latency from observations) every 30 min at a 0.1x0.1deg gridbox

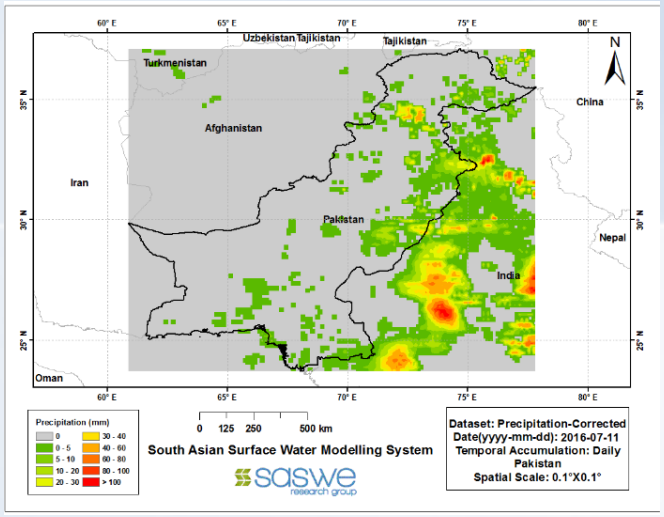
Real-world Application of IMERG

Stakeholder Agency: PCRWR (Federal)
Country: Pakistan; Goal: Water Conservation & Food Security
People Impacted: 700 farmers (2016) 10,000 (2017), 1 million (2018+)

- P-ET (irrigation demand) information pushed to farmers via SMS cellphone broadcast weekly to Pakistani farmers since April 2016.
- Precipitation from IMERG-late (dynamically corrected through a web-crawling system)
- ETo (FAO56) estimated using GFS and Satellite data at 10 km daily grids.
- Housed in UW South Asian Surface Water Modeling system (http://depts.washington.edu/saswe) + Stakeholder agency system (coming soon)
- Reference ETo validated against lysimeter tests for cash crops to advise farmers on ways to conserve water and increase crop yield.
- Project supported by UW and PCRWR



Eto Map for July 11 2016



Dynamically corrected IMERG-late map for July 11 2016

To make a burger, first you need 660 gallons of water ...

The diet of a typical American requires more than 1,000 gallons of water a day to produce. (Kirk McKoy / Los Angeles Times)

By Betty Hallock

JANUARY 27, 2014, 2:35 PM

California's severe drought has probably made a lot of us more aware of our water footprint, which is the amount of fresh water we use plus the amount used for the goods and services we consume every day.

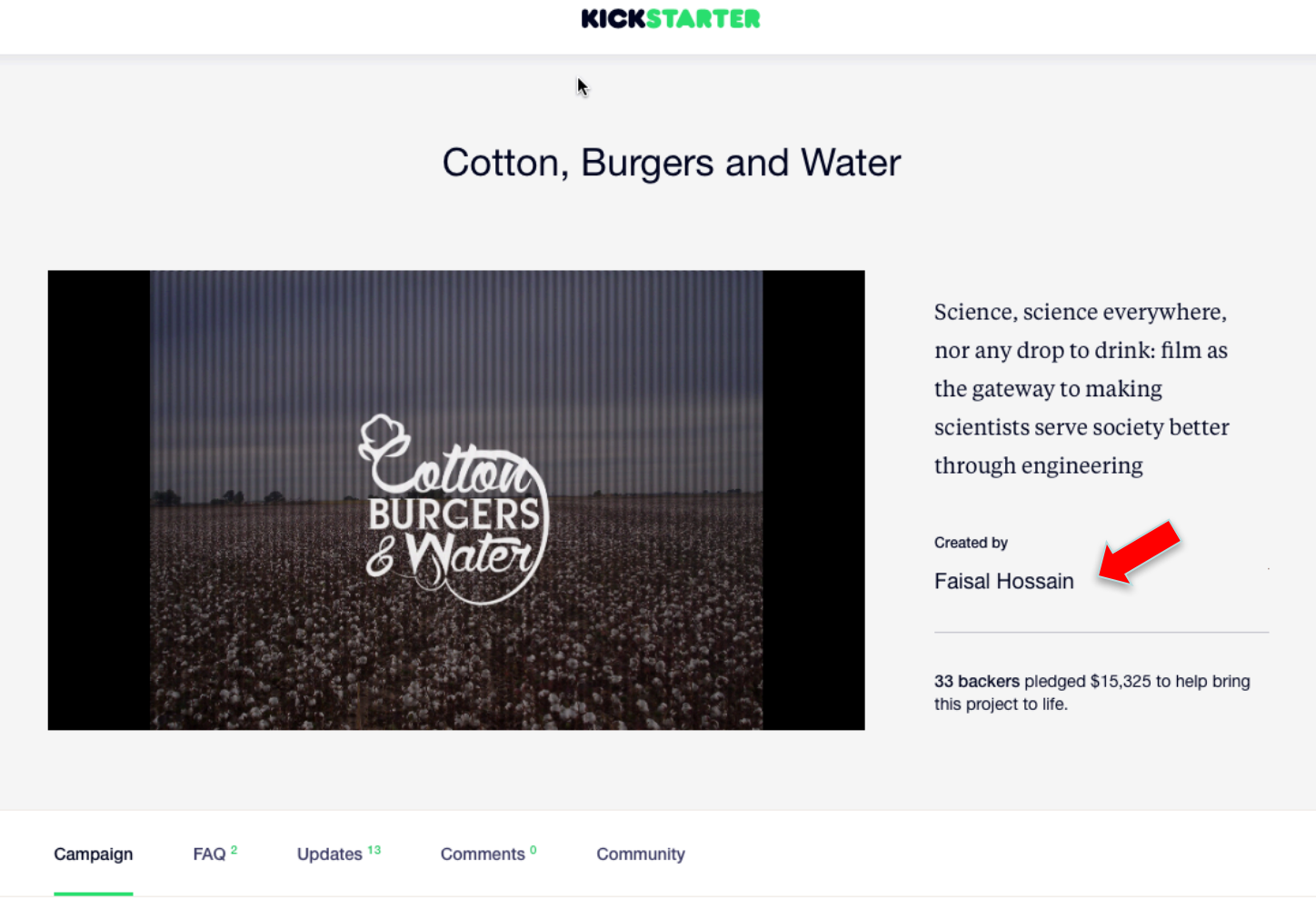
The obvious contributors to our water footprint are washing clothes and dishes, cooking and bathing. But the biggest contributor to our water footprint is our diet.

On average, the water we use in our households is about 98 gallons a day, says a U.S. Geological Survey. The industrial goods we use -- paper, cotton, clothes -- that's about another 44 gallons a day. But it takes more than 1,000 gallons of water a day per person to produce the food (and drinks) in the average U.S. diet, according to several sources. More than 53 gallons of water go into making 1 cup of orange juice, for example.

Food	#Gallons Req
1 slice bread	11
1# wheat	132
1 gal wine	1008
1 gal beer	68
1 gal milk	880
1# beef	1799
1 apple	18
1 cup apple juice	59
1 cup coffee	37

http://www.latimes.com/food/dailydish/la-dd-gallons-of-water-to-make-a-burger-20140124-story.html

Cotton, Burgers & Water tells us the story of a Pakistani cotton farmer and a researcher based in the US. Our two protagonists are from two different parts of the world and their surroundings are quite different and yet they are bound by a common theme - cotton and water.



https://www.youtube.com/watch?v=rIWus8OVocc

https://www.kickstarter.com/projects/fhossain/cotton-burgers-and-water

Looking Ahead

During my presentation, GPM collected another 600,000 observations or so…..

There was 16 years of TRMM before GPM….

CloudSat, while hobbling, is still functioning....

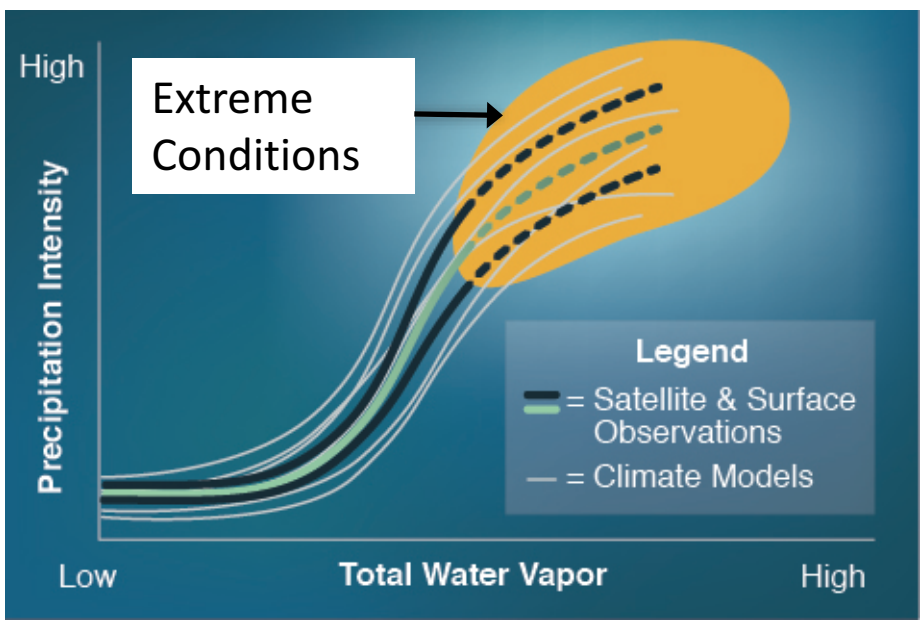
Extreme Precipitation

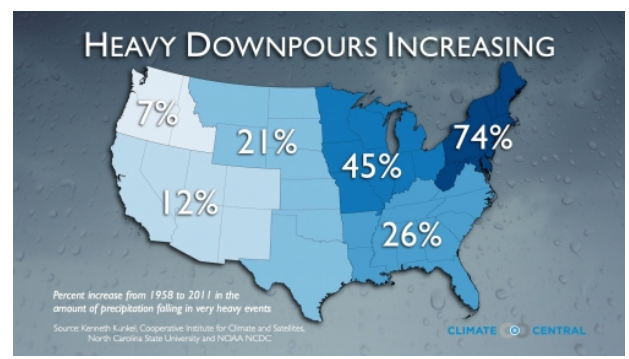
From a GPM perspective, the precipitation is coexists with the surrounding water vapor structure; can't readily separate the two

Moreover, the precipitation estimation procedure utilizes water vapor from NWP models or reanalysis

Current space-based water vapor measurements such as from AIRS/Aqua are degraded in the presence of clouds and precipitation

How to obtain global, vertically resolved water vapor profiles under extreme precipitation conditions?



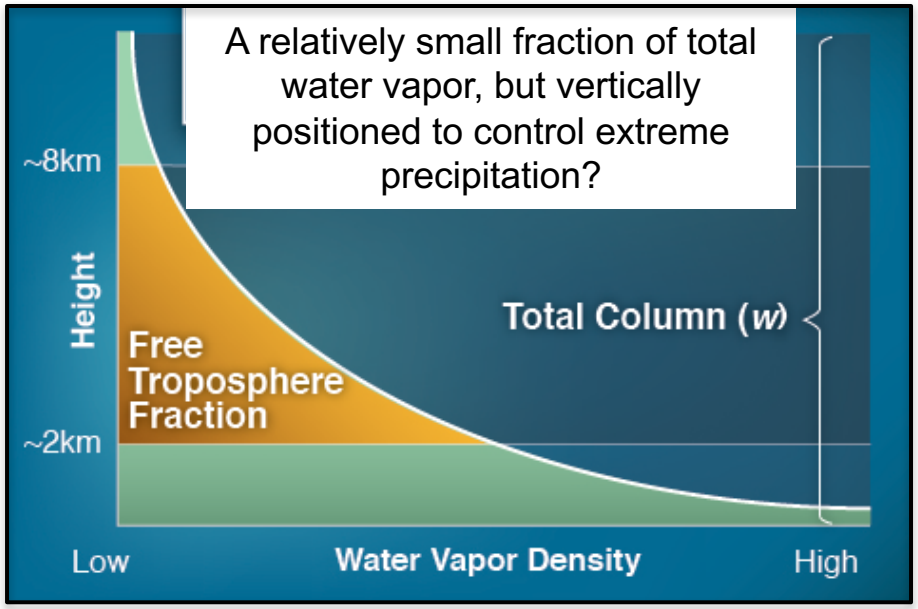


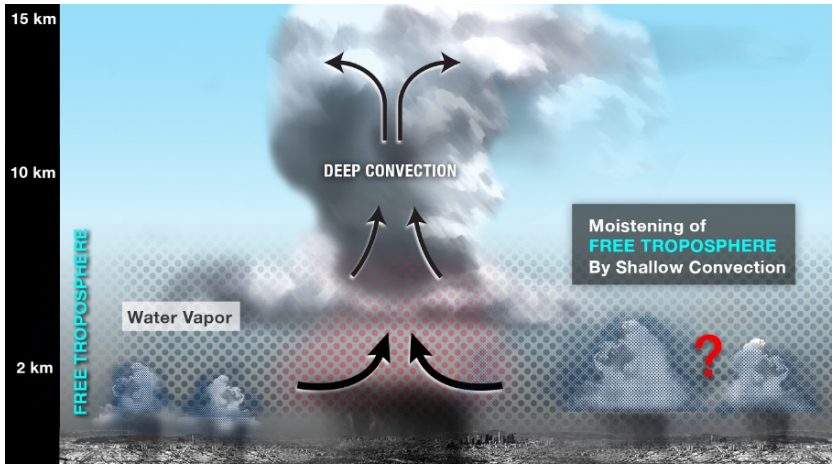
Extreme Precipitation

Ideas and concepts studied extensively by D. Neelin/UCLA & his students, colleagues

Most of the Earth's water vapor is in the lowest few km of the surface, where surface and boundary layer processes predominate

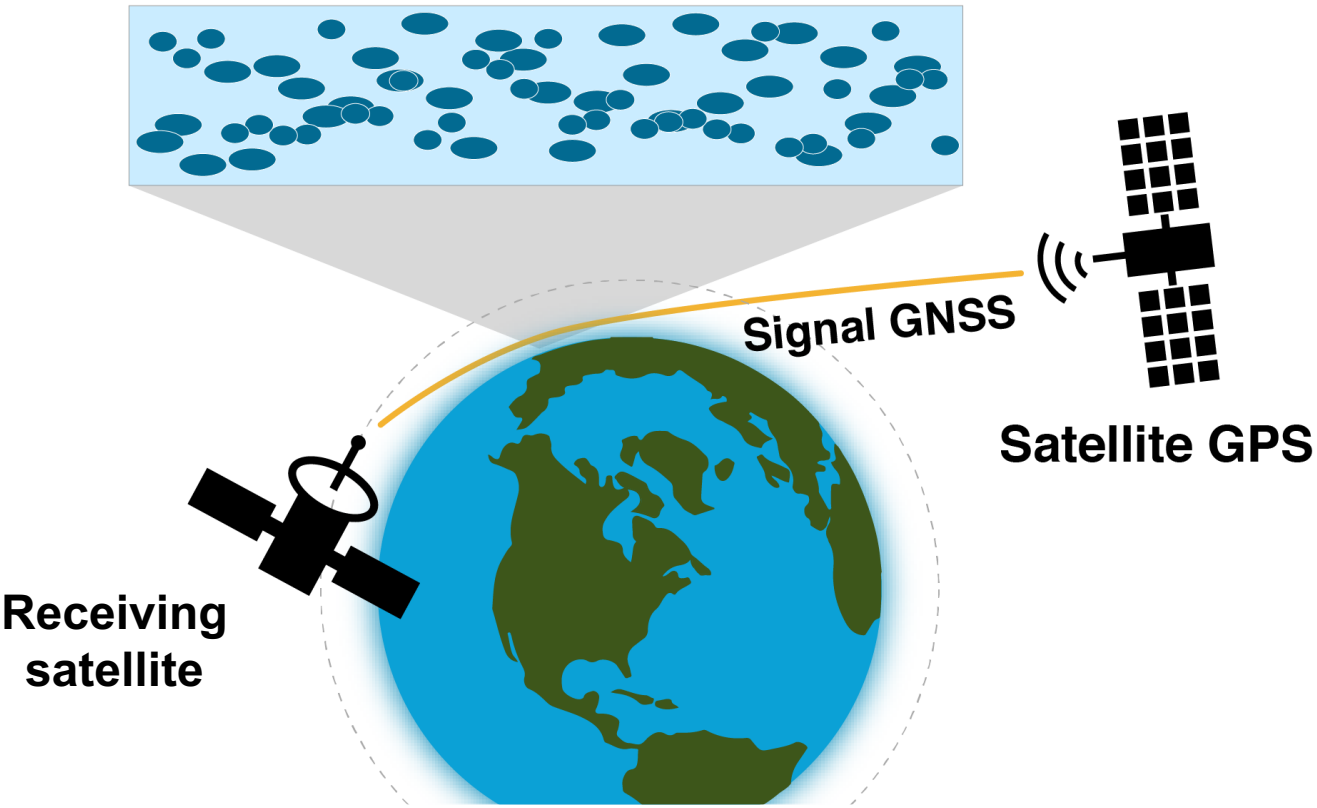
Origin and role of free-tropospheric (above the BL) water vapor?





Global Navigation Satellite System (GNSS) Radio Occultations (RO)

- Current RO observing system came of age in 2006 with the deployment of the 6-satellite COSMIC constellation, COSMIC-2A to follow in 2017
- Provide high-resolution vertical refractivity structure from which vapor structure is inferred; coarse horizontal (limb type measurement)
- Have demonstrated very high impact when assimilated into forecast models

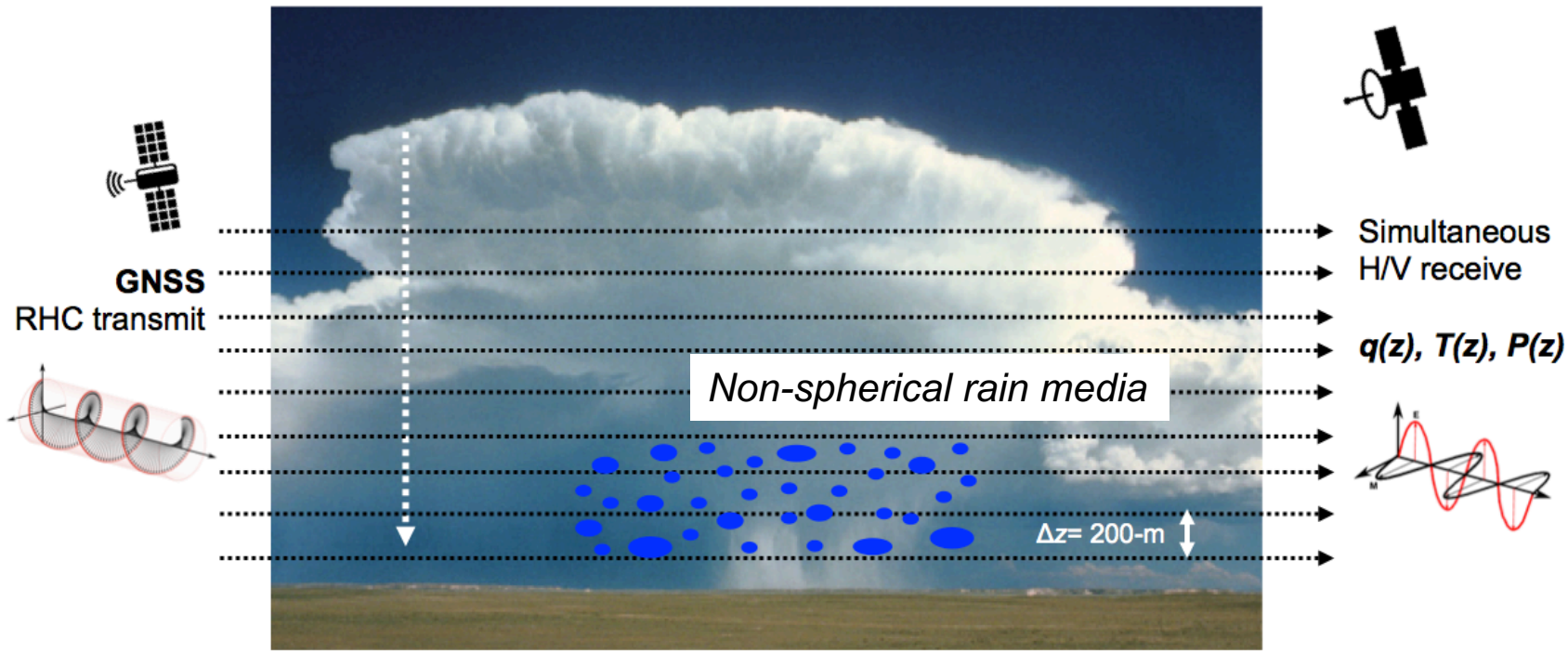


Polarimetric Radio Occultations Concept

Typical GPS signals are transmitted near 1.4 GHz….essentially, no loss of intensity even when passing through heavy precipitation

However, the same propagation through heavy precipitation induces a *cross-polarized* component, measured as a differential phase delay by accurate GPS clocks.

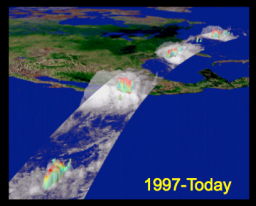
If feasible, such a measurement has potential to extend the capabilities of normal RO, with *simultaneous* measurements of the profile of water vapor (q), temperature (T) and an indication of heavy precipitation.



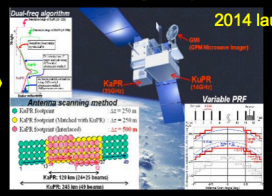
Future: Cloud and Precipitation Process

Courtesy S. Tanelli, JPL/Caltech

TRMM/PR – NICT/JAXA
Ku, Scanning, Tropical Rain

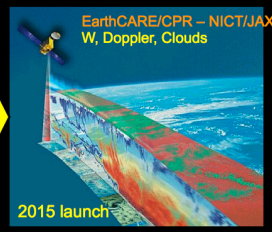


GPM/DPR – NICT/JAXA
Ku/Ka, Scanning, Precipitation



CloudSat/CPR – JPL/NASA/CSA
W, Nadir, Clouds

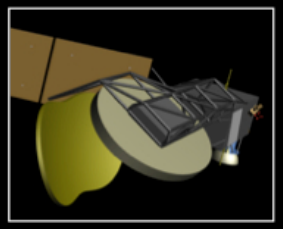
EarthCARE/CPR – NICT/JAXA
W, Doppler, Clouds



Examples of radar concepts under study by the international community

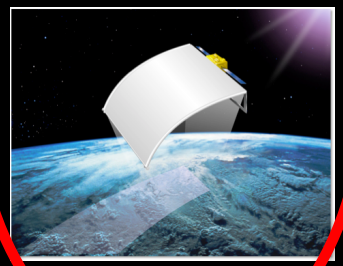
For US Decadal ACE meas. concept

ACERAD
W/Ka, Scanning Ka, Doppler



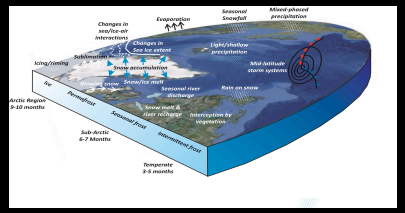
Reflectarray Radar
W/Ka, Scanning Ka, Doppler

CaPPM* Radar Ku/Ka/W, Doppler, Scanning



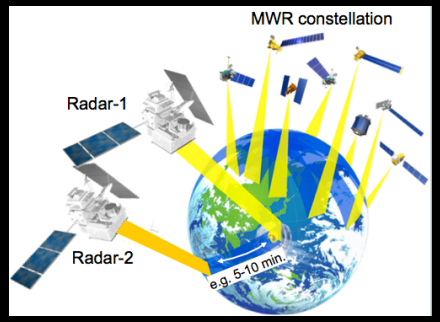
Artist's concept

SnowSat* / PPM
W/Ka, Doppler

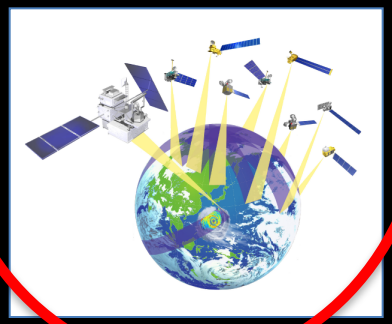


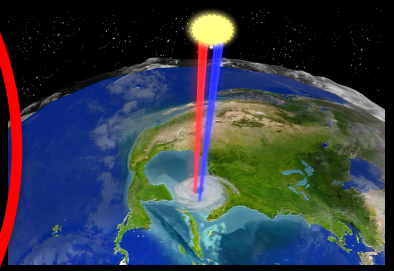
GEORadSat*
W, Scanning, Doppler, GEO

GPM* w/ Radar in Train Formation
Radar 1 & 2: Ku/Ka/W, Scanning

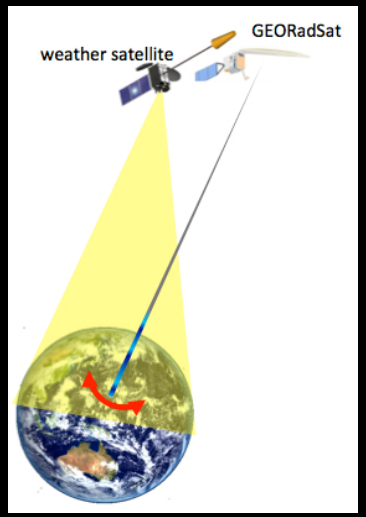


RadarGPM* Constellation
Core S/C: Ku/Ka/W, Scanning
SmallSat: One freq radar

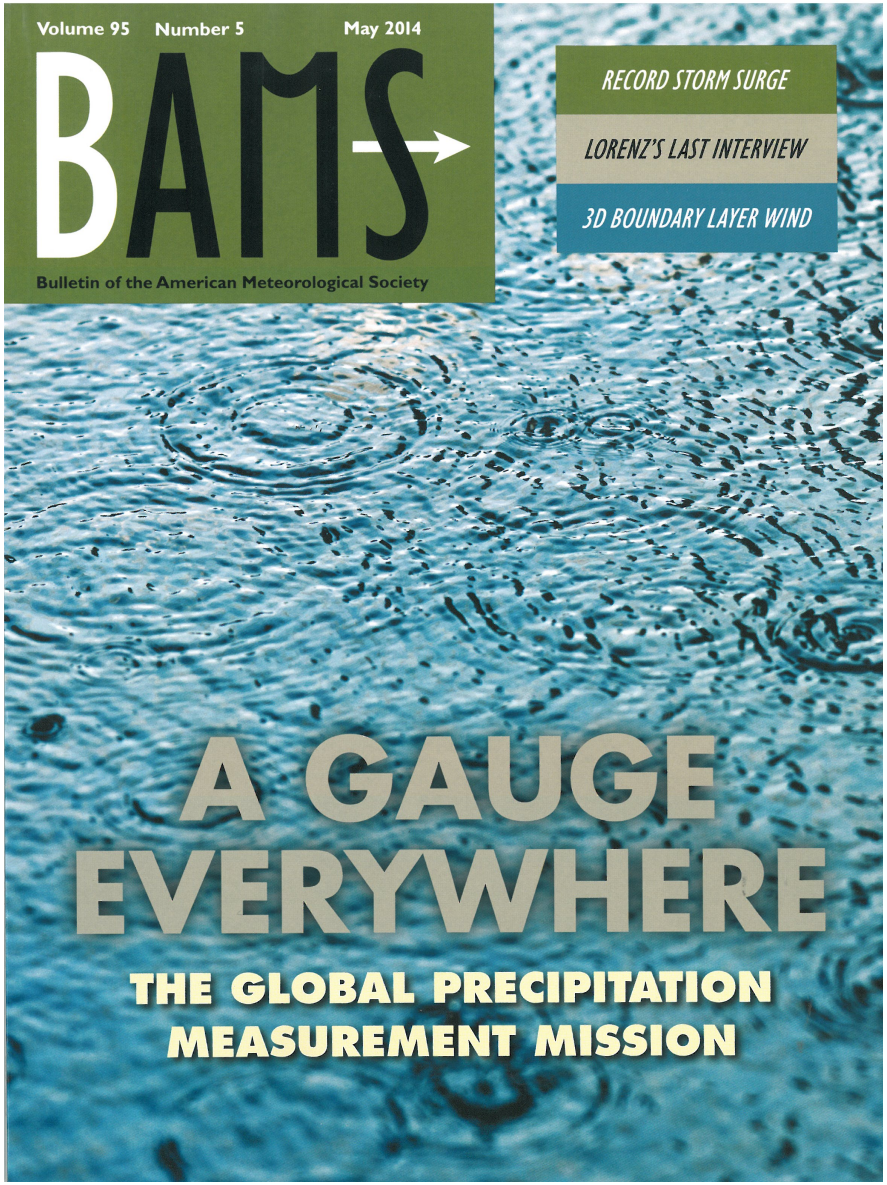




NEXRAD-In-Space*
W/Ka, Scanning,
Doppler, GEO



*Mission Concept – Pre-decisional – Planning and Discussion Purposes Only



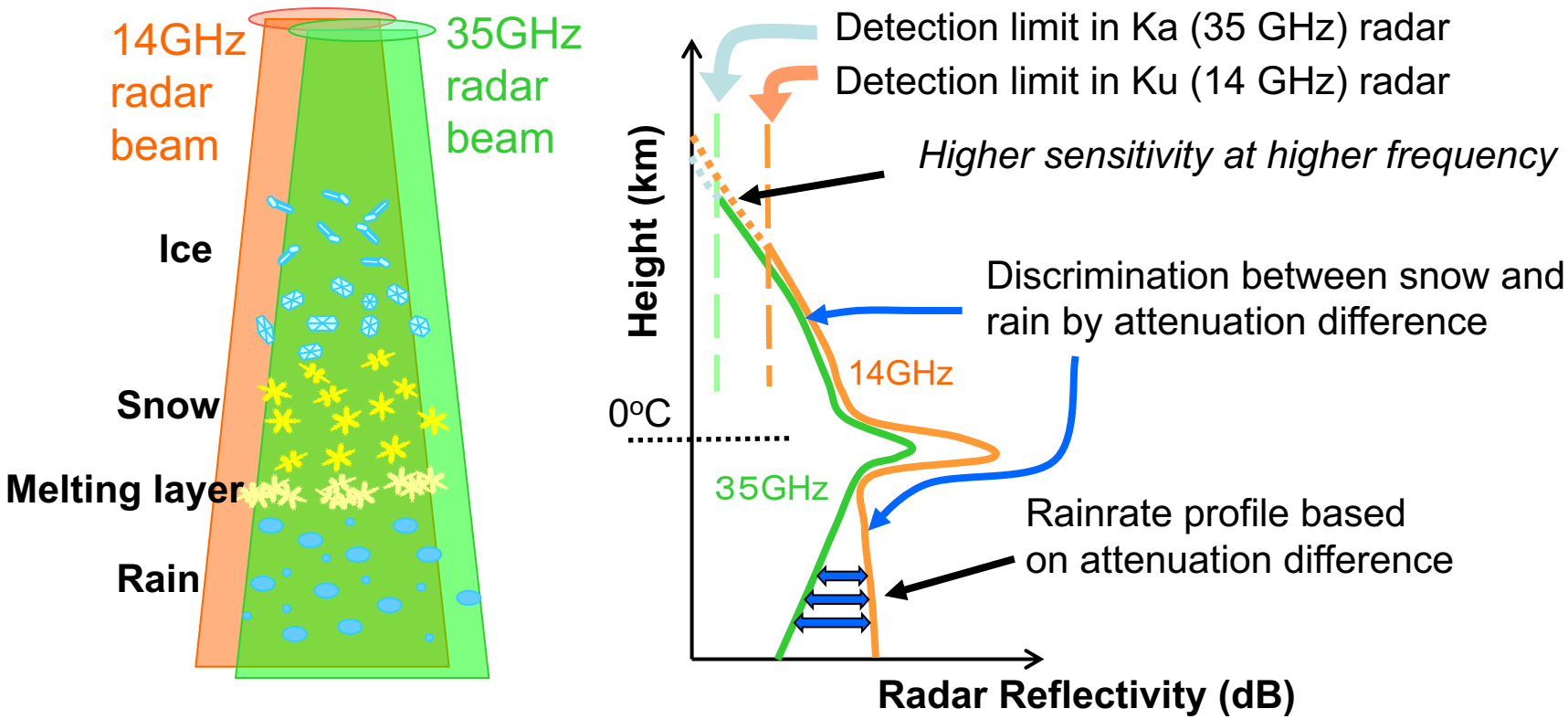
BAMS, Vol. 95, pp. 701-722, May 2014

Thank you for the invitation to visit.

There was quite a bit of material presented here, and contact me if you have questions, ideas, comments, etc.

jturk@jpl.nasa.gov

Dual Frequency Precipitation Radar (DPR)



Roles of DPR (TRMM Ku-only heritage carries over)

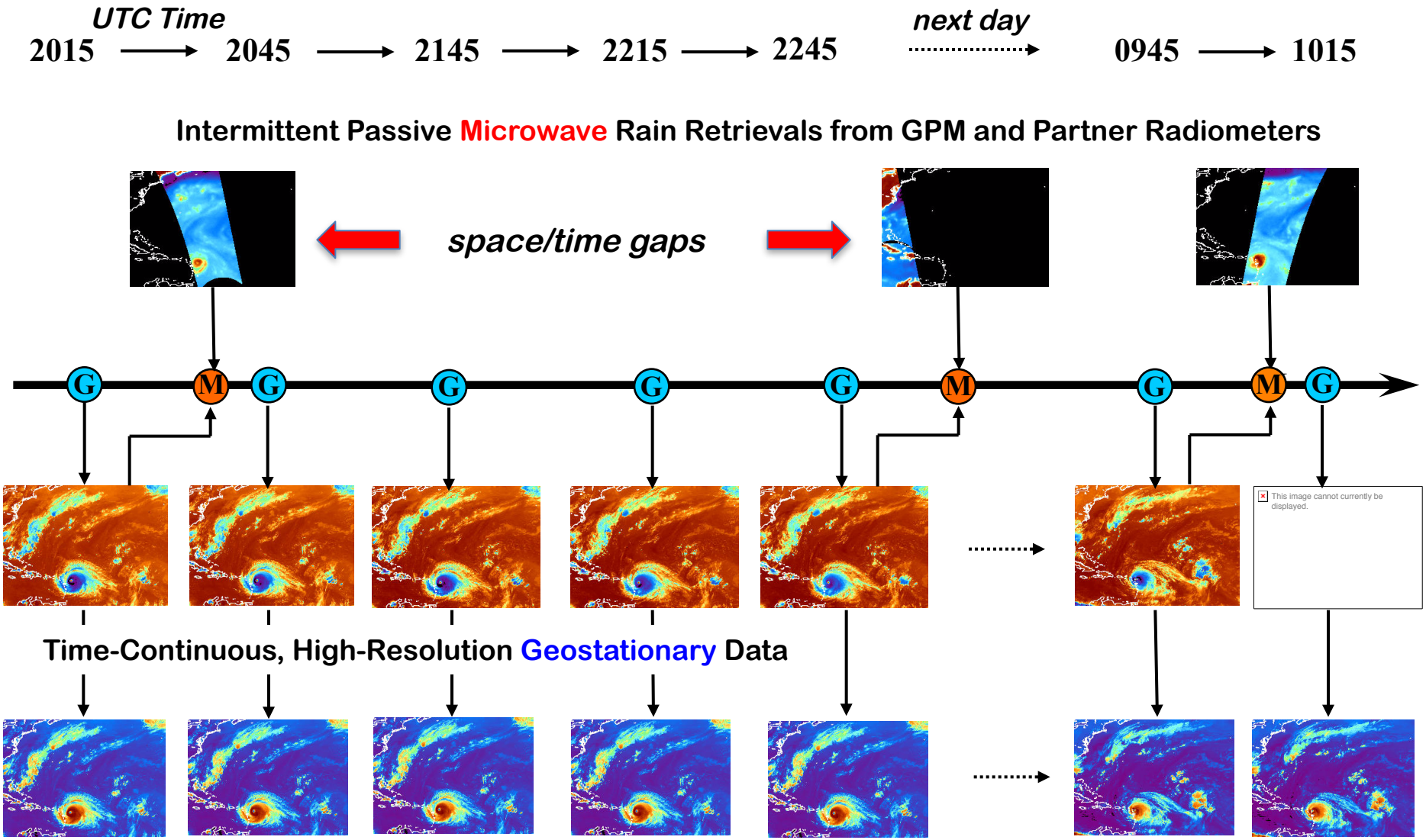
Improvement of estimation accuracy with the two frequencies

Better identification of hydrometeor type, phase state

To advise the radiometers in the GPM constellation

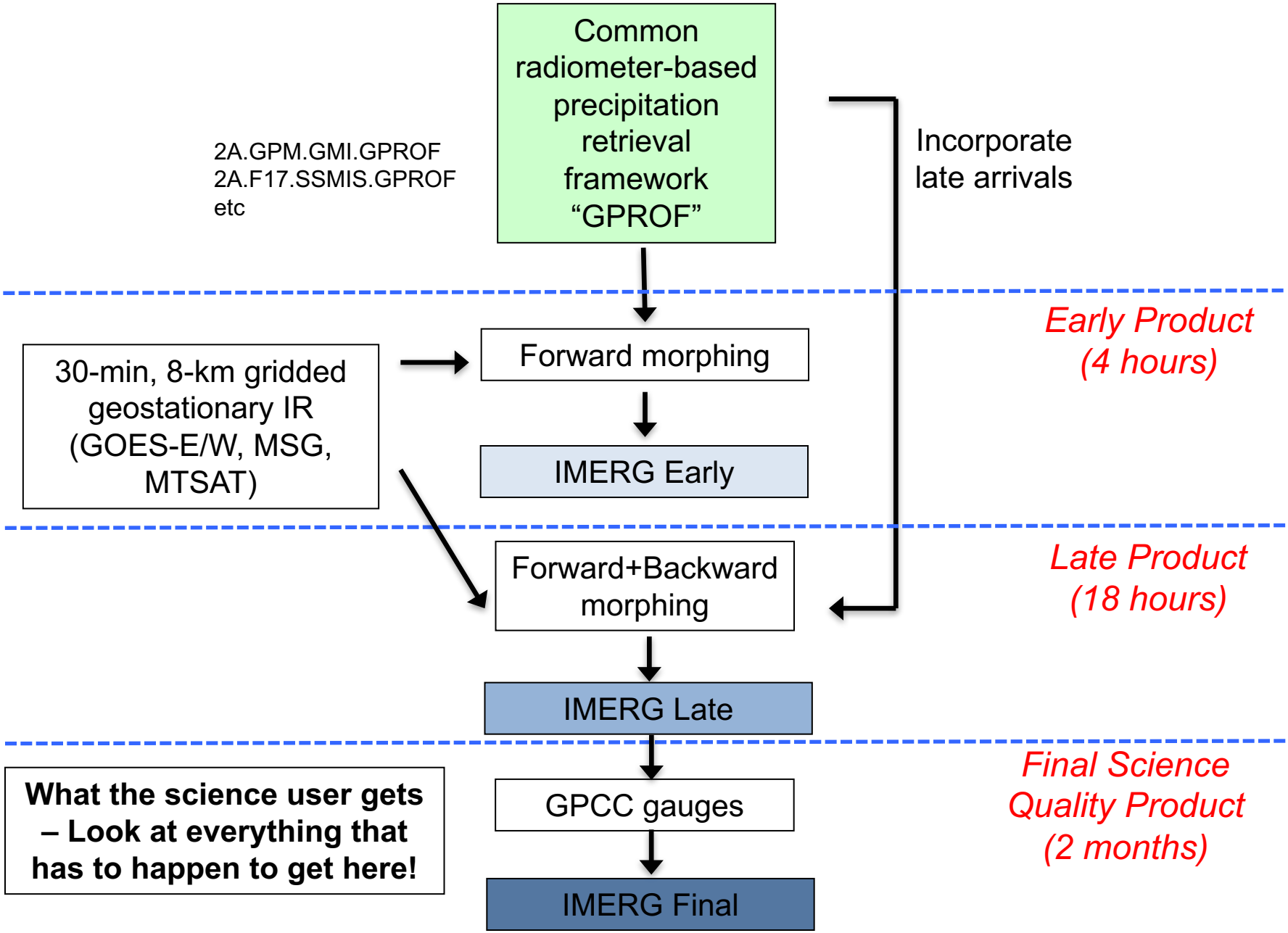
Improve global precipitation mapping over land and ocean

High Temporal/Spatial Resolution Precipitation (30 min, 0.1-degree)



Desired Output: Fast-refresh Continuous Rainfall Rate and Accumulations

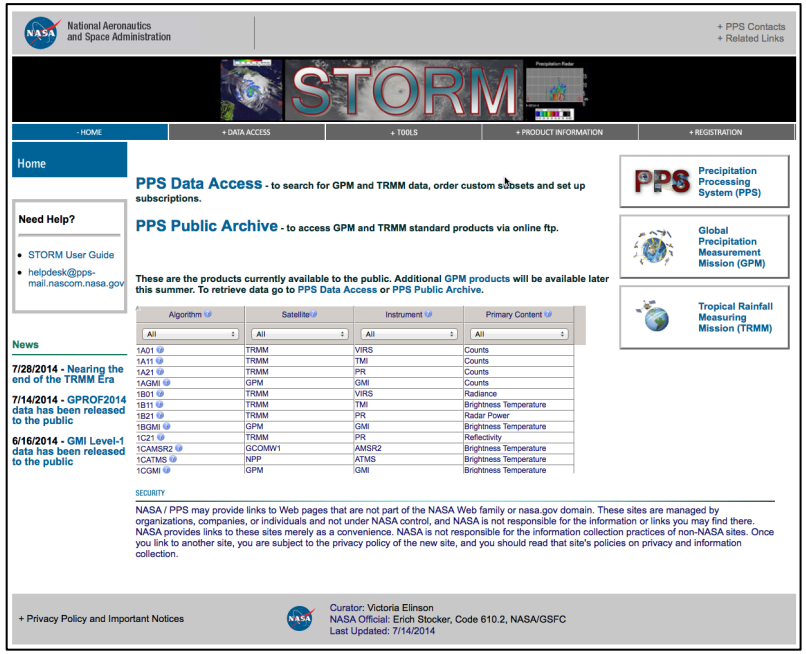
GPM Level-3 "Merged" Dataset: IMERG

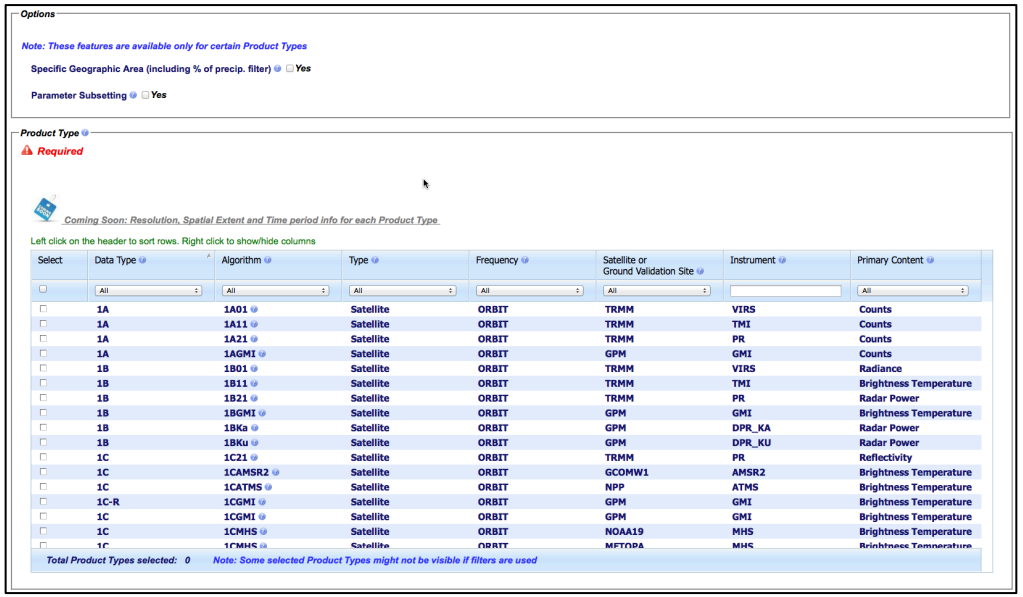


All GPM Data Are Open Access at the Precipitation Processing System (PPS) at NASA GSFC

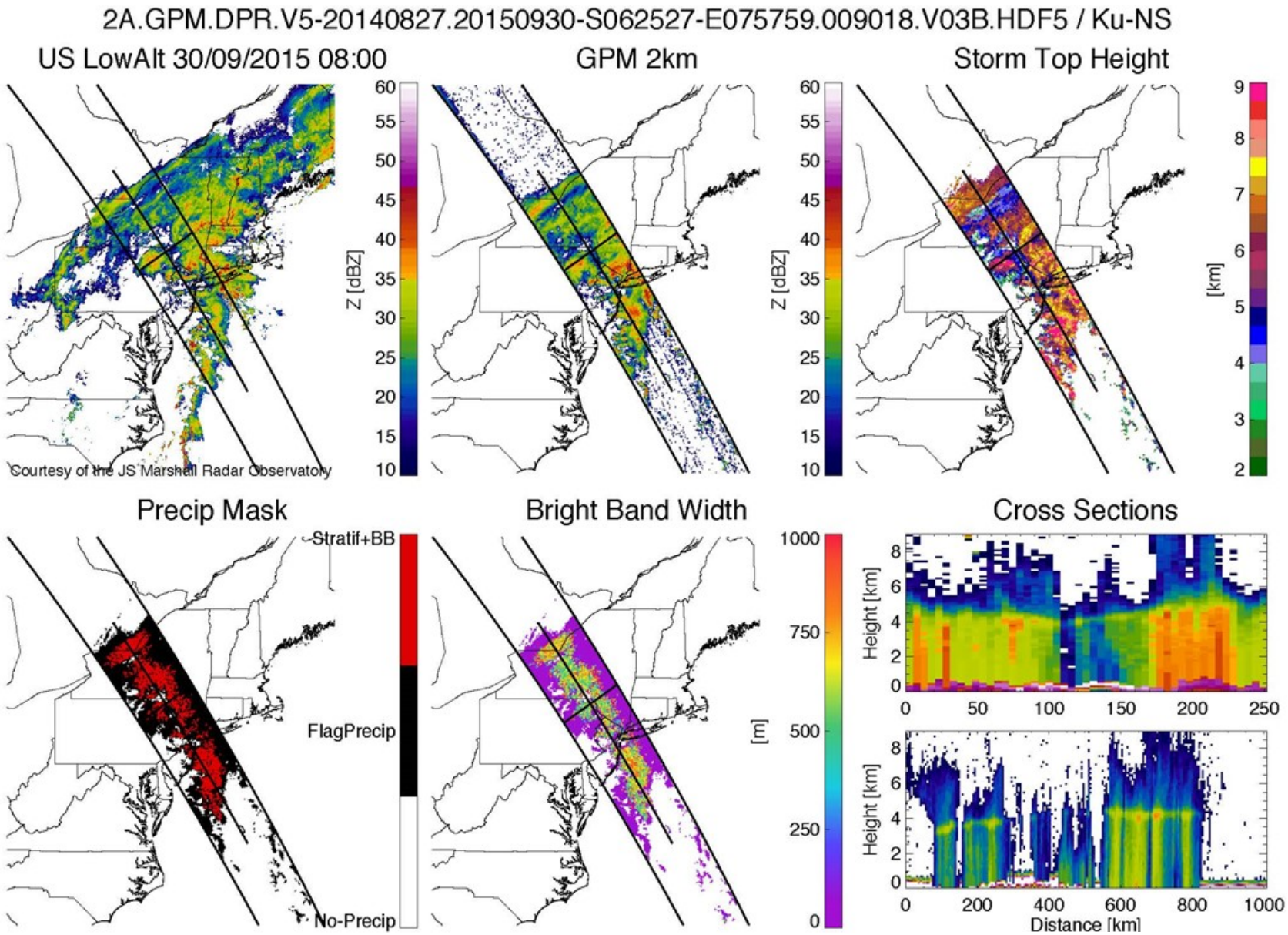
Science Team Online Request Module (STORM) Access:
http://storm-pps.gsfc.nasa.gov

Anonymous ftp access:
ftp://arthurhou.pps.eosdis.nasa.gov Science production (requires registration)
ftp://jsimpson.pps.eosdis.nasa.gov/NRTPUB Near realtime products (GMI latency about 20 minutes!)





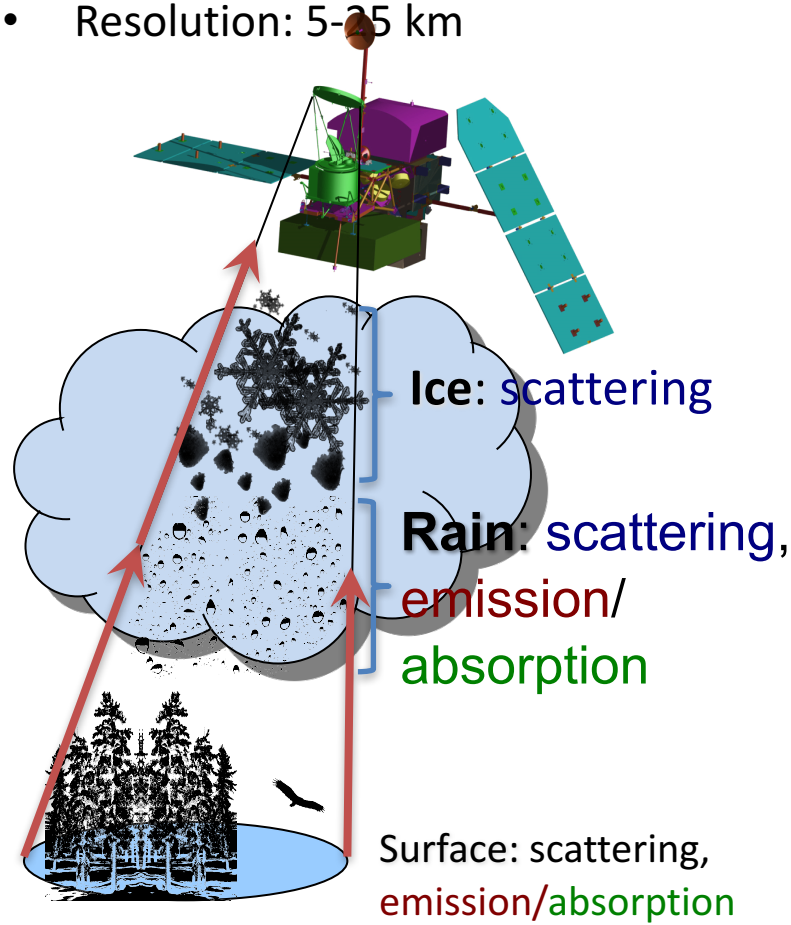
GPM Observations – Microphysical 3D Views

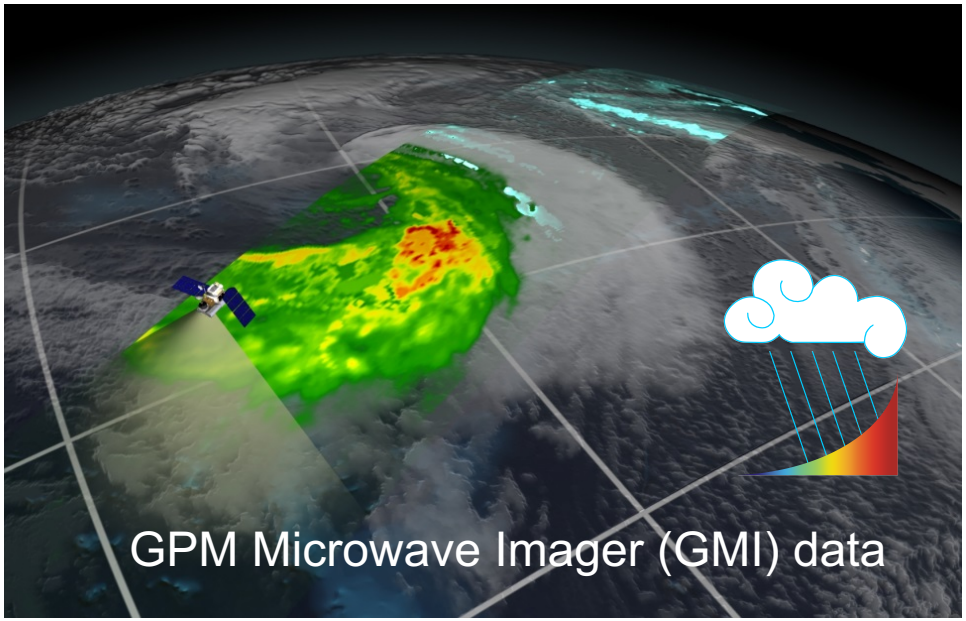


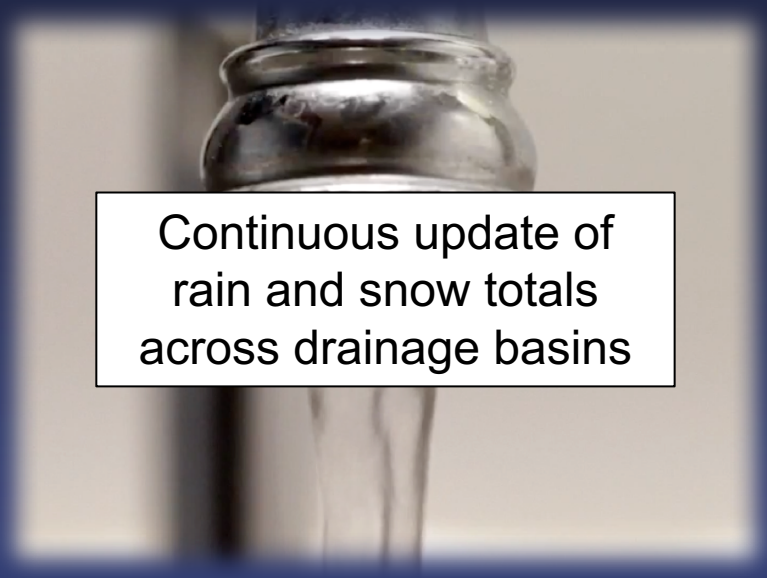
Courtesy Ann Fridlind, GISS

GPM Microwave Imager (GMI)

- Precipitation & surface features emit energy at different frequencies (GHz). The GMI passively observes this energy to estimate surface precipitation
- Proven best calibrated instrument of its kind (to within 0.5 K or 1.0 F)
- Resolution: 5-25 km

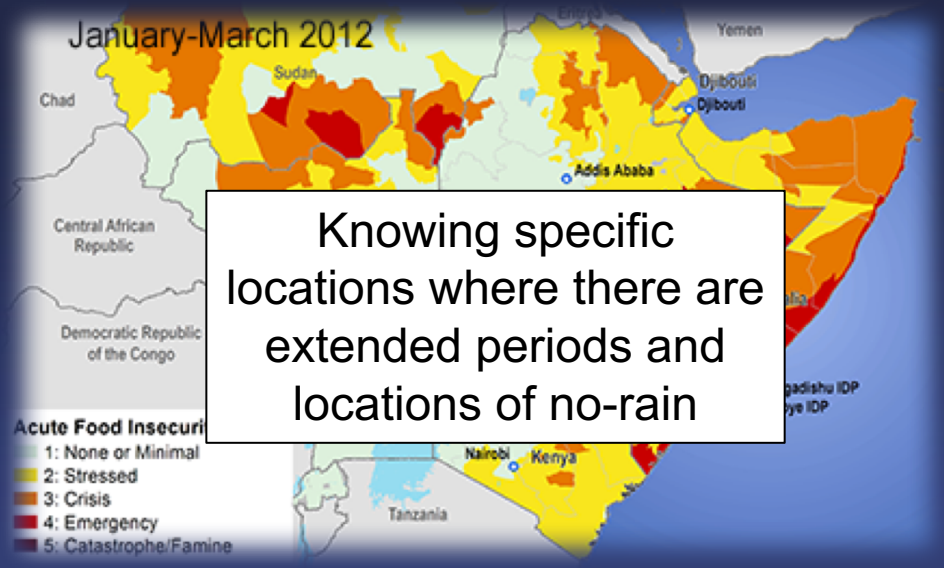






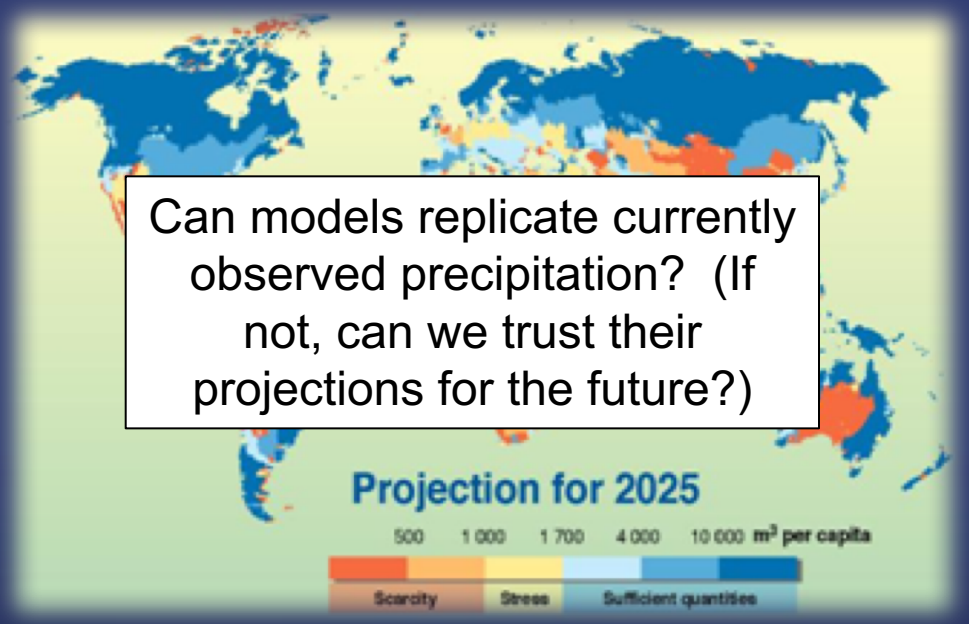
Continuous update of rain and snow totals across drainage basins

Freshwater Availability

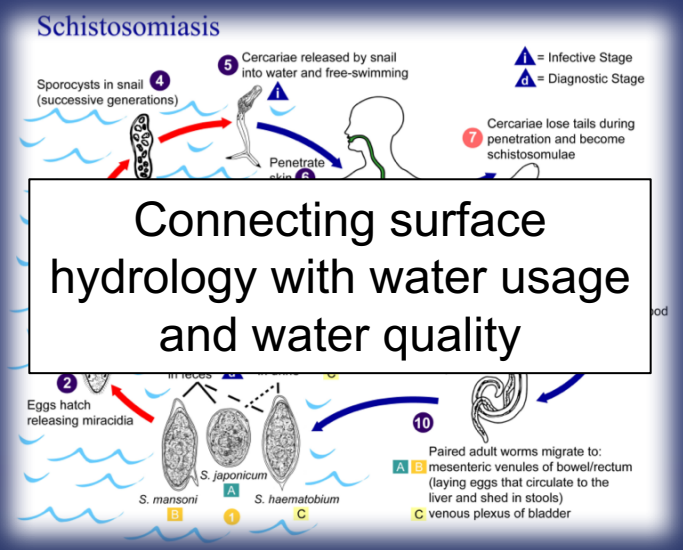


Knowing specific locations where there are extended periods and locations of no-rain

Agriculture/Famine Early Warning



Can models replicate currently observed precipitation? (If not, can we trust their projections for the future?)



Connecting surface hydrology with water usage and water quality

World Health

Creating “High Resolution” Multi-Satellite Precipitation Products (4)

- The collection of constellation satellites provide instantaneous “snapshots” of the precipitation, as the satellite flies above

- As we saw in the earliest slides, even with the many constellation satellites, there are significant spatial and temporal gaps in global coverage

- Fill in space-time sampling gaps between the intermittently-spaced PMW radiometric-only precipitation retrievals using geostationary satellite data

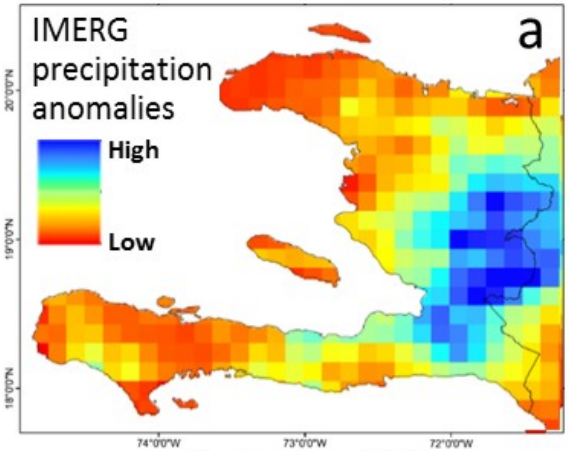
The **GPM Core Observatory** carries **two advanced instruments** to observe rain & snow and serve as a **calibrator** for measurements taken on partner satellites.

GPM Microwave Imager (GMI): 10-183 GHz (NASA)
13 channels provide an integrated picture of the energy emitted by precipitation, including light rain to heavy rain to falling snow.

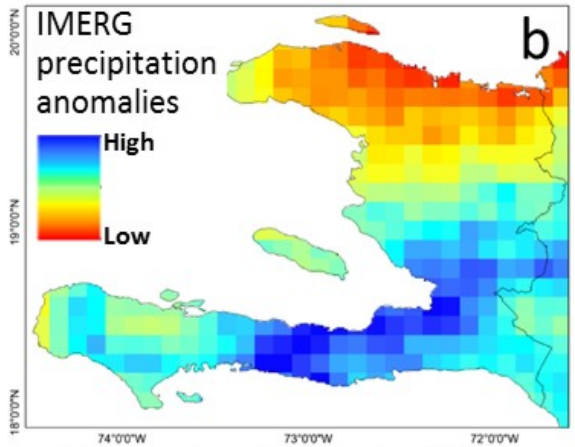
Dual-frequency Precipitation Radar (DPR): Ku-Ka bands (JAXA)
Two different radar frequencies that measure precipitation in 3-D throughout the atmospheric column.

Launched February 28, 2014 by JAXA

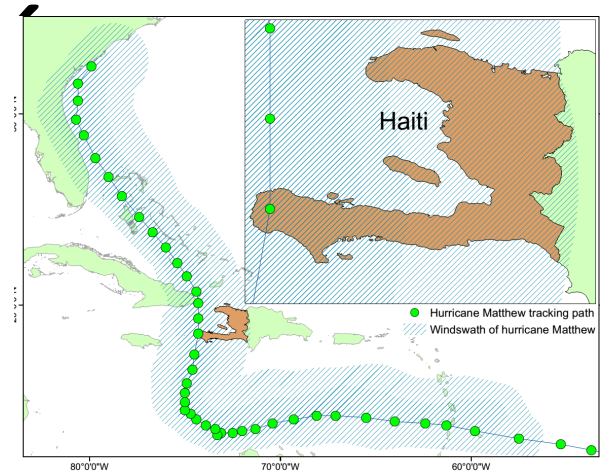
GPM Used to Estimate



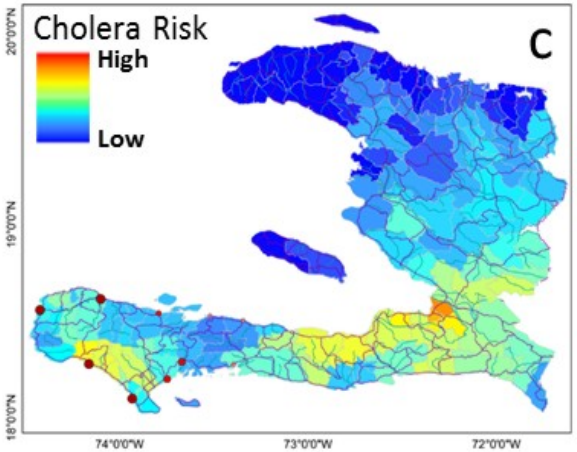
September 2016



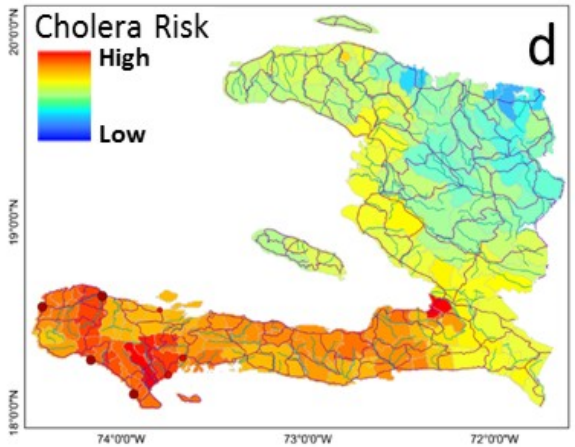
1 September- 13 October 2016



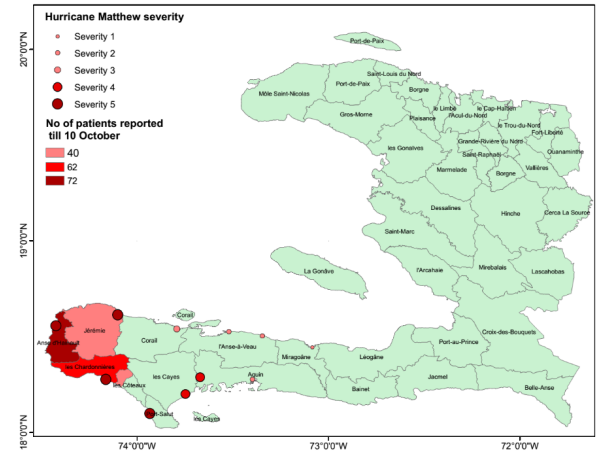
Hurricane Matthew
track over Haiti



Pre-hurricane cholera risk map
based on hydro-climatic
condition



Post hurricane cholera risk map
based on 2 weeks hydro-climatic
condition



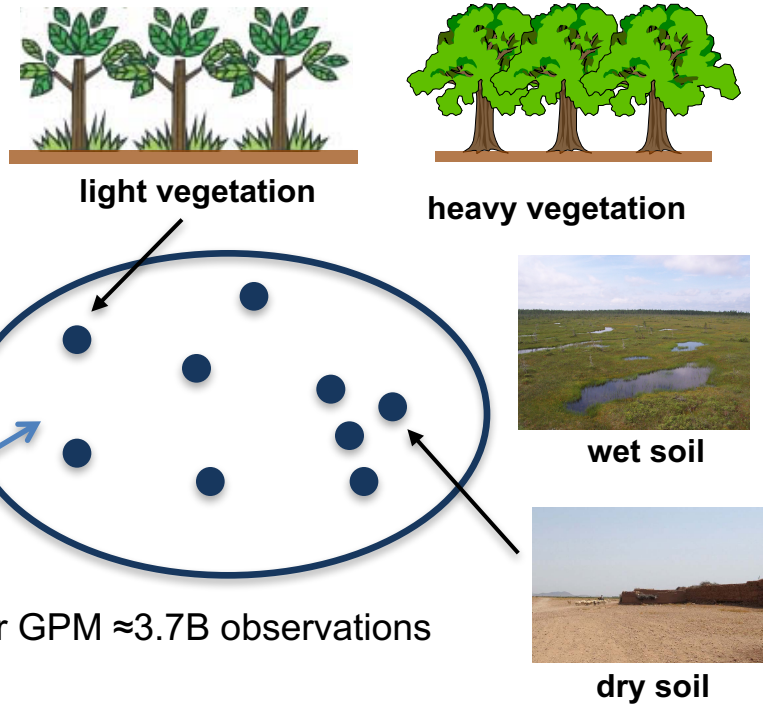
Cholera condition in Haiti till 10 October

GPM IMERG data was used along with air temperature anomalies and population to compute maps of estimated cholera risk in Haiti following the passage of Hurricane Matthew 1-2 October, 2016. Plots show a) IMERG precipitation anomalies prior to and b) following Hurricane Matthew; c) track forecast for Matthew over Haiti, d) shows a Cholera risk map based on pre-hurricane hydroclimatic conditions, e) updated Cholera risk map 2 weeks after Hurricane Matthew, and f) reported cases of Cholera as of 10 Oct 2016

Over-Land Precipitation Estimation

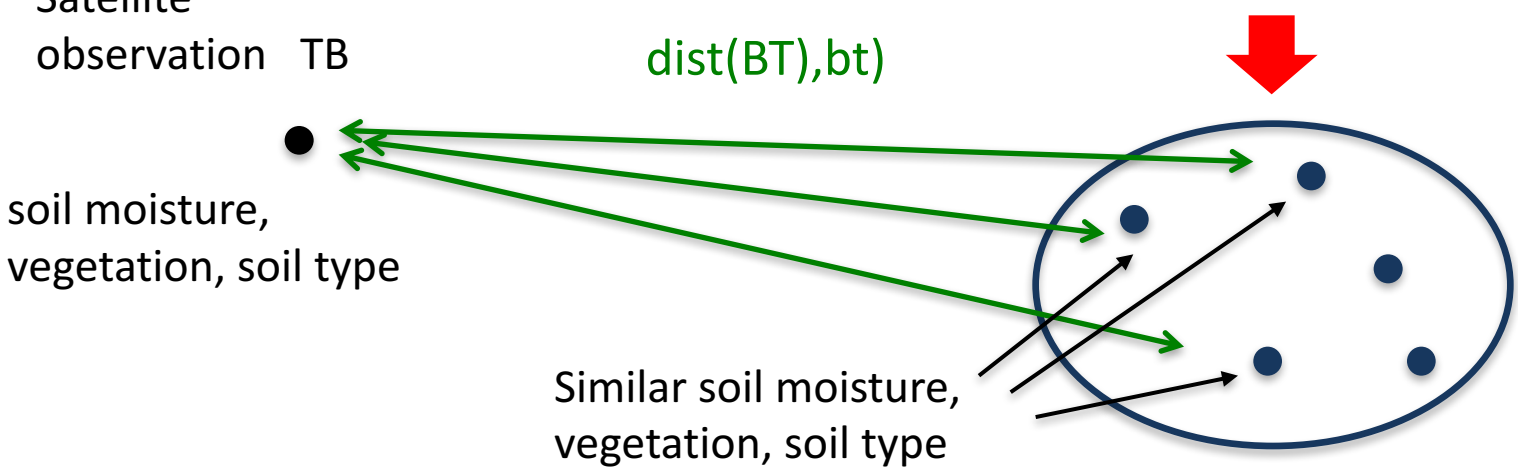
Bayesian Retrieval

Find "similar" precipitation conditions from a large collection of previous GPM observations



Encompasses range of all possible solutions, under wide variety of surface and environmental conditions

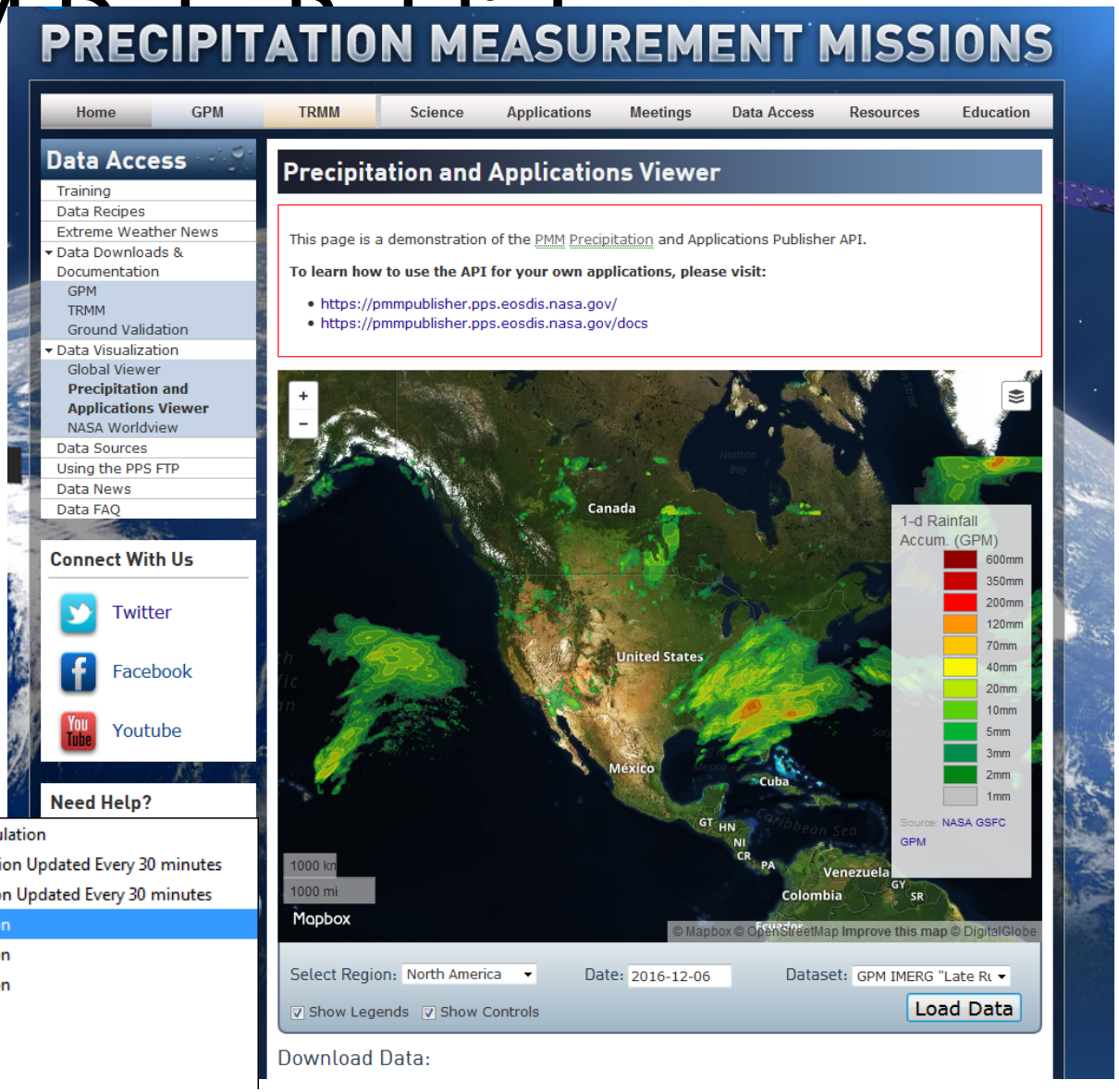
(*example*) similar surface properties (soil moisture, vegetation, ?)



GPM Data Publish

Available datasets:

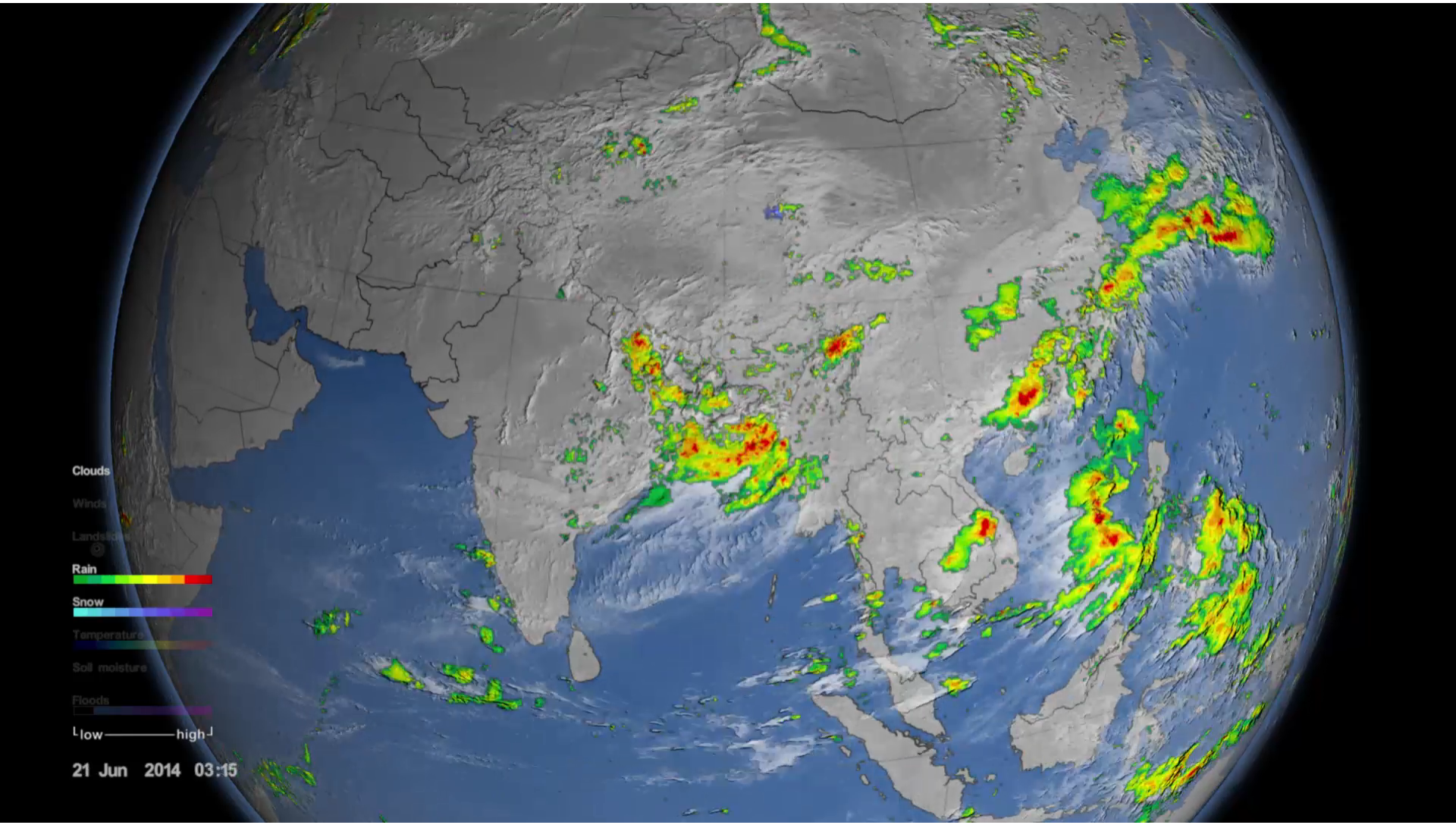
- IMERG 30mn, 3hr, 1day, 7day
- Flood Nowcast (GFMS, U of MD)
- Global Landslide Nowcast Model (NASA GSFC)
- Export file formats: geoJSON, topoJSON, arcJSON, TIF, SHP
- Publisher / consumer architecture – use the API to automate data collection or write your own consumer UI.



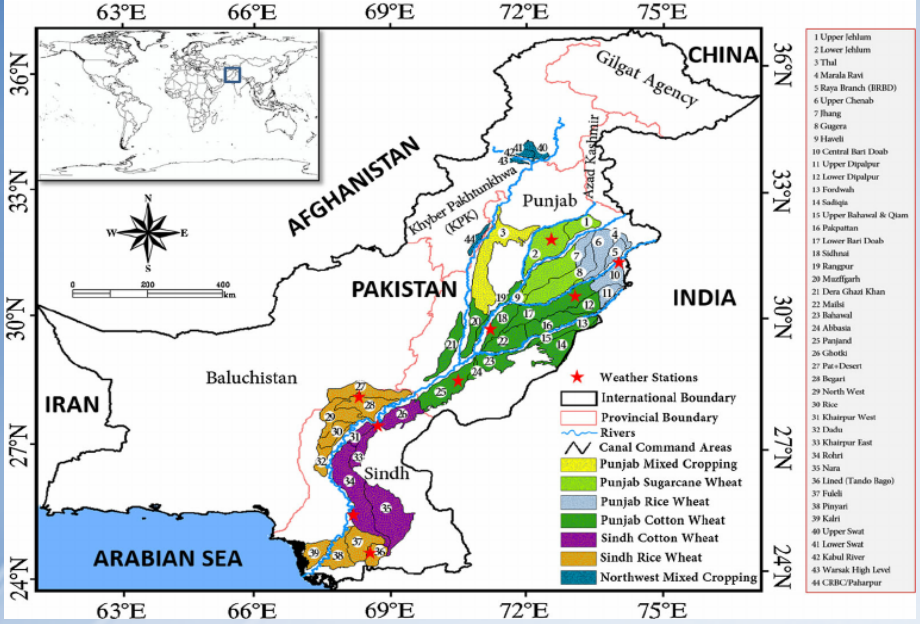
GPM IMERG "Early Run" 30 Minute Precip. Accumulation
GPM IMERG "Early Run" 3 Hour Precip. Accumulation Updated Every 30 minutes
GPM IMERG "Early Run" 1 Day Precip. Accumulation Updated Every 30 minutes
GPM IMERG "Late Run" 1-Day Precip. Accumulation
GPM IMERG "Late Run" 3-Day Precip. Accumulation
GPM IMERG "Late Run" 7-Day Precip. Accumulation
Floods Nowcast
Global Landslide Nowcast
Global Landslide Nowcast Updated Every 30mn

NOW AVAILABLE: https://pmm.nasa.gov/precip-apps

Monsoons, Soil Moisture, Floods & Landslides



AGRICULTURAL IRRIGATION WATER CONSERVATION & YIELD INCREASE



Indus Basin Irrigation System

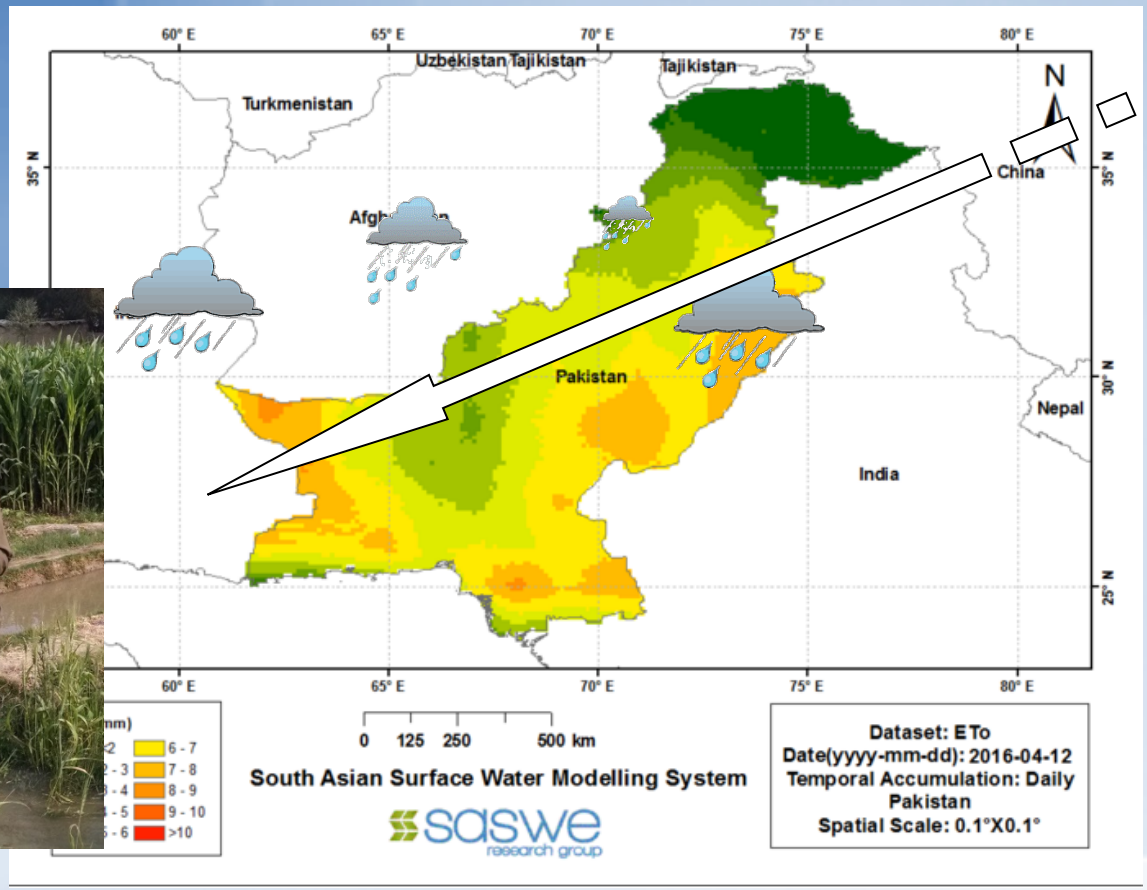
Original design: One crop/year

Reality Today: 2.5 crops/year

- Crop water requirements for rice **> 60 percent** of irrigation water
- 600 mm in Punjab province, **1,400 mm** in Sindh province
- Farmers apply 2,200 mm – tremendous water loss, groundwater decline and costlier pumping
- Water use efficiency of rice averages **0.45 kg of rice/m3** (world average **0.71 kg/m3**) – lowest - **0.08kg/m3**
- Several indigenous water conservation-irrigation technology available

How do we change farmer mindset (that they do not need to 'irrigate' that much) when there is enough from nature?

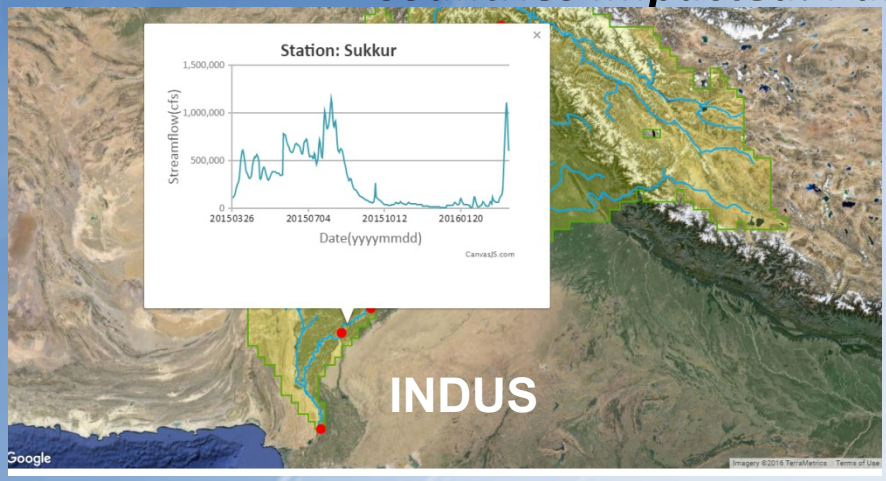
AGRICULTURAL IRRIGATION WATER CONSERVATION & YIELD INCREASE

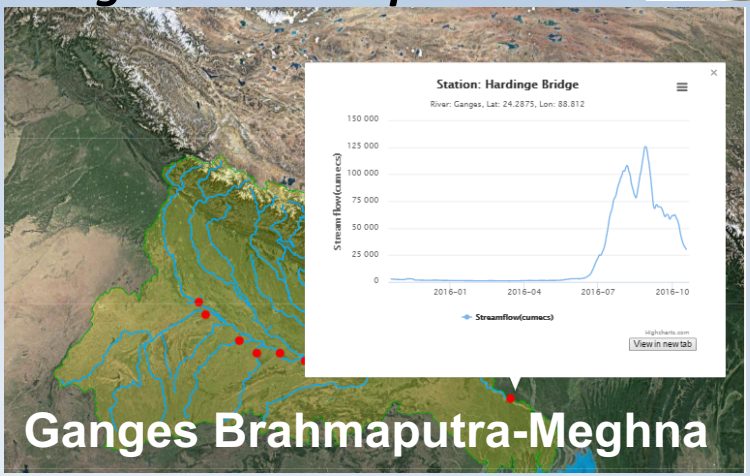


- Crop water demand estimated using global Weather model – Precipitation (IMERG) data = Net water demand **(irrigation advisory)**
- **Irrigation Advisory** based pushed to farmers via cellphone SMS.
- Pilot implementation from April 17, 2016 on **700** farmer followed by full-scale implementation 2017 to **10,000** farmers (On January 11, 2017)

Real-world Application of IMERG

Stakeholder Agencies: South Asian Nations (Govt Water Agencies)
Countries Impacted: Pakistan, Bangladesh & Nepal





- Key precipitation product - IMERG-Late/TMPA (dynamically corrected).
- Nowcast (hindcast) information on water availability rendered on UW South Asian Surface Water Modeling System (SASWMS) at http://depts.washington.edu/saswe and agency system
- Pakistan Govt. Agency PCRWR using it for extracting groundwater storage anomalies from GRACE data.
- Bangladesh Water Board using it for flood monitoring (July-October) and for low-flow monitoring from (Dec-April).
- Nepal Department of Hydrology and Meteorology using it for seasonal project of irrigation water at 3 basins (west, central and eastern Nepal) with GRACE data.