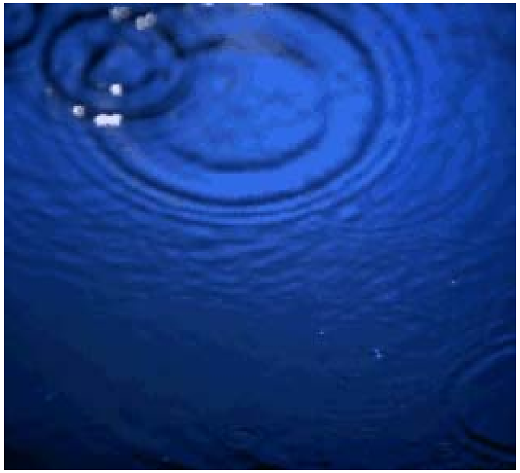
GPM

Global Precipitation Measurement (GPM) Mission

An International Partnership &
Precipitation Satellite Constellation

for Research
on Global Water & Energy Cycle



GPM Mission
Science Requirements

- System Requirements Review

- Eric A. Smith; NASA/Goddard Space Flight Center, Greenbelt, MD 20771
  [tel: 301-286-5770; fax: 301-286-1626; easmith@pop900.gsfc.nasa.gov; http://gpmscience.gsfc.nasa.gov]

- June 4-5, 2002; NASA/GSFC, Greenbelt, MD

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Relevance of Global Water Cycle

Availability & quality of water is essential to life on earth.

- ***Global Water Cycle is core of climate system, affecting every physical, chemical, & ecological component & their interaction.***
- ***Accurate assessment of spatial-temporal variation of land surface water cycle is essential for addressing wide variety of socially relevant science, education, applications, & management issues:***
  - rainfall-runoff, flood, & drought prediction
  - meteorological processes & weather prediction
  - climate system & ecosystem modeling
  - soil system science
  - crop systems & agriculture production
  - water supply, human health, & disease
  - forest ecology & management
  - civil engineering
  - water resources management
  - military operations

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Cinepak decompressor
are needed to see this picture.

- ***Additionally, as people increasingly modify land surface, concern grows about ensuing consequences for weather, climate, water supplies, crop production, biochemical cycles, & ecological balances of biosphere at various time scales.***

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GPM Reference Concept

OBJECTIVES

- *Understand horizontal & vertical structure of rainfall, its macro- & micro-physical nature, & its associated latent heating*
- *Train & calibrate retrieval algorithms for constellation radiometers*

Core

Constellation

OBJECTIVES

- *Provide sufficient global sampling to significantly reduce uncertainties in short-term rainfall accumulations*
- *Extend scientific and societal applications*

Core Satellite

- *TRMM-like spacecraft (NASA)*
- *H2-A rocket launch (NASDA)*
- *Non-sun-synchronous orbit*
  - *~ 65° inclination*
  - *~400 km altitude*
- *Dual frequency radar (NASDA)*
  - *K-Ka Bands (13.6-35 GHz)*
  - *~ 4 km horizontal resolution*
  - *~250 m vertical resolution*
- *Multifrequency radiometer (NASA)*
  - *10.7, 19, 22, 37, 85, (150/183 ?) GHz V&H*

Constellation Satellites

- *Pre-existing operational-experimental & dedicated satellites with PMW radiometers*
- *Revisit time*
  - *3-hour goal at ~90% of time*
- *Sun-synch & non-sun- synch orbits*
  - *600-900 km altitudes*

Precipitation Processing Center

- *Produces global precipitation products*
- *Products defined by GPM partners*

Precipitation Validation Sites

- *Select/globally distributed ground validation "Supersites" (research quality radar, up looking radiometer-radar-profiler system, raingage-disdrometer network, & T-q soundings)*
- *Dense & frequently reporting regional raingage networks*

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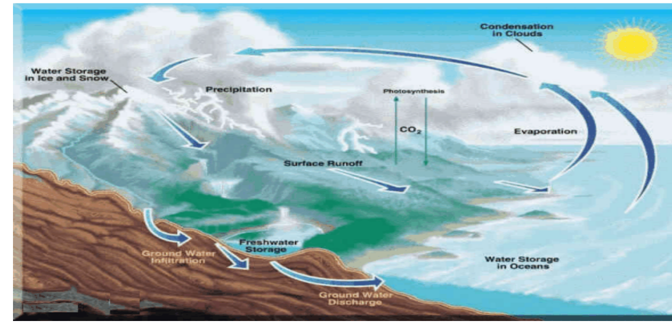
Tracibility to ESE's Strategic Plan

GPM
GLOBAL PRECIPITATION MEASUREMENT



How is Earth changing and what are consequences for life on Earth?

I. How is global Earth system changing? (Variability)

1. **How are global precip, evap, & water cycling changing?**
2. How is global ocean circulation varying on interannual, decadal, & longer time scales?
3. How are global ecosystems changing?
4. How is stratospheric ozone changing, as abundance of ozone-destroying chemicals decreases & new substitutes increases?
5. What changes are occurring in mass of Earth's ice cover?
6. What are motions of Earth & its interior, & what information can be inferred about its internal processes?

II. What are primary forcings of Earth system? (Forcing)

1. What trends in atmospheric constituents & solar radiation are driving global climate?
2. What changes are occurring in global land cover & land use, & what are their causes?
3. How is Earth's surface being transformed & how can such information be used to predict future changes?

III. How does Earth system respond to natural & human-induced changes? (Response)

1. **What are effects of clouds & surf hydrology on climate?**
2. How do ecosystems respond to & affect global environmental change & carbon cycle?
3. How can climate variations induce changes in global ocean circulation?
4. How do stratospheric trace constituents respond to change in climate & atmospheric composition?
5. How is global sea level affected by climate change?
6. What are effects of regional pollution on global atmosphere, & effects of global chemical & climate changes on regional air quality?

IV. What are consequences of change in Earth system for civilization? (Consequences)

1. **How are variations in local weather, precipitation & water resources related to global climate variation?**
2. What are consequences of land cover & use change for sustainability of ecosystems & economic productivity?
3. What are consequences of climate & sea level changes & increased human activities on coastal regions?

V. How well can we predict future changes in the Earth system? (Prediction)

1. **How can weather forecast duration & reliability be improved by new space obs, data assim, & modeling?**
2. **How well can transient climate variations be understood & predicted?**
3. **How well can long-term climatic trends be assessed & predicted?**
4. How well can future atmospheric chemical impacts on ozone and climate be predicted?
5. How well can cycling of carbon through Earth system be modeled, & how reliable are predictions of future atmospheric concentrations of carbon dioxide & methane by these models?

Asrar, G., J.A. Kaye, & P. Morel, 2001: NASA Research Strategy for Earth System Science: Climate Component. *Bull. Amer. Meteorol. Soc.*, **82**, 1309-1329.

GPM Mission is Being Formulated within Context of Global Water & Energy Cycle with Foremost Science Goals Focusing On

- **Improved Climate Predictions:** through progress in quantifying trends & space-time variations of rainfall & associated error bars in conjunction with improvements in achieving water budget closure from low to high latitudes -- plus focused GCM research on advanced understanding of relationship between rain microphysics/latent heating/DSD properties & climate variations as mediated by accompanying accelerations of both atmospheric & surface branches of global water cycle.

- **Improved Weather Predictions:** through accurate, precise, frequent & globally distributed measurements of instantaneous rainrate & latent heat release -- plus focused research on more advanced NWP techniques in satellite precipitation assimilation & error characterization of precipitation retrievals.

- **Improved Hydrological Predictions:** through frequent sampling & complete continental coverage of high resolution precipitation measurements including snowfall -- plus focused research on more innovative designs in hydrometeorological modeling emphasizing hazardous flood forecasting, seasonal draught-flood outlooks, & fresh water resources prediction.

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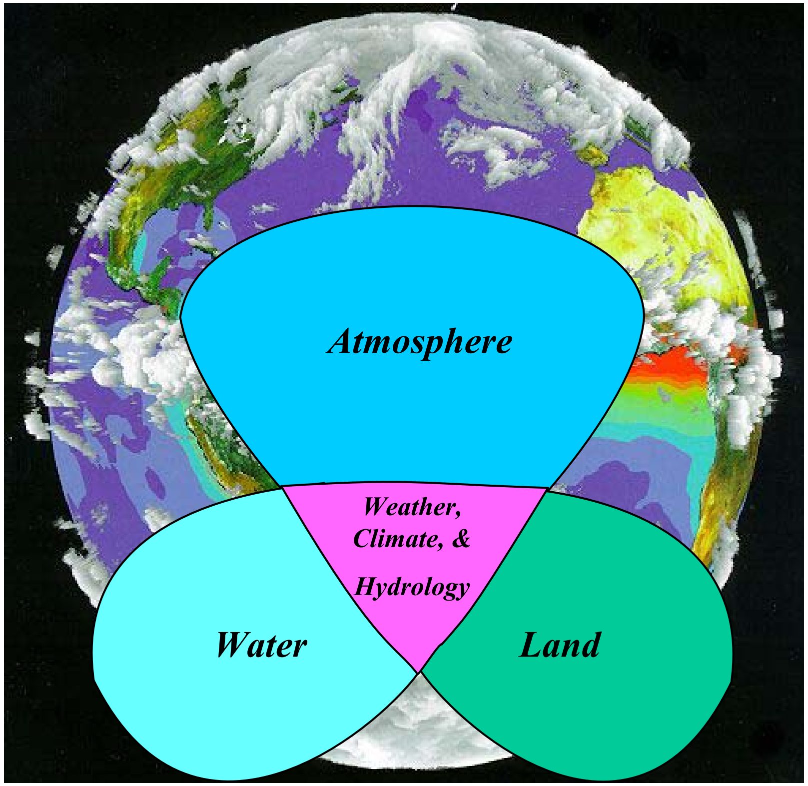
GPM Mission's Nine (9) Science Working Groups

USGCRP WCSG, 2001: A plan for a new science initiative on the global water cycle. *UCAR Report.*, sponsored by USDA, DOE, NASA, NOAA, NSF, USGS, ACE, BREC, & EPA, 118 pp.



*(1) **Global Water & Energy Cycle Processes & Modeling: Role of Precipitation** (Prof. Eric Wood, Princeton)*

*(2) **Climate System Variability & Climate Diagnostics: Role of Precipitation** (Dr. Franklin Robertson, NASA/MSFC @ GHCC)*

*(3) **Climate Model Simulations & Reanalysis, NWP Techniques, & Data Assimilation: Role of Precipitation** (Dr. Arthur Hou, NASA/GSFC)*

*(4) **Land Surface Hydrology & Hydrometeorological Modeling: Role of Precipitation** (Dr. Harry Cooper, Fla. State Univ.)*

*(5) **Ocean Surface & Marine Boundary Layer Processes: Role of Precipitation** (Dr. Vikram Mehta, NASA/GSFC)*

*(6) **Coupled Cloud-Radiation Modeling: Physical Interpretation of Precipitation Processes** (Prof. Gregory Tripoli, Univ. Wis. & Dr. Wei-K. Tao, NASA/GSFC)*

*(7a) **Precipitation Retrieval: Reference Radar-Radiometer Core Algorithm & Radar Simulator** (Dr. Ziad Haddad, NASA/JPL)*

*(7b) **Precipitation Retrieval: Parametric Radiometer Constellation Algorithm & Radiometer Simulator** (Prof. Christian Kummerow, Colo. State Univ.)*

*(7c) **Precipitation Retrieval: Cal Transfer, Bias Removal, & Merged Products** (Prof. Eric Smith, NASA/GSFC)*

*(8) **Calibration & Validation of Satellite Precipitation Measurements** (Dr. Sandra Yuter & Prof. Robert Houze, Univ. Washington)*

*(9) **Forecast Apps, Public Service, TV, & Educational Outreach** (Dr. Marshall Shepherd, NASA/GSFC)*

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Document Status

NASA GPM Report Series (Smith & Adams, eds)

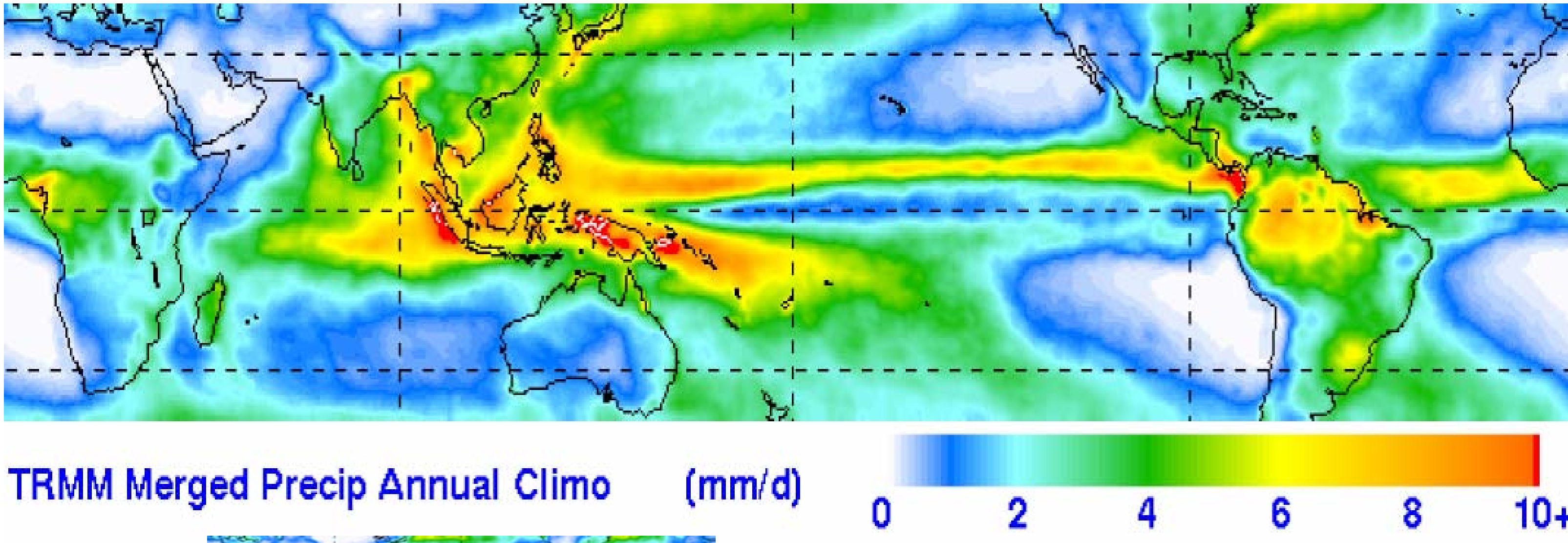
Summary of 1st GPM Partners Planning Workshop	Shepherd, Mehta, Smith	printed
Benefits to Partnering with GPM Mission	Stocker	printed
Scientific Assessment of High-Frequency Radiometer Channels on GPM Core Satellite for Warm and Light Rain plus Snow Measurement	Liu & Flaming	in press
Scientific Assessment of Cross-Track STAR Radiometer Flown Bore-Sighted with Dual-Frequency Radar on GPM Core Satellite	Wilheit & Everett	
Potential Tropical Open Ocean Precipitation Validation Sites	Adkins & Yuter	in press
6 Description of Global Precipitation Measurement (GPM) Mission	Smith, Mehta, Shepherd	in review
7 Bridging from TRMM to GPM to 3-Hourly Precipitation Estimates	Shepherd & Smith	in press
8 Description of GPM Project	Adams et al	in review
9 GPM Core Satellite Trade Space Analysis	Everett et al	draft form

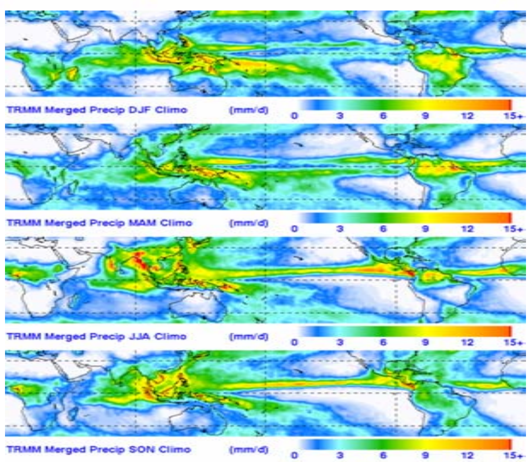
Additional Publications

1. The Global Precipitation Measurement (GPM) Mission	Smith et al	Plinius 3
2. Potential Applications of LRR-STAR Technology for GPM Mission	Smith et al	ESTC-2
3 Draft GPM Science Implementation Plan (SIP)	Smith (editor)	rough draft

Three-Year TRMM Climatology

January 1998 - October 2000





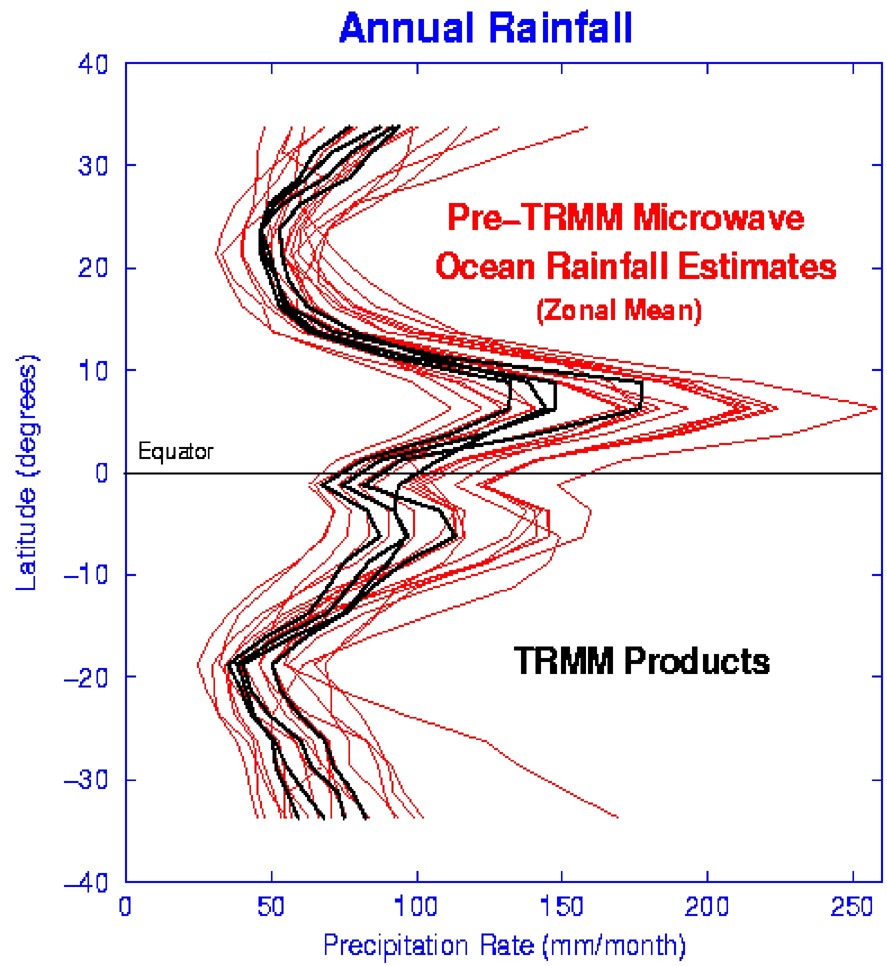
N.H. Winter

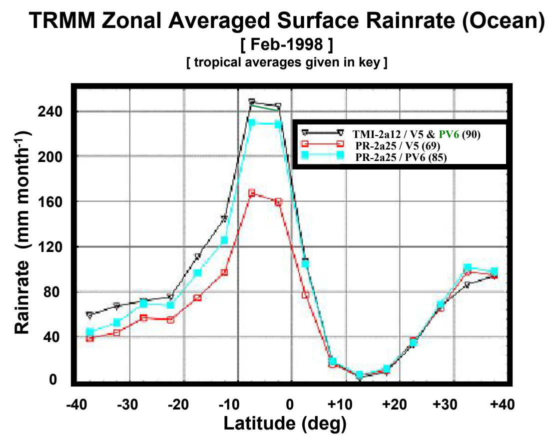
N.H. Spring

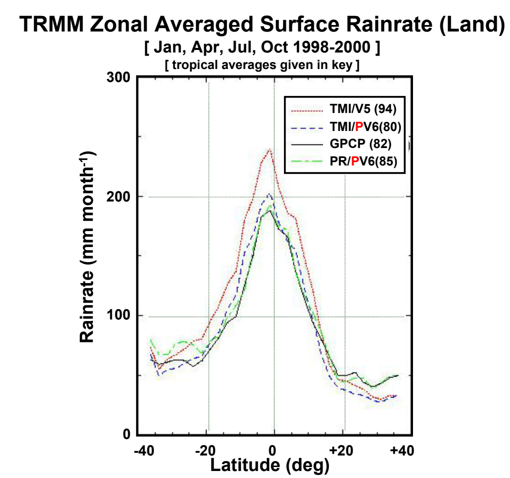
N.H. Summer

N.H. Fall

Algorithm Improvement







Comparing Science Agendas of TRMM & GPM

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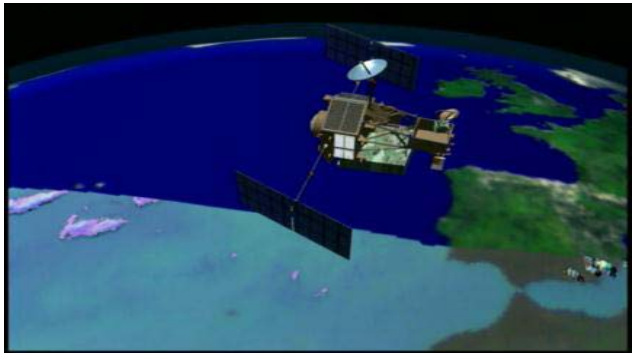
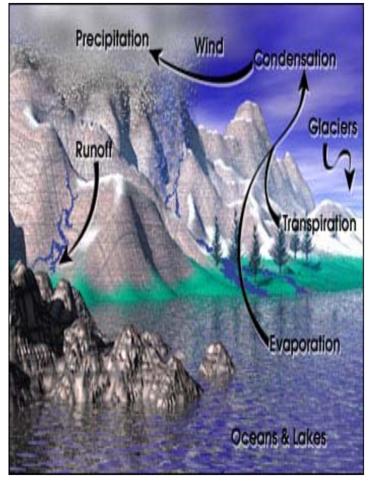
TRMM Science Focus

- Generate 1st complete climatology of oceanic rainfall using high quality space-based rain measuring instruments & physics-quality retrieval algorithms.
- Determine vertical structure of rainrate & associated latent heating for improved understanding of climate.
- Acquire unique views and new information on hurricanes and typhoons.
- Develop calibration standard for correcting 15-year old satellite rainfall record obtained from SSM/I.
- Produce merger of TRMM rainfall measurements with estimates from satellite infrared observations to produce higher frequency rainfall time sampling.
- Use extended rainfall datasets for global climate modeling, storm monitoring, and hydrological applications.



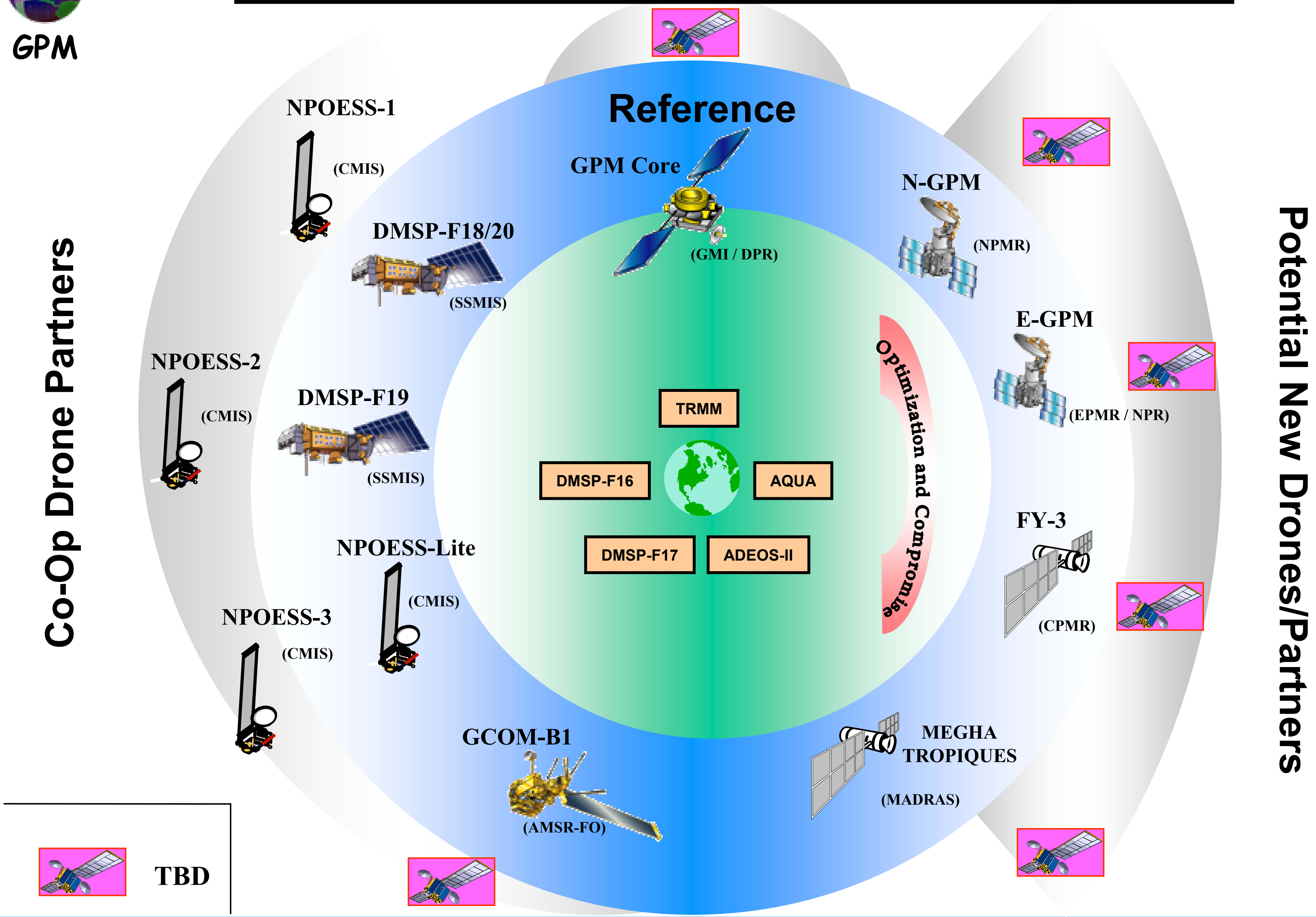


Key Ongoing & Future Components of NASA's GWEC Initiative

GPM Science Focus

- Extend high quality rainfall observations to mid- & high-latitudes (i.e., > 35N).
- Use microwave satellite constellation to significantly improve spatial & temporal sampling of global rainfall.
- Improve accuracy & reduce uncertainty in rainfall measurements from better radar microphysics capability (i.e., size of drops, fall velocity of drops, phase of water).
- Observe broader spectrum of precipitation (e.g., light/warm rain, & snow).
- Extend high quality precipitation record (from TRMM onward) for detection of important trends and variations in global water cycle & climate.
- Expand applications to climate change simulations, weather forecasts, fresh water resource management, flood prediction, oceanography, public outreach, & TV broadcasting.

Currently Conceived Constellation Architecture



GPM: Constellation Mission of Opportunity & Good Citizenship

Satellite	Main Purpose	Critical Role in Constellation
1. GPM Core [NASA/NASDA]	GPM rain reference system	calibration, rain radar physics, liquid/frozen precip, tropical-midlatitude sampling
2 & 3. DMSP [IPO]	US: NOAA/DOD met-ops & res	liquid/frozen precip, full global sampling
4. NPOESS-Lite [IPO]	US: NOAA/DOD met-ops & res	liquid/frozen precip, full global sampling
5. GCOM-B1 [NASDA]	Japan: environ/hydro res & JMA met-ops	liquid/frozen precip, full global sampling
6. E-GPM [ESA]	EU: cold seasons/flash flood/ data-assim res & EU met-ops	rain radar physics, liquid/frozen precip, full global sampling
7. N-GPM [NASA]	US: MW radiometer technology testbed	liquid precip, full global sampling
8. Megha Tropiques [ISRO/CNES]	India/France: tropical water cycle res	liquid/frozen precip, intensive tropical sampling
9. FY-3 [CSM]	China: CMA met-ops & res	liquid/frozen precip, full global sampling

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Animation decompressor
are needed to see this picture.

Percent Sampling of 3-Hr Bins & Global Mean Revisit Time

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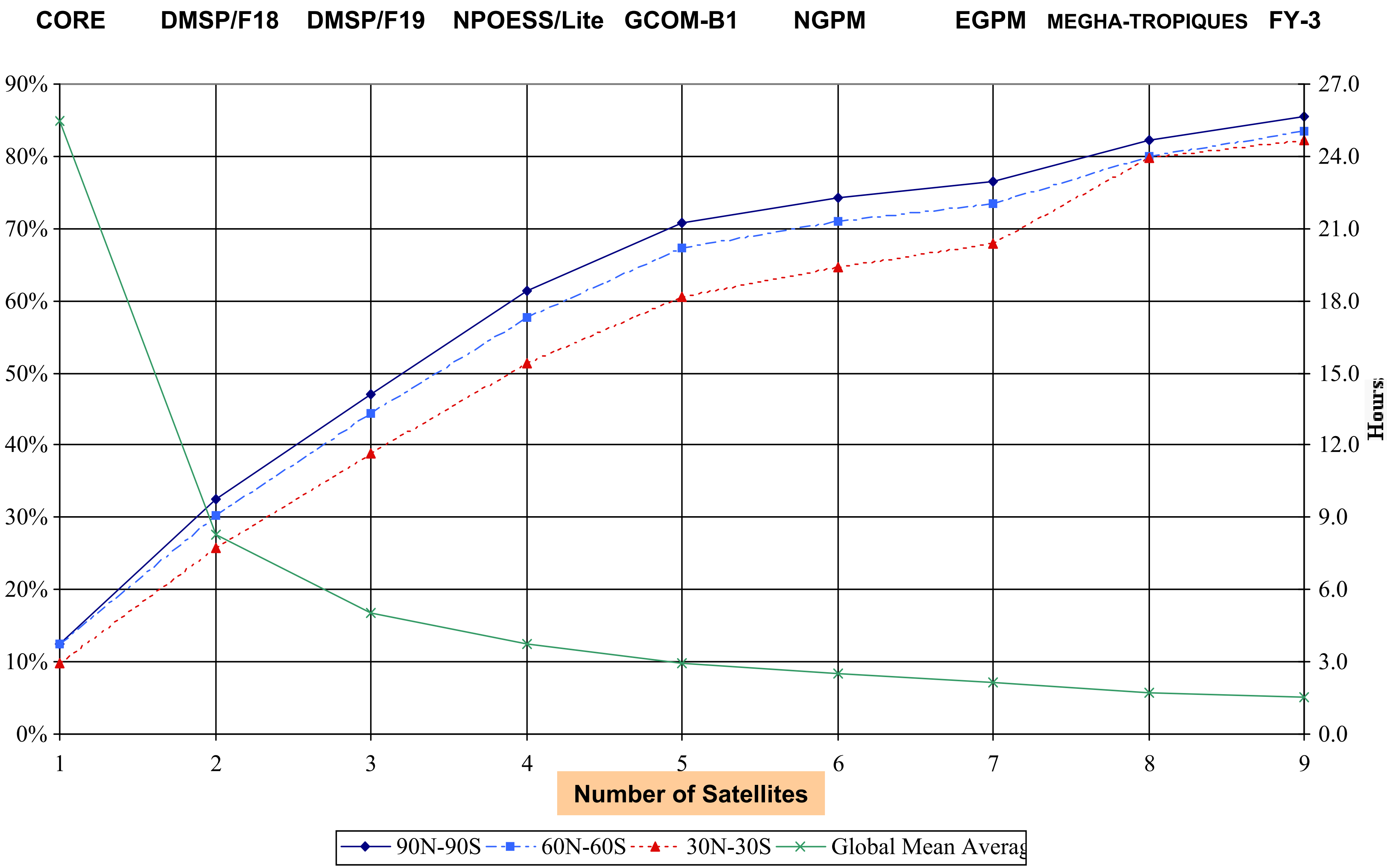
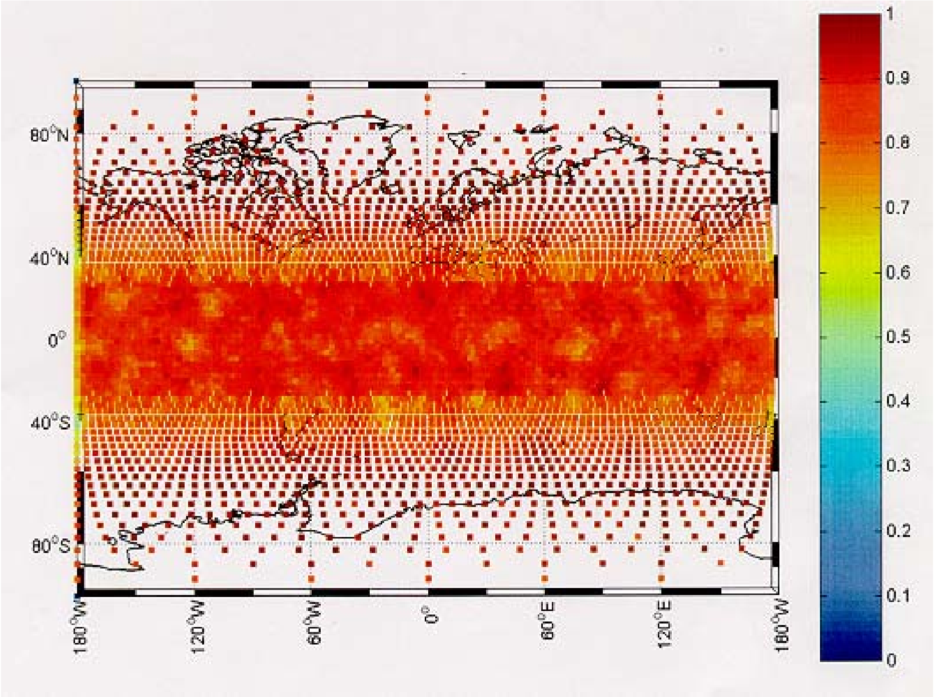


Percentage of 3-Hour Intervals Sampled in 7-Day Period

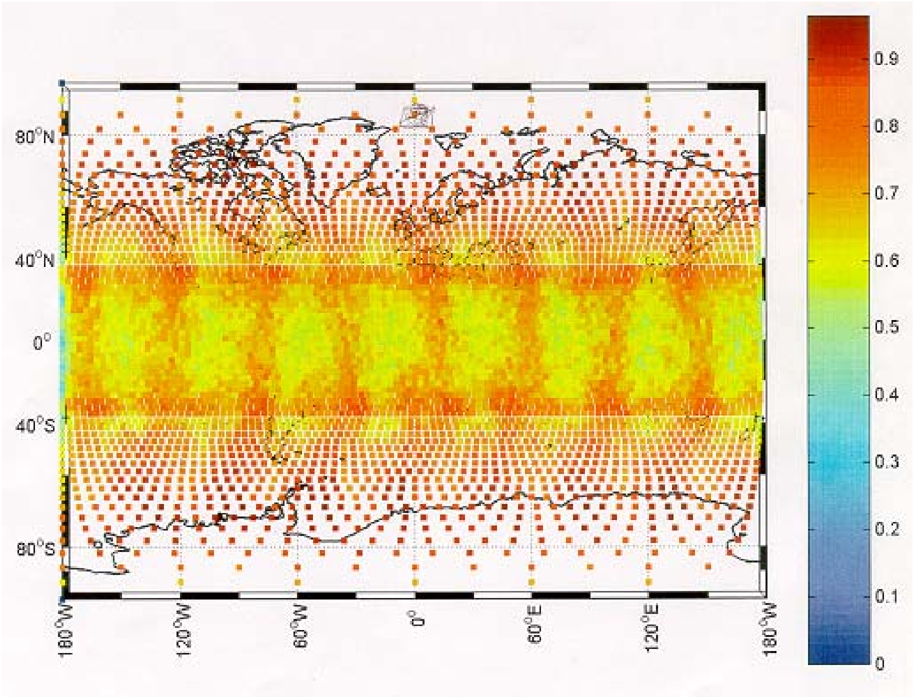
Precipitation Sampling Worldwide: Constant Area Pixels

GPM Era



GPM Core, DMSP-F18 & -F19, GCOM-B1, Megha-Tropiques, & Three 600-km Drones @ 34°, 84°, 90° Inclination

EOS Era



TRMM, DMSP-F13, -F14, & -F15, Aqua, & ADEOS-II

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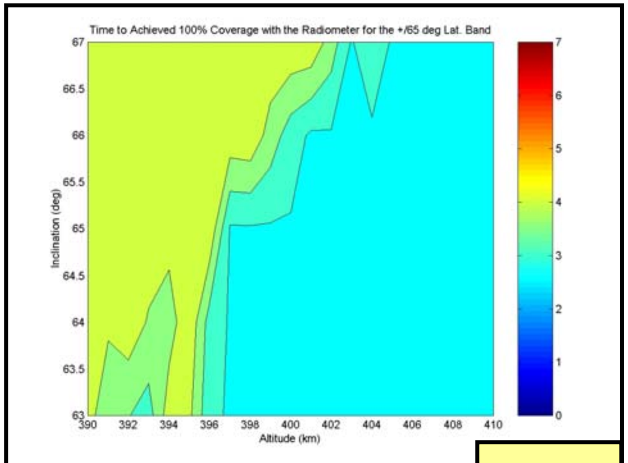
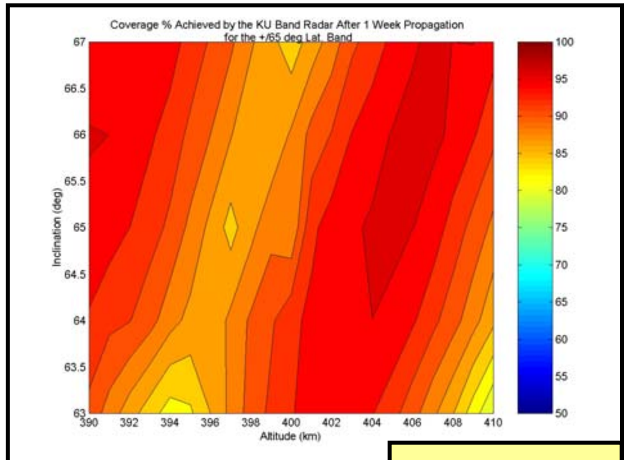
Core Satellite Trade Space Analysis (Earth coverage)

[for GMI -- days to achieve 100% coverage over ±65° latitude zone]

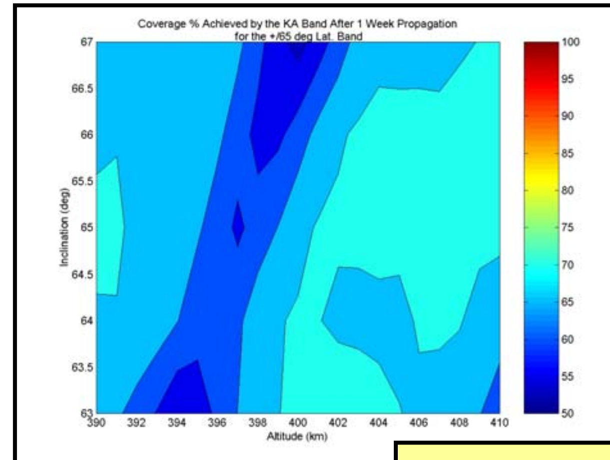
[for Ku- & Ka-band radars -- % coverage achieved after 7 days over ±65° latitude zone]



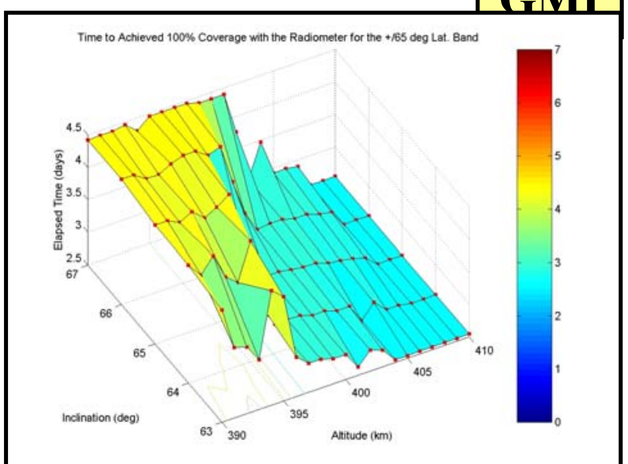
GMI

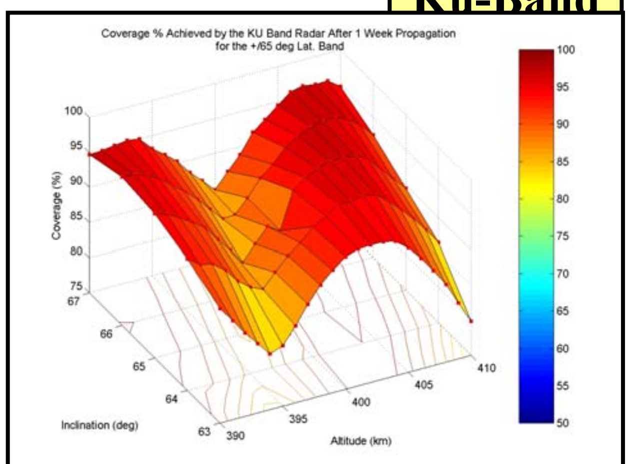


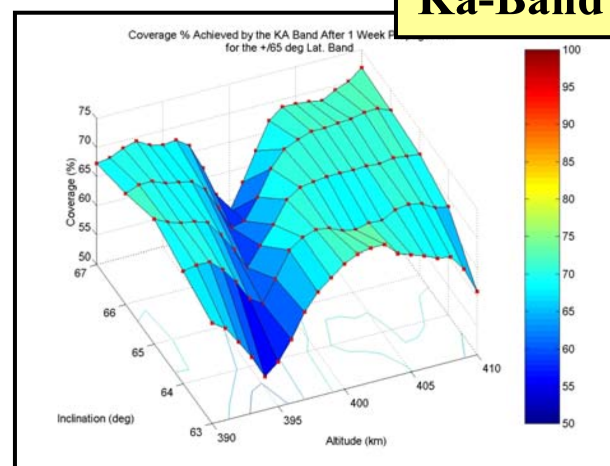
Ku-Band



Ka-Band







[390 - 410 km altitude range / 63 - 67 deg inclination range]

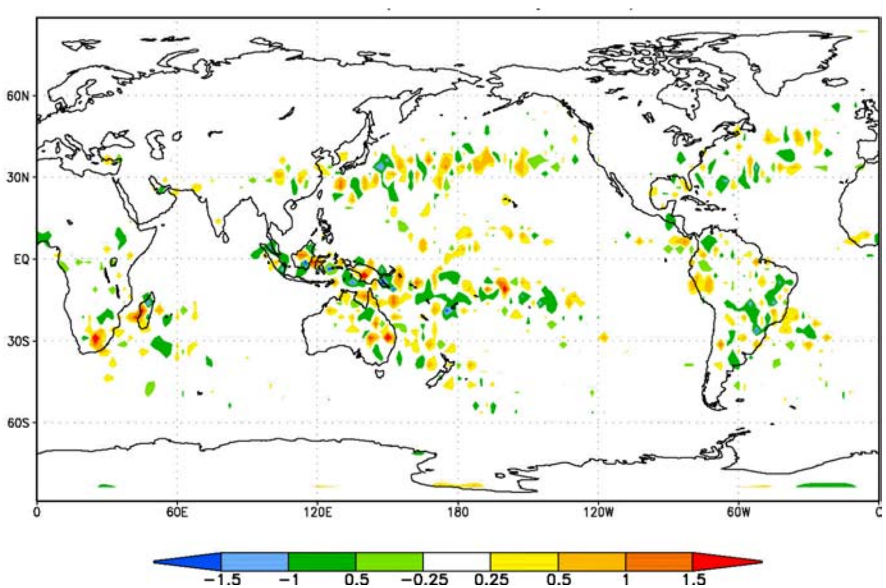
Observing Simulation System Experiment (OSSE) for Orthodox 8-Member Sun-Synchronous Constellation Producing Global 3-Hour Sampling

[Flown at Two Swath Widths]

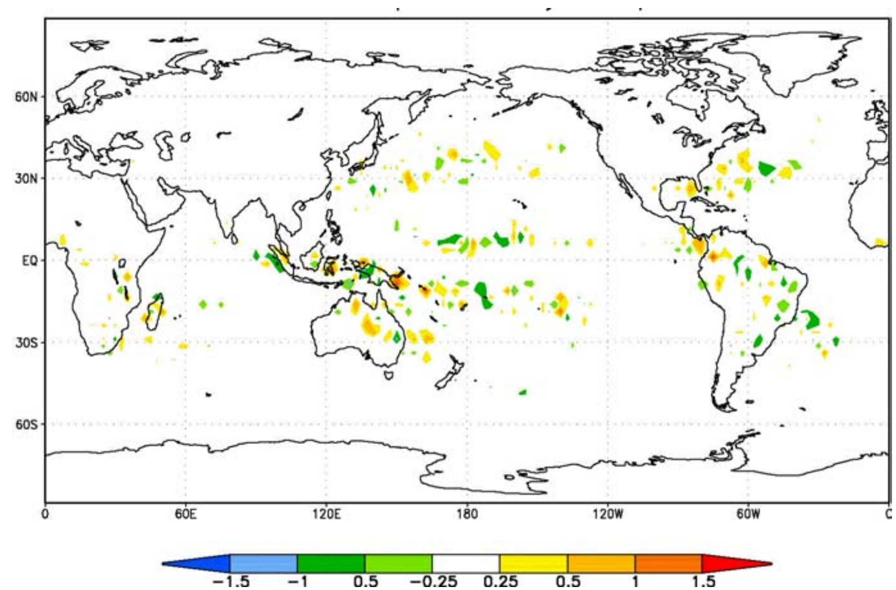
Precipitation field produced by Colorado State University General Circulation Model (GCM) simulating January conditions

[characteristic monthly errors order 0.25 mm day^{-1} or ~7 W m^{-2}]

800 km Swath Width viz TMI

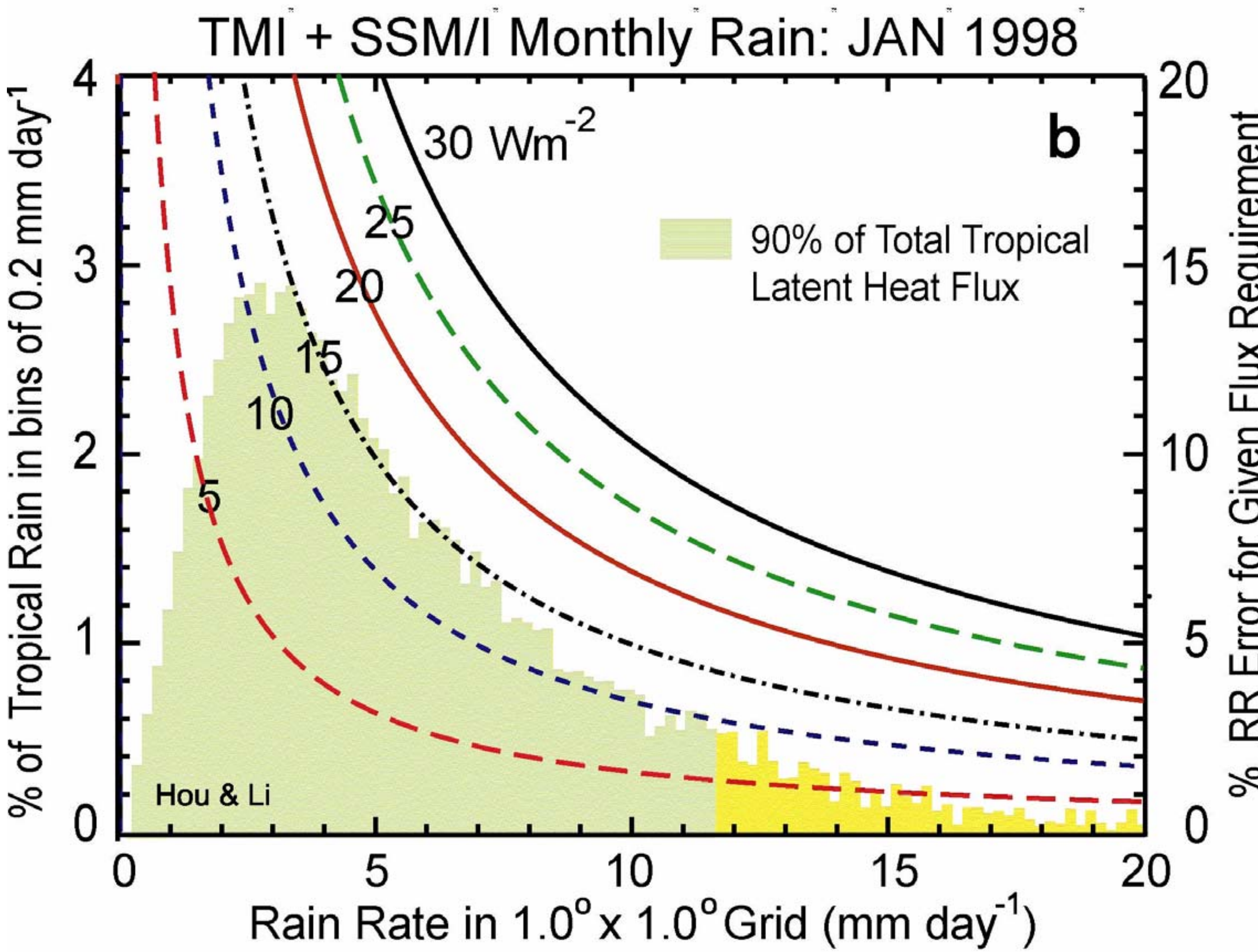


1600 km Swath Width viz SSM/I



Rainfall Deviations (satellite sampled minus fully sampled in mm day^{-1})

Quantification & Interpretation of Required Precipitation Accuracy in Context of Tolerable Energy Flux Error



Improving Precipitation Retrievals

Cloud Macrophysical & Microphysical Fundamentals

Determination of:
drop size distribution [DSD(r)],
mass mixing ratio [$q(z)_{hydro(r)}$],
rain mass flux [$F_r(z)$],
fall velocity [$w(z)_{hydro(r)}$],
& latent heating [LH(z)]

$$q(z)_{hydro(r)} = \sigma_w \, (4/3 \pi r^3) \, DSD(r)$$

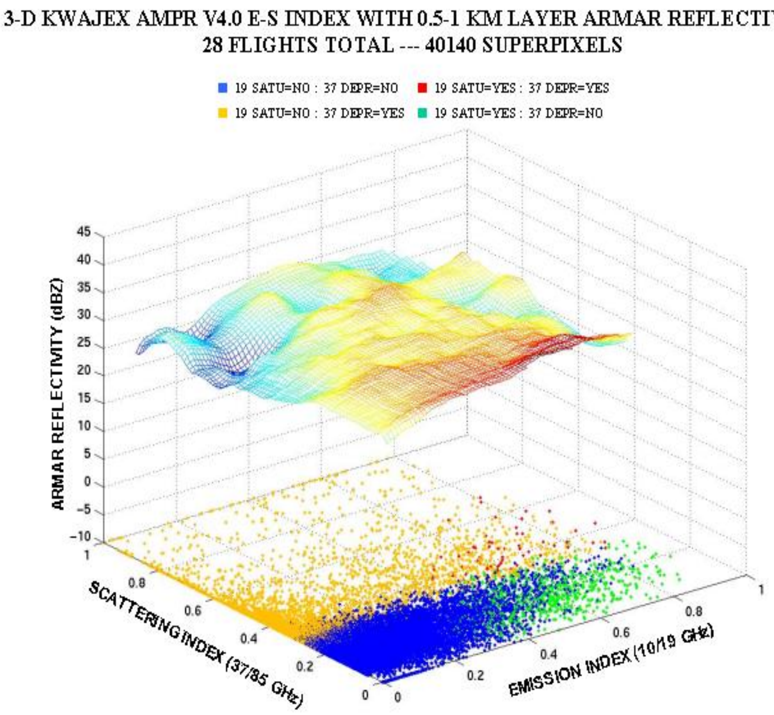
$$w(z)_{hydro(r)} = GFO \, [q(z)_{hydro(r)}]$$

$$F_r(z) = \int q(z)_{hydro(r)} \, w(z)_{hydro(r)} \, dr$$

$$LH(z) = C \, [\partial F_r(z) / \partial z]$$

$$RR(z) = F_r(z) / \sigma_w$$

$$RF_{sur} = RR(z_{sur}) \, \square \, \Delta t$$



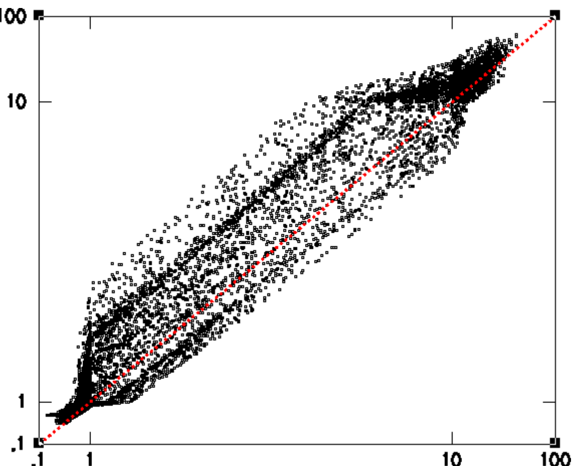
Implementation of Fully Modular OPEN ACCESS Facility Algorithms Accompanied by COMPREHENSIVE TESTING Capability within WPDC

TRMM & GPM Rainrate Retrieval Simulations Under Varying Mean Adj Drop Diameter Profiles

[simulations based on Monte Carlo proliferation of Hurricane Bonnie observations]

TRMM Single-Frequency Algorithm

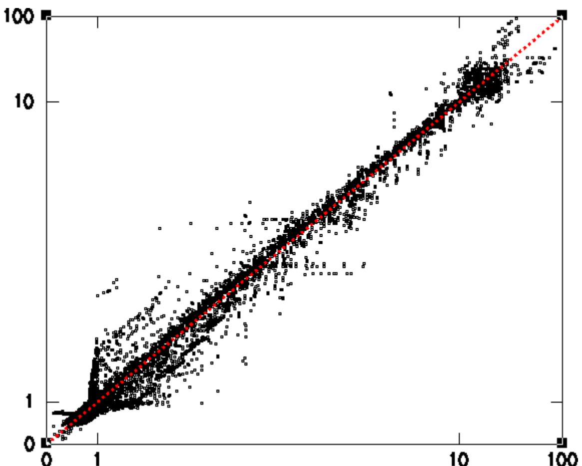
(bias due to irretrievable DSD variability)



Actual R (mm hr^{-1})

GPM Dual-Frequency Algorithm

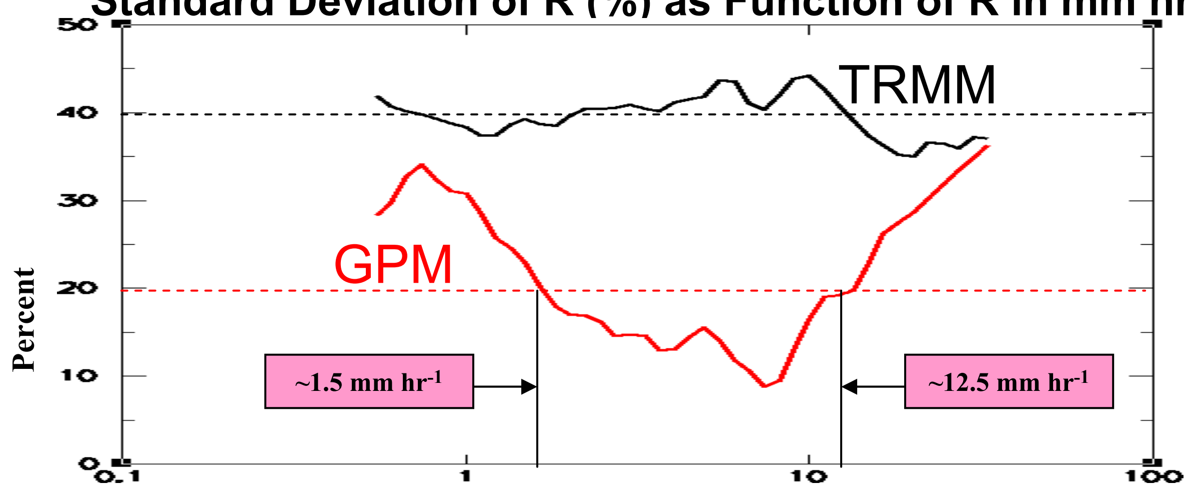
(near-zero bias & reduced scatter in mid-range)



Actual R (mm hr^{-1})

Retrieved R (mm hr^{-1})

Standard Deviation of R (%) as Function of R in mm hr^{-1})

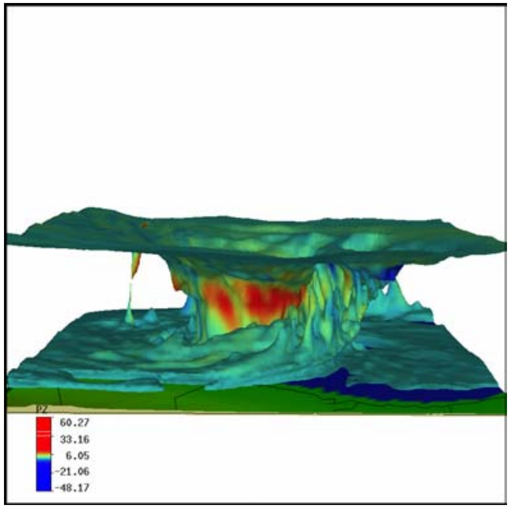


with R approximately log-normal then σ_R proportional to R

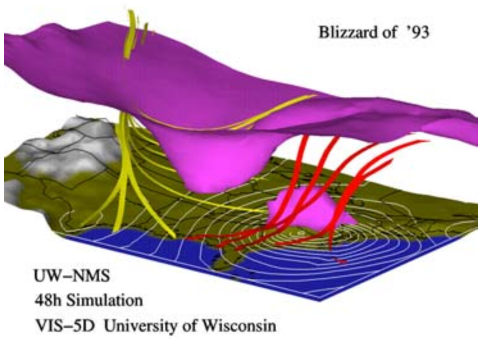
exact variability depends on DSD variability in altitude

Example for Weather Prediction

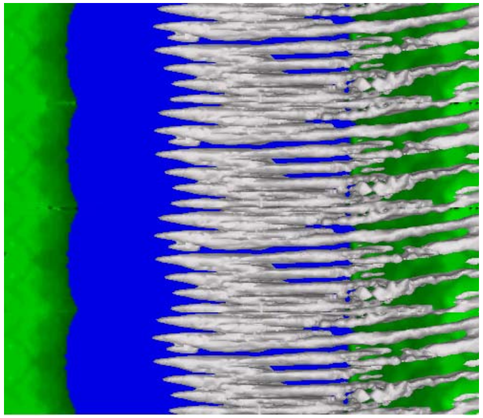
Cloud Resolving Model Simulations from UW-NMS for Establishing Cloud-Radiation Relationships



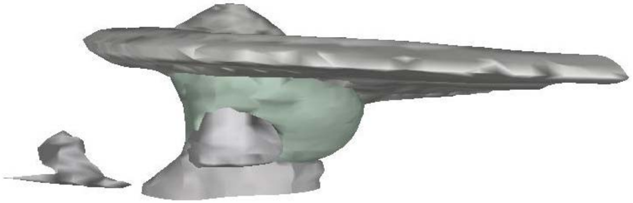
Explicit Convection in Hurricane Bonnie



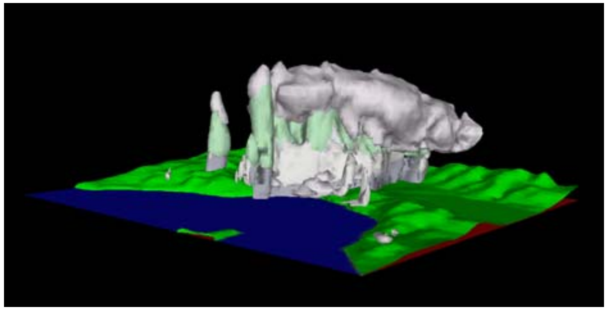
Middle-Latitude Cyclone



Lake-Effects Roll Convection

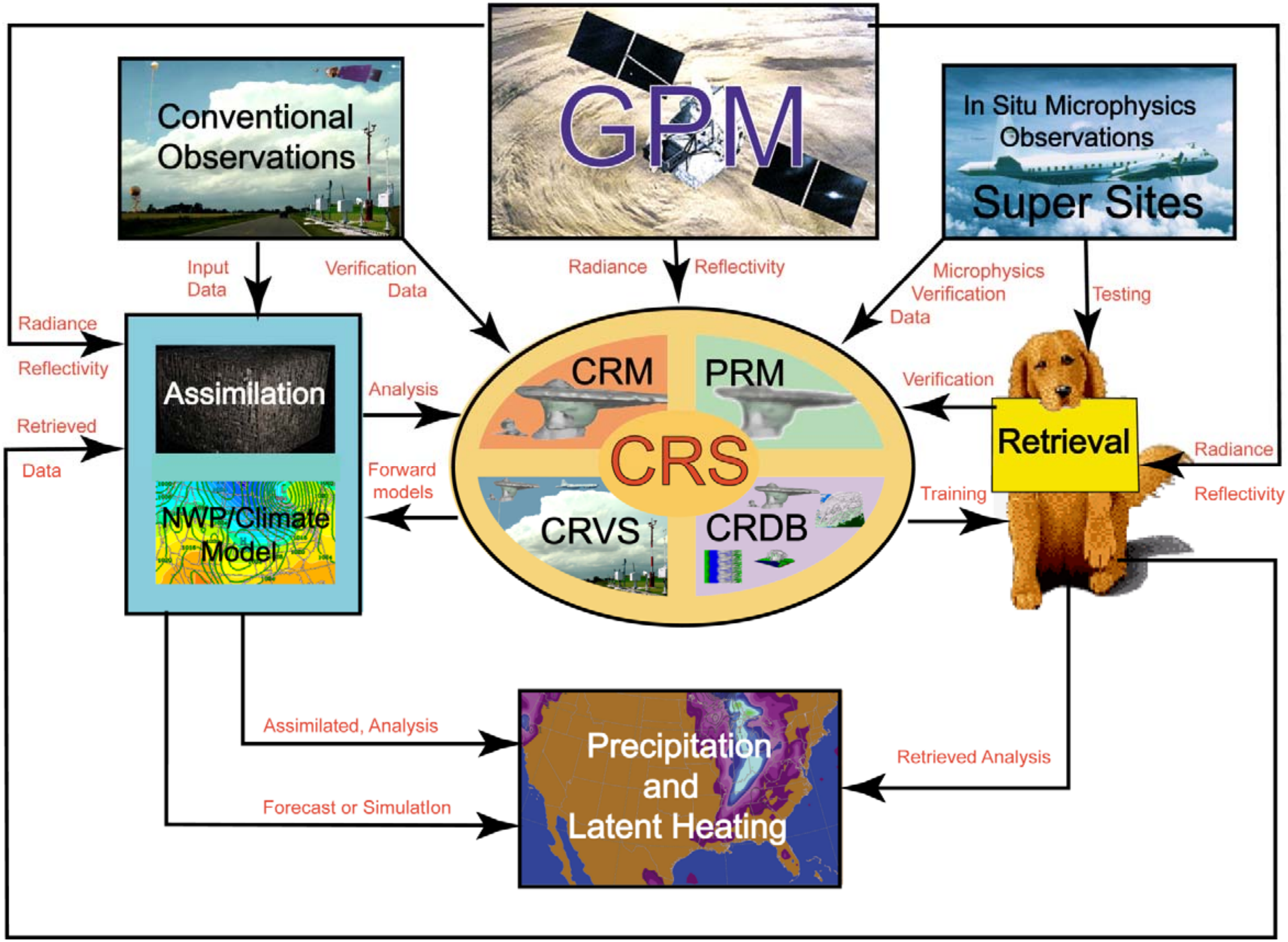


Supercell Thunderstorm



Alps Orographic-Convective Storm

Principles of Cloud-Radiation Modeling



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GPM

Proposed GPM Precipitation Products

I. Level 2 Orbit Swath Products (similar to TRMM)

II. Level 3 Grid Products (modification to TRMM)

- *arithmetically consistent succession:*
  (1) 3-hourly @ 0.1 x 0.1 deg; (2) daily @ .25 x .25 deg;
  (3) pentad @ 1.0 x 1.0 deg; (4) monthly @ 5.0 x 5.0 deg
- *simplified & integrated parameter set:*
  (1) surface rainrate/rainfall & grid variance; (2) convective-stratiform separation;
  (3) bulk DSD parameters; (4) latent heating profile; (5) confidence index
- *four (4) types of retrieval results ordered by retrieval quality:*
  (1) core sat result (combined DPR - GMI); (2) constellation sat result (rain radiometers)
  (3) non-rain radiometer result (e.g., AMSU); (4) geo-infrared result (GOES, GMS, METEOSAT, MSG)

III. Full Resolution Pixel Tables (extension to TRMM)

- *tabulates all instantaneous rain pixels from all satellite sources within individual 3-hourly 0.1 x 0.1 deg grid elements, identified in space & time*

IV. Level 4 Scale Invariant Blended Products (new)

- *properly transformed to constant space-time scales*

Goal is relatively seamless transition of precipitation products from TRMM to GPM eras, thus minimizing mission change impacts on science community.

Validation Expectations from Research & Operations End Users

- Validation should be treated as important as retrieval because improved prediction depends on it.

- Error characterization of satellite precipitation retrievals is needed to support:

  (a) **Algorithm Improvement** -- for reducing bias & precision errors in retrieved precipitation estimates;

  (b) **Climate Diagnostic Analysis** -- for assessing physical significance of trends/variations in observed precipitation time series;

  (c) **Data Assimilation** -- for improving climate reanalyses, numerical weather prediction, & hydrometeorological forecasting.

  (d) **Validation Research** -- for advancing validation techniques, validation measuring systems, & space instrumentation.

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GPM Validation Strategy

Confidence
sanity checks

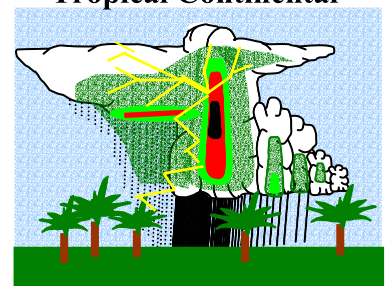
Research Quality Data

I. Basic Rainfall Validation

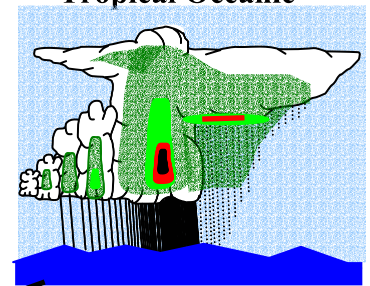
- Raingauges/Radars

new/existing gauge networks
new/existing radar networks

Tropical Continental



Tropical Oceanic



GPM Satellite Data Streams

Continuous Synthesis

- error variances
- precip trends

Calibration

II. GPM Supersites

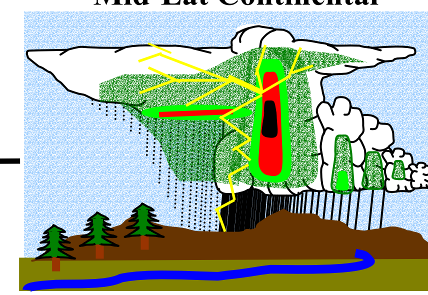
- Basic Rainfall Validation

hi-lo res gauge/disdrometer networks
polarametric Radar system

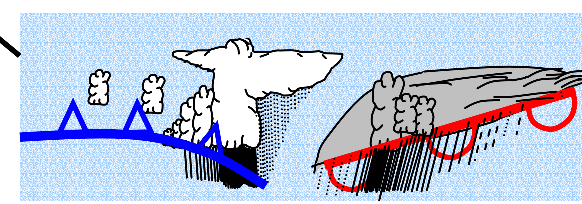
- Accurate Physical Validation

scientists & technicians staff
data acquisition & computer facility
meteorological sensor system
upfacing multifreq radiometer system
D_o/DSD variability/vertical structure
convective/stratiform partitioning

Mid-Lat Continental



Extratropical Baroclinic



High Latitude Snow

Algorithm Improvements

Supersite Products

Research

- cloud macrophysics
- cloud microphysics
- cloud-radiation modeling

FC Data

III. GPM Field Campaigns

- GPM Supersites

cloud/ precip/radiation/dynamics processes

- GPM Alg Problem/Bias Regions

targeted to specific problems

Error Characterization (accuracy)

Bias & Bias Uncertainty

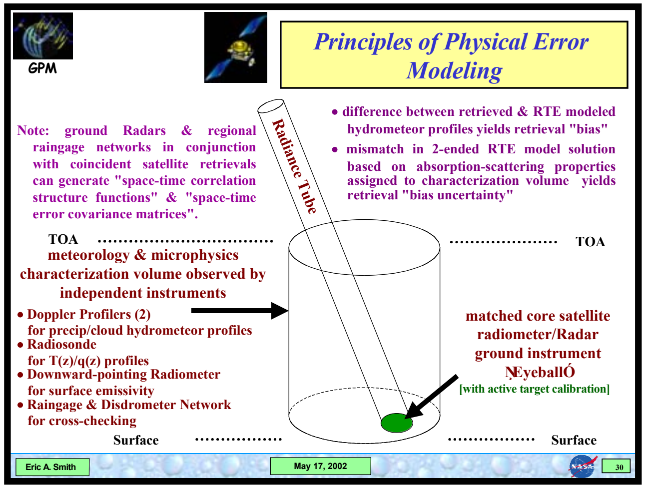
bias — bias uncertainty

$$\overline{\varepsilon}(\theta, t, RR)_{i,j} \pm \Delta\,\overline{\varepsilon}(\theta, t, RR)_{i,j}$$

i = 1,2 for ocean, continent

j = 1,2 for convective, stratiform

Based on Physical Error Model



based on:

- physical error model (passive-active RTE model)
- matched satellite radiometer/radar instrument on ground with continuous calibration (eyeball)
- independent measurements of observed inputs needed for error model

All retrievals from constellation radiometers & other satellite instruments are bias adjusted according to bias estimate for reference algorithm from core satellite.

Error Characterization (precision)

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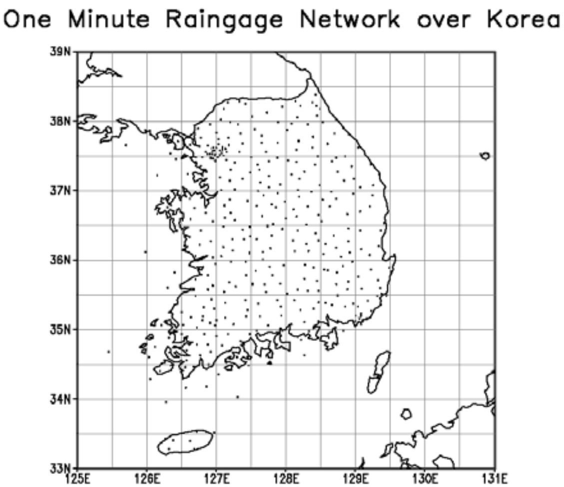
$$J(x) = (x^b - x)^T F^{-1} (x^b - x) + (y^o - H(x))^T (O + P)^{-1} (y^o - H(x))$$

P, O, & F are error covariance matrices associated with forecast model, observations, & forward model (precip parameterization), where y^o, H, & x are observation, forward model, & control variable.



Space-Time Error Covariance

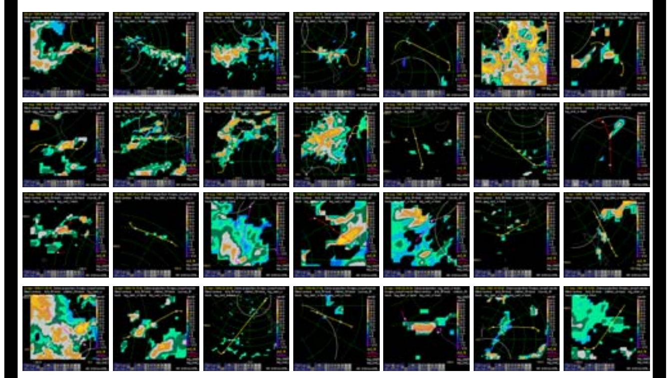
regional (validation sites) space-time structure funcs from grnd radars/ regional gage nets & coinc satellite retrievals

$$COR(x,y,z,t)_{obs} \ \& \ COR(x,y,z,t)_{sat}$$

global space-time error covariance function from

$$COV(x,y,z,t)_{err} = F[DPR(Z\ field)] - T\ [\Sigma(COR(x,y,z,t)_{sat} - COR(x,y,z,t)_{obs})^2]$$

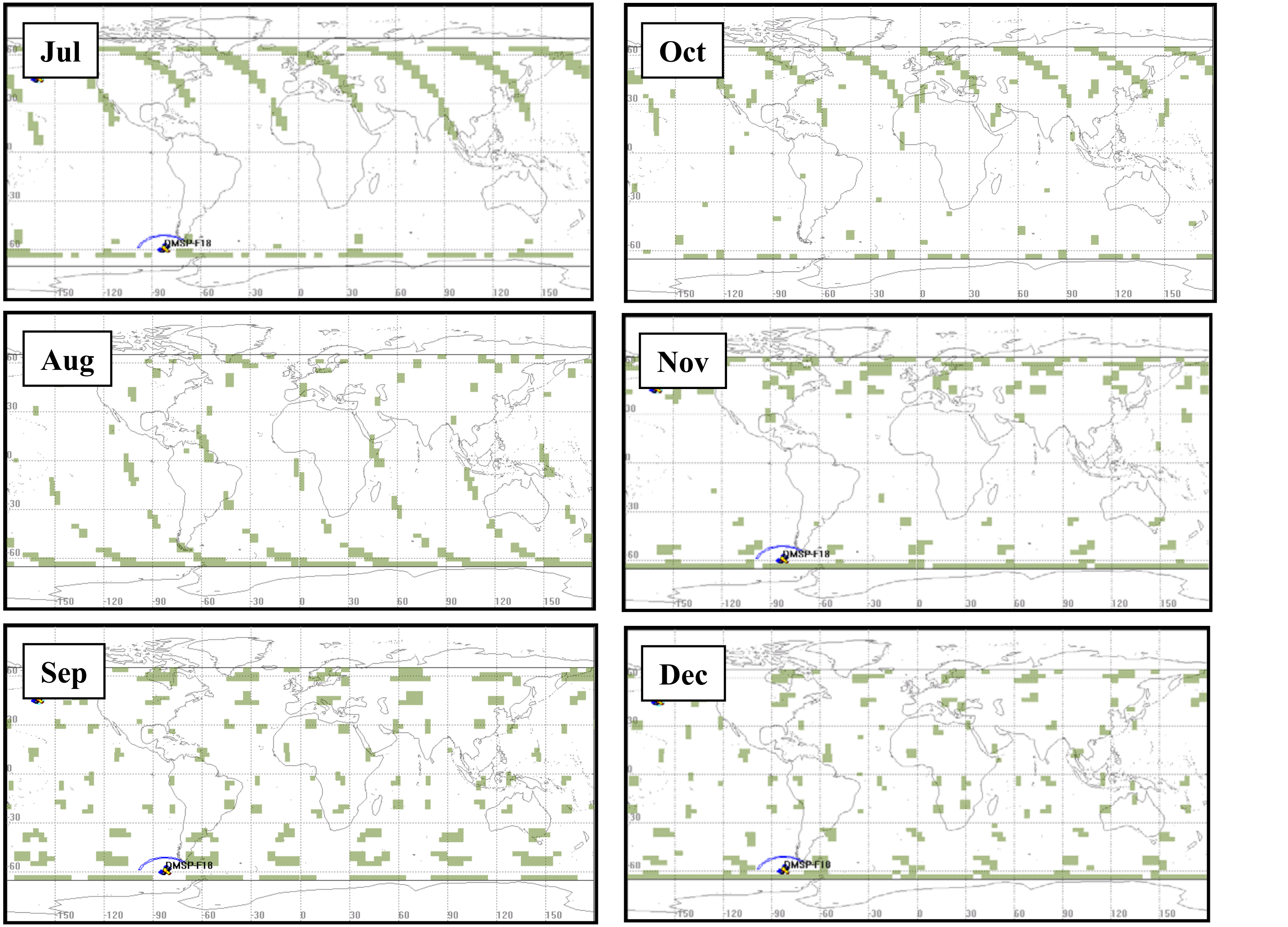
for all x,y,z, & t where F based on val-site training data



based on:

- ground Radars (polarization diversity enables cross-checking)
- high-quality, uniformly distributed, dense, & hi-frequency sampled raingage networks

Core Satellite/GMI - DMSP/SSMIS Intersections (1-min proximity)
July through December [*touch resolution is 5x5 deg*]



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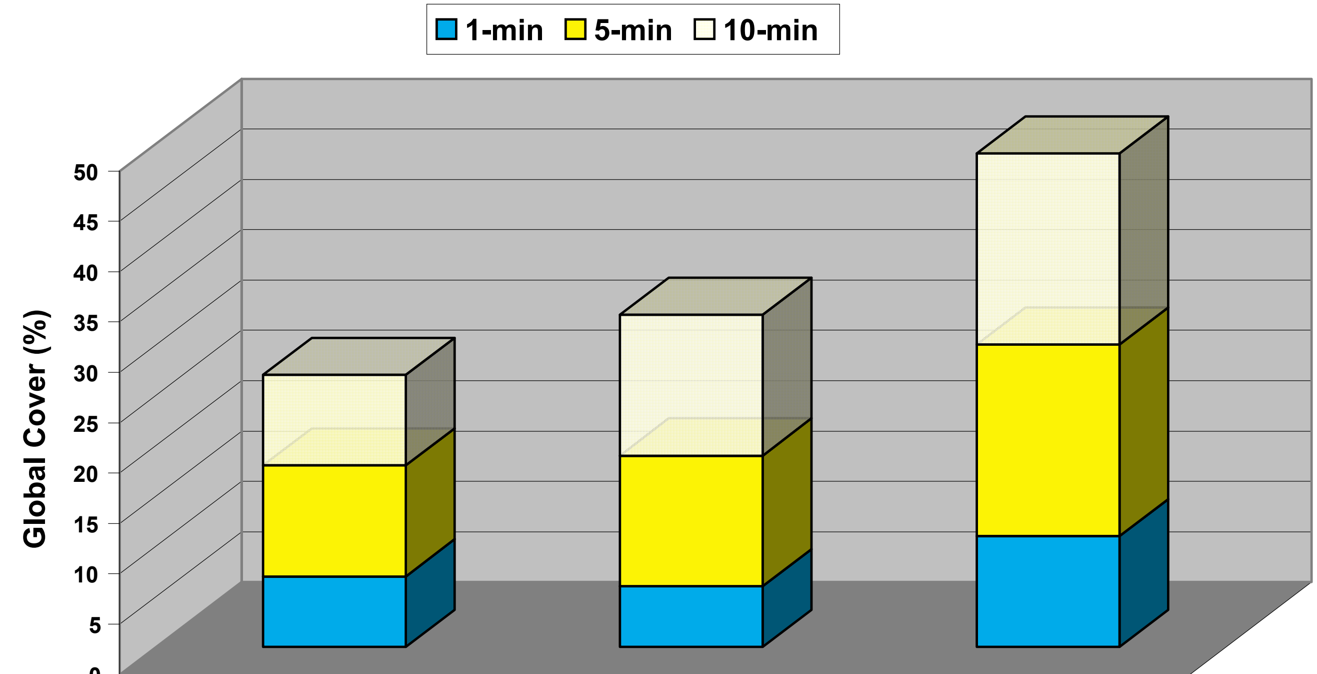
Percentage Global Coverage of Intersection Regions

Core Satellite/GMI - DMSP/SSMIS Intersections
July - August [*touch resolution is 5x5 deg*]

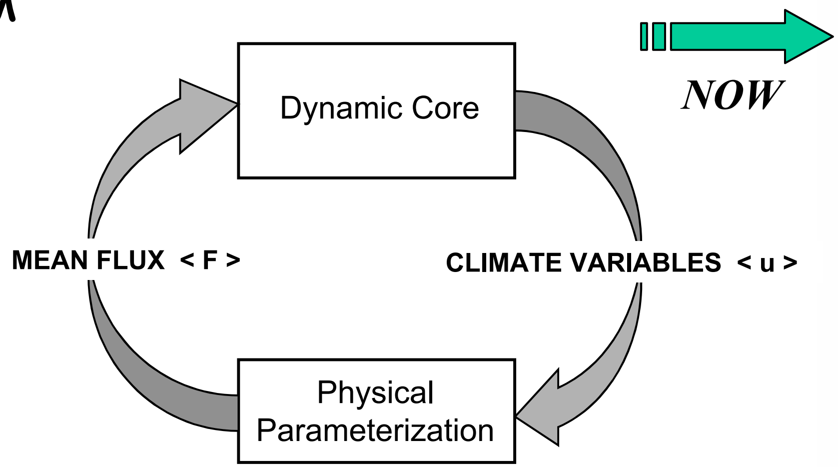


	Jul	Aug	Sep
10-min	9	14	19
5-min	11 (27)	13 (33)	19 (49)
1-min	7 (18)	6 (19)	11 (30)

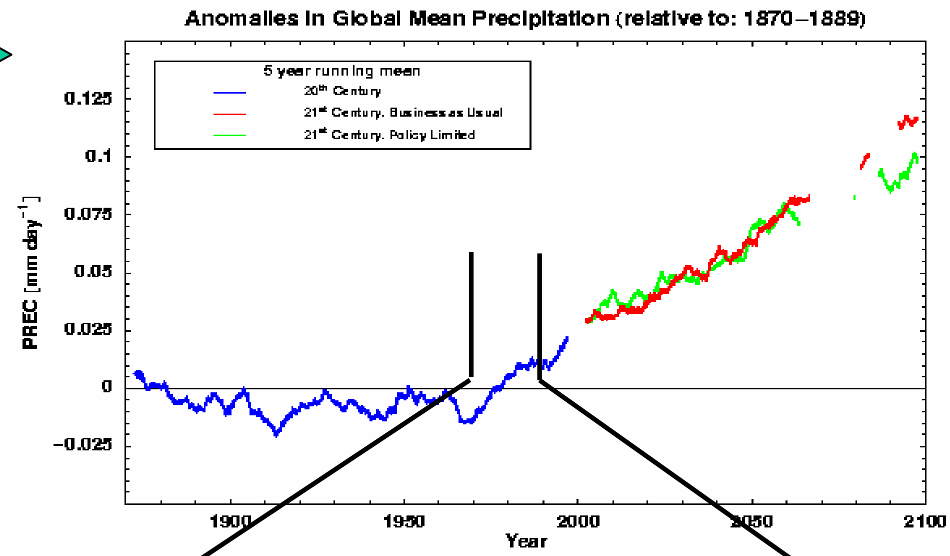
Month

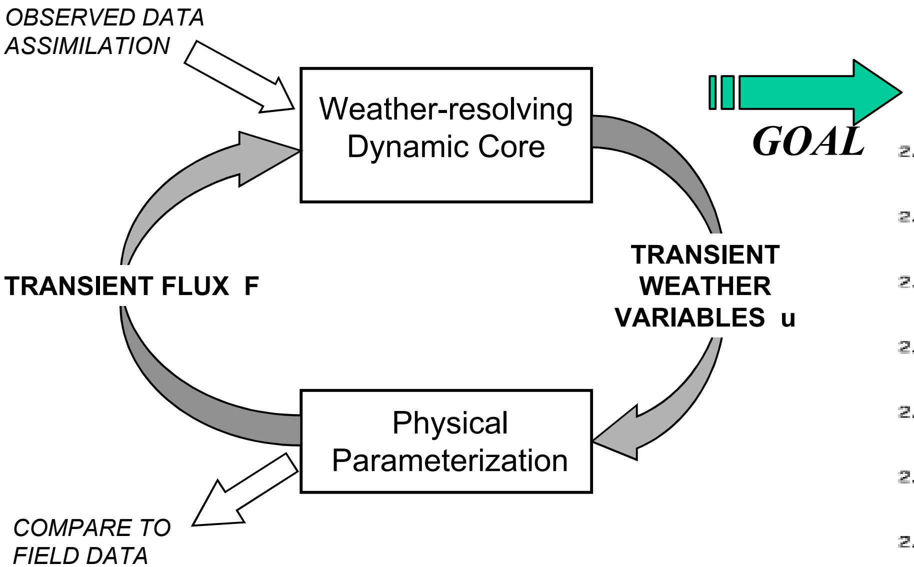
Precipitation Prediction: Key Objective of Water Cycle Research

GPM

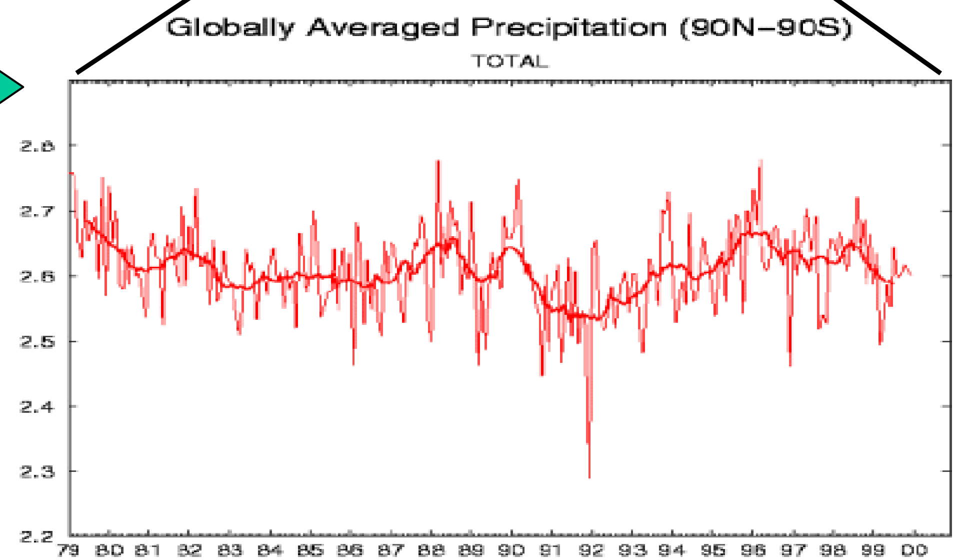


State of Art Climate Model (CCM-3)



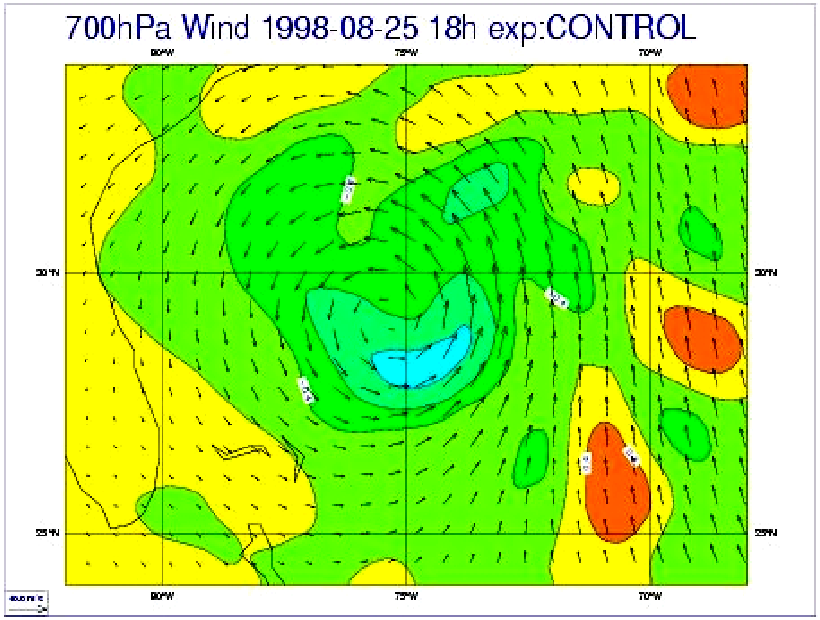


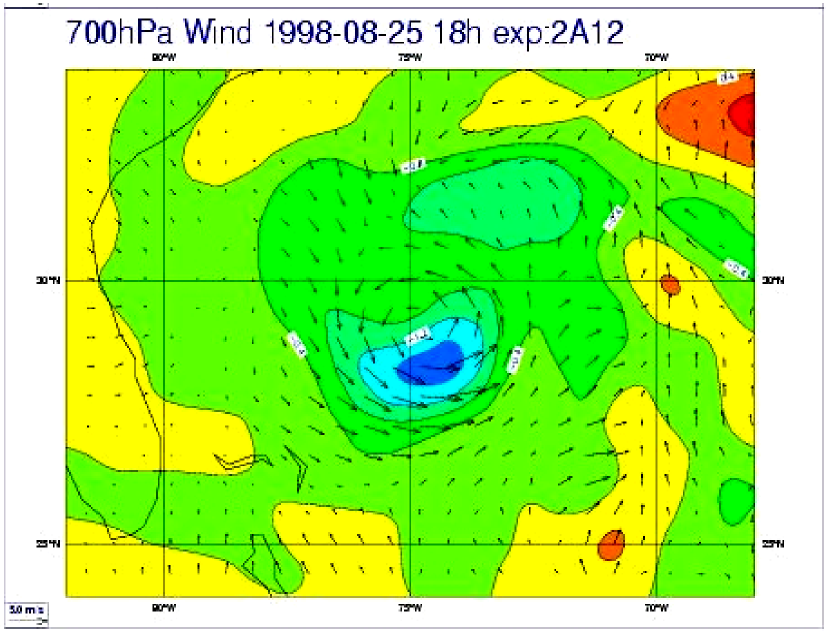
Next Generation Climate Model



Impact of TMI Rain Assimilation on Tropical Cyclone Dynamics

Horizontal & Vertical Winds in Tropical Cyclone Bonnie





ECMWF

J.-F. Mahfouf

GPM

brown trajectories: > 2.0 km precipitation feed
green trajectories: < 1.5 km precipitation feed

QuickTime™ and a Microsoft Video 1 decompressor are needed to see this picture.

Better Flood Predictions:

CRM Simulation & Microphysical Analysis of Three (3) Late Season Mediterranean Floods

Barrier Convergence Zone

- *surface flow convergence set up off-shore*
- *due to flow normal to high alps terrain*
- *flow surge lifted over convergence zone off-shore (335 θ_e surface)*

QuickTime™ and a Microsoft Video 1 decompressor are needed to see this picture.

Amplifying Mesoscale Storms Arising within Mobile Westerly Disturbances under Control of Fixed Geography & Orography

35/50 m s^{-1} jet cores; 5 km MSL isobars (2 mb); surface temperature

QuickTime™ and a Microsoft Video 1 decompressor are needed to see this picture.

Piemonte - 2000

Simulation of Low-Level Flows within Tyrrhenian, Ligurian, Ionian, & Adriatic Seas

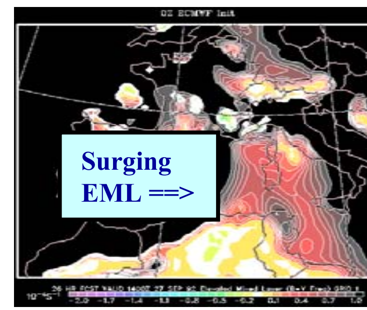
white (surface) -- orange (1.5 km)

QuickTime™ and a TIFF (LZW) decompressor are needed to see this picture.

Friuli - 1998

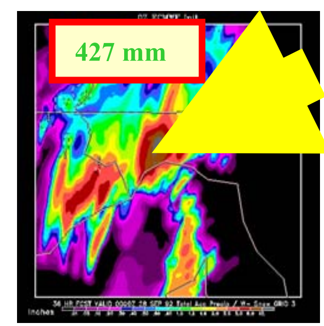
Elevated Mixed Layer

3 km MSL Brunt Vaisala Frequency



Inflow Cross-Section Surface θ_e (shaded)
Stable Brünt-Vaisala Frequency (dark shading)

QuickTime™ and a Microsoft Video 1 decompressor are needed to see this picture.



Genova - 1992

NASA GPM Level 1 Science-Measurement Requirements

GPM

NASA GPM Science-Measurements Requirements [[i] Version 2/Feb 2002]

Measurement Factor	3-hourly (Instantaneous)			Daily Accumulation			Monthly Accumulation		Applications/Outreach	
	Climate	Weather	Hydromet	Climate	Weather	Hydromet	Climate	Hydromet	Weather	Hydromet
Dynamic Range (mm hr^{-1})	[ii, iii] *0.3 to 65*	[iii] *0.3 to 110*	[iii] *0.3 to 110*	*0 to 200 mm dy^{-1}*	*0 to 600 mm dy^{-1}-*	*0 to 600 mm dy^{-1}*	*0 to 600 mm mo^{-1}*	*0 to 600 mm mo^{-1}*	[iii] *0.3 to 110*	[iii] *0.3 to 110*
Sampling Period (hrs)	*² 3*	*² 3*	*² 3*	*² 3*	*² 3*	*² 3*	*² 6*	*² 6*	*² 3*	*² 3*
Spatial Resolution (km)	*² 20*	*² 10*	*² 10*	*² 50*	*² 20*	*² 20*	*² 100*	*² 50*	*² 10*	*² 10*
Vertical Res of Radar (km)	*0.5*	*0.25*	*NA*	*0.5*	*0.5*	*NA*	*1*	*NA*	*0.25*	*NA*
[iv] *Meas Accuracy or Bias (%)*	*5*	*5*	*10*	*5*	*5*	*10*	*2.5*	*10*	*5*	*10*
Meas Precision or Random Error (%)	*25*	*25*	*25*	*20*	*20*	*20*	*10*	*10*	*25*	*25*
Snow Detection	*Yes*	*No*	*Yes*	*Yes*	*No*	*Yes*	*Yes*	*Yes*	*No*	*No*
Snowfall Rate and/or Snow Accumulation	*No*	*No*	*No*	*No*	*No*	*Yes*	*Yes*	*Yes*	*No*	*No*
Minimum Latitudinal Extent of Core (deg)	*65*	*65*	*65*	*65*	*65*	*65*	*65*	*65*	*65*	*65*
Minimal Latitudinal Extent of Drone (deg)	*90*	*65*	*90*	*90*	*65*	*90*	*90*	*90*	*65*	*90*
[v] *Data Latency*	*~1 day*	*~3 hrs*	*~3 hrs*	*~1 day*	*~1 day*	*~1 day*	*² 3 mo*	*² 3 mo*	*² 45 min*	*~3 hrs*

Footnotes

[i] Science-Measurement requirements table will undergo refinements out through GPM Mission Confirmation Review (MCR) in 2003. There will be four distinct versions with deadlines of December-2000 for Version 0 (preliminary estimates), August-2001 for Version 1 (1st major modification), February-2002 for Version 2 (2nd major modification), and mid-2003 for Version 3 (final minor refinements).

[ii] Factors in red are considered underlying drivers for GPM science Š factors in blue may not be achievable with 1st generation GPM technology.

[iii] Specification of 0.3 mm hr^{-1} for low end dynamic range needs further study before being considered as valid preliminary estimate.

[iv] 5% accuracy requirement depends upon radar measurements being sensitive to DSD variability (thus requiring 2-frequency radar) and low end dynamic range of 0.3 mm hr^{-1} (thus requiring Ku-band radar sensitivity of at least that of TRMM PR).

[v] Data latency greater that 45 minutes will negatively impact GPM's applications and outreach program.

Scientific Challenges for GPM Mission

1. Shift *intellectual inquiry paradigm* from "curiosity driven" to "quintessential water problem driven" -- via GPM science team working group cooperation.
2. Shift *research paradigm* from "measurement takes precedent" to ”measurement & prediction are of equal importance" -- through mandate from GPM science team.
3. Shift *derived products paradigm* (e.g., latent heating, bulk DSD properties, macro/microphysical cloud properties, error characterization, solid precipitation, vertical rain mass flux) from "cautious release" to "aggressive release" -- through modeler involvement in product assessment.
4. Shift *fast delivery data paradigm* from "only operational users need them" to "research users need them too" -- through transfer of data products from GPM-PPC to operational & research partners conducting prediction experiments.
5. Shift *validation paradigm* from "scatter diagram approach" to "physical error modeling approach" involving inverting flow of data “from & to” ground validation centers and deploying new instruments at various ground validation supersites.
6. Shift *cloud/precipitation paradigm* from "separate & distinct problems" to " cloud macro/microphysical life cycle continuum" leading to integrated cloud-precipitation missions, research programs, textbooks, and teaching.

Coordinate GPM Science Implementation Plan with WCRP/GEWEX