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Current Scientific Progress & Future Scientific Prospects
Enabled By Spaceborne Precipitation Radar Measurements

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Current and Future Spaceborne Radar Technologies for Measurement of Precipitation

**CURRENT**

1. LEO Platform *TRMM Satellite* with Precipitation Radar (DPR): Through-Nadir-Scan, Ku-Band (13.8 GHz), Non-Coherent Precipitation Radar along with Conical-Scan, Multiple-Frequency TRMM Microwave Imager (GMI) Radiometer for Tropical Precipitation Measurement

2. LEO Platform *CloudSat Satellite* with Cloud Profiling Radar (CPR): Nadir-Viewing, W-Band (94 GHz), Non-Coherent Cloud Radar for Cloud Microphysics Research

**FUTURE**

3. LEO Platform *GPM Satellite* with Dual Frequency Precipitation Radar (DPR): Separate Pair of Through-Nadir-Scan, Ku-Band (13.6 GHz) & Ka-Band (35 GHz), Non-Coherent Precipitation Radars along with Conical-Scan, Multiple-Frequency GPM Microwave Imager (GMI) Radiometer for Global Precipitation Measurement

4. LEO Platform *ACE Satellite* with Dual Frequency Cloud/Precipitation Radar: Through-Nadir-Scan & Multi-Beam Nadir-Pointing, Ka-Band (35 GHz) & W-Band (94 GHz), Doppler Cloud & Precipitation Radar System for Coupled Cloud - Precipitation Processes & Microphysics Research

5. GEO Platform *NIS Satellite* with NEXRAD in Space (NIS) Radar: Spiral Scan, Ka-Band (35 GHz), Doppler Precipitation Radar for 4D Hurricane Precipitation & Dynamics Monitoring and Improved Realtime Hurricane Forecasting through Rapid Update Data Assimilation of High Resolution Reflectivity & Doppler Velocity Profiles
NIS Deployment & Operations Concept

1
2
3
4 (Deployed)
Rain Rate Retrievals from Level 2 TRMM PR-TMI Combined Algorithm 2b31

I Use This Algorithm For 3 Main Reasons:

1. Z. Haddad and I developed it:


2. It is physically optimal, on theoretical basis.

3. It is used as calibration reference for TRMM Algorithm 3b42.

4. It’s extreme value properties are superior to 2a25.

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**2b31 Rain Rate Spectra for 2007**

**2a25 Rain Rate Spectra for 2007**
Diurnal Variability of Precipitation

Main Scientific Goal: Better understand multi-modal properties of precipitation’s diurnal cycle -- over local, regional, and global spatial scales -- for monthly, intraseasonal, seasonal, annual, and interannual temporal scales.

Our Recent Publications Concerning Diurnal Precipitation Variability from TRMM Measurements


Yang, S., and E. A. Smith, 2008: Convective - stratiform precipitation variability at seasonal scale from eight years of TRMM observations: Implications for multiple modes of diurnal variability. J. Clim., 21, 4087-4114.


9-Year Mean Rain Rate (1998-2006) during Indian Summer Monsoon Period (JJAS) from TRMM Blended Algorithm 3b42 (0.25°x0.25° spatial resolution)
Gujarat Floods: Early August 2006
Important MCS Element [6 - 7 August]

TRMM 3b42 Algorithm Observations

NMS CRM Model Simulation

TRMM 3B42 Rain Rates in mm/day: August 6, 2006 – 0 GMT

NMS Rain Rates in mm/day: August 6, 2006 – 0 GMT
• 24-Hour Clock Period Indicates Diurnal Time Period
• If Inner Clock Face is Shaded White, Both 1st and 2nd Diurnal Modes are Present

Late Evening to Morning Maximum (midnight - noon)
Afternoon to Early Evening Maximum (noon-midnight)

Primary Peak
Secondary Peak
Tertiary Peak
Quarternary Peak
[Level 2 TRMM PR-TMI Combined Algorithm 2b31]

Summer (JJA)

Autumn (SON)

1998
SUMMARY

- NW Subdivision exhibits continental diurnal signature for three seasons but exhibits oceanic signature during Summer.
- Indian Sub-continent exhibits uniform continental diurnal signature during Spring and Autumn, while during Winter and Summer, diurnal signature is mixed continental-oceanic.
- Surrounding Indian Ocean regions exhibit oceanic diurnal signature for most part during Winter, Summer, and Autumn -- during Spring, Indian Ocean becomes largely continental vis-à-vis its diurnal character.
Vertically-Dependent Spectral Diurnal Variability of Precipitation

Scientific Objective: Better understand diurnal variability of precipitation and latent heating by way of their dependence on vertical structure and rain rate spectra -- including impact of CloudSat-CPR’s enhancement of TRMM-PR’s rain rate spectra. [This latter step is accomplished via application of our newly developed CPR-PR profile matching algorithm.]
Stained Glass Grid Box Template of Spectrally / Vertically Dependent Diurnal Precipitation
[two 5-deg grid boxes along east coast of Argentina -- Jan 2007]

Layer Heights Key (4)
✓ Lower Triangle: 0 - 1 km
✓ Middle-left Triangle: 1 - 4 km
✓ Middle-right Triangle: 4 - 7.5 km
✓ Upper Triangle: > 7.5 km

Raining Pixels Key
✓ Grid Box NOT Present: Zero Raining Pixels or <0.5% Raining Pixels in Lowest Layer (i.e., lower triangle)
✓ Grid Box Present: >0.5% Raining Pixels in Lowest Layer (i.e., lower triangle) [0.5% selected to match 2.5 deg resolution Stained Glass rain cover map with TRMM PR precipitation climatology map]
✓ Triangle Lines NOT Present: Zero Raining Pixels in Hat / Sector

Spectral Bin Thresholds & Colors Key (5)
✓ Left Hat: >0 to 2 mm hr⁻¹ (Blue Shades)
✓ Left Sector: >2 to 5 mm hr⁻¹ (Green Shades)
✓ Top Sector: >5 to 10 mm hr⁻¹ (Orange Shades)
✓ Right Sector: >10 to 20 mm hr⁻¹ (Purple Shades)
✓ Right Hat: >20 to 500 mm hr⁻¹ (Red Shades)

Bin Population Colors Key (6)
Bin color varies in 6 discrete color steps, ranging from:
✓ White -- indicating zero raining pixels for given bin, through
✓ 6 levels of color up to,
✓ Full Saturation -- indicating >20% raining pixels for given bin

Daily Period Diurnal Amplitudes & Phases Key
Amplitudes: denoted by shapes of spindle object-ends
✓ — (flat top): 0 - 1 mm hr⁻¹
✓ — (diamond): 1 - 5 mm hr⁻¹
✓ — (round top): > 5 mm hr⁻¹

Phases: denoted by positions of spindle object-ends along boulevards which are divided into eight 3-hour segments from spindle centers to boulevard ends
e.g.: phase = 16.5 MST

Blue Spindle: 0 - 12 MST phase (midnight-to-noon) -- ocean-type behavior
Brown Spindle: 12 - 24 MST phase (noon-to-midnight) -- continent-type behavior

Additional Notes
✓ (a) “Un-weighted” denotes no weighting procedure is used in representing bin populations -- (b) “Weighted” denotes bin populations are given ‘occurrence’ weights according to associated rain rate magnitudes, while retaining percentage scale.

Maps are cast in one of four (4) spatial scales: two for tutorial purposes at (1) 24-deg & (2) 15-deg and two for analysis purposes at (3) 5-deg & (4) 2.5-deg.
Tutorial View of Vertically / Spectrally Dependent Diurnal Precipitation: Jan 2007

15 Degree Grid Scale

24 Degree Grid Scale
Explicit & Implicit Properties of Spectrally / Vertically Dependent Diurnal Precipitation: Jan 2007 [weighted -- 2.5-deg grid scale]

Map Properties

Explicit Properties
1. Vertical structure of spectrally dependent monthly rainfall
2. Vertical structure of diurnal amplitude & phase of monthly rainfall
3. Vertical structure of spectrally dependent diurnal amplitude & phase of monthly rainfall -- given in separate map

Implicit Properties
1. Location of significant monthly rainfall
2. Location of vertically deep monthly rainfall
3. Distribution of convective & stratiform monthly rainfall -- also explicitly given in separate maps
4. Distribution of morning (oceanic-type) & afternoon (continental-type) phase-mode of maximum-amplitude monthly rainfall
5. Distribution of spectrally similar monthly rainfall
Central Sector Total Rainfall: Jan 2007 [5 deg grid scale]

- Convective
- Deep convection
- Continental-type diurnal
- Stratiform
- Maritime-type diurnal
Central Sector Convective Rainfall: Jan 2007 [5 deg grid scale]
Central Sector Stratiform Rainfall: Jan 2007 [5 deg grid scale]
Central Sector Rainfall: Jul 2007 [2.5 deg grid scale]

One-point Correlation Map of Rain Rate Spectra for Lowest 3 Layers

Reference Point = 23.75°S / 56.25°W [Red Contour = 0.9 corr; Purple Contour = 0.8 corr]
Extraction of CloudSat/CPR - TRMM/PR Orbit Crossing Data

Advantages of Combining TRMM/PR and CloudSat/CPR Data for Investigation of Vertically-dependent Spectral Diurnal Precipitation Cycle

<table>
<thead>
<tr>
<th>Advantages of PR Measurements</th>
<th>Advantages of CPR Measurements</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Diurnal sampling</td>
<td>1. Sensitivity to light precipitation spectrum</td>
</tr>
<tr>
<td>(non-sun-synchronous inclined orbit)</td>
<td>(low noise down to reflectivity of -25 dBZ)</td>
</tr>
<tr>
<td>2. Spatial coverage</td>
<td>2. Full global coverage</td>
</tr>
<tr>
<td>(cross-track scanning over 200 km wide swath)</td>
<td>(sun-synchronous over-the-Pole orbit)</td>
</tr>
<tr>
<td>(reliable $Z_h$’s as low as 0.25 km)</td>
<td>(surface clutter in bins 3 &amp; 4 are now suppressed)</td>
</tr>
<tr>
<td></td>
<td>4. Mid- &amp; upper troposphere observations</td>
</tr>
<tr>
<td></td>
<td>(another advantage of sensitive radar)</td>
</tr>
</tbody>
</table>

Exploit “Blossoming” Effect
One Month CloudSat-TRMM Intersect Location Progression
December 2006 -- 50 Minute Orbit Proximity

[ 0 min $\leq |\Delta t| \leq 5$ min ] [ 5 min $< |\Delta t| \leq 15$ min ] [ 15 min $< |\Delta t| \leq 25$ min ]

[ 25 min $< |\Delta t| \leq 35$ min ] [ 35 min $< |\Delta t| \leq 50$ min ]

2006335
Selection of Intersect Curtains
[78 of 837 intersections indicate meaningful TRMM precipitation -- 9.3%]

day 342 $\Delta t = 11.7$ min (17.5ºS)

day 342 $\Delta t = -14.8$ min (20ºS)

day 344 $\Delta t = 3.4$ min (10ºS)

day 344 $\Delta t = -19.8$ min (12.5ºN)

day 340 $\Delta t = -13.4$ min (26.5ºS)

day 349 $\Delta t = -14.5$ min (11.5ºS)
Multiple Coupled Mechanisms Governing Propagation of Precipitation

Scientific Objective: Confirm our hypothesis concerning not previously recognized coupling of mechanisms governing propagation of warm season precipitation downstream from north-south aligned mountain ranges which support formation of low level jets. Such propagation is 2-stage process, initially consisting of slope-flow driven diurnally-phased precipitation line process which begins around and forward of peak elevations of mountain ranges, terminating at locations along front range at which point precipitation line properties transform to blob-like properties consisting of mesoscale convective system (MCS) and jet streak elements which take over and control propagation according to quasigeostrophic dynamics.
By compositing over diurnal time period (i.e., 8-year - 4 month composite) using TRMM Combined PR-TMI 2b31 data over lower portion of Central North America Study Area (Rocky Mountains) observed by PR, we see how (I) precipitation initially forms in high mountains throughout afternoon period, then (II) propagates eastward forced by mountain slope flow dynamics out to front range, where (III) near-midnight Mesoscale Convective System (MCS) forms and precipitation propagation continues eastward with different phase determined by quasigeostrophic advection dynamic, after which (IV) east of Mississippi River basin, precipitation is either continuous with diurnal peak throughout afternoon or undergoes very weak phase shift across eastern U.S. up to Eastern Continental Divide, until finally (V) heavy early morning rainfall regulates diurnal pattern across Eastern Seaboard.

**Diurnal Cycle of Central US Warm Season Rain Rate (Total Rain): PR-TMI 2b31**

*Summertime Diurnal Time - Longitude Section Averaged Over 30° - 37.5°N Latitude Zone*

[Based on 4-Month (Jun - Sep) / 8-Year (1998 - 2005) Time Period - Partial Latitude Compositing]

**5-Stage Precipitation Propagation Process over Central U.S. Study Area, during North American Warm Season**

Stages II and III are Propagating Stages, i.e., Diurnally-forced Mountain Slope Flow & Quasigeostrophically-forced MCS Travel

**Underlying Terrain**

1. Central United States

<table>
<thead>
<tr>
<th>City</th>
<th>Latitude</th>
<th>Longitude</th>
<th>Elevation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Denver, CO, USA</td>
<td>39.8°N</td>
<td>104.7°W</td>
<td>1600 m</td>
</tr>
<tr>
<td>Oklahoma City, OK</td>
<td>35.5°N</td>
<td>97.5°W</td>
<td>399 m</td>
</tr>
<tr>
<td>St. Louis, MO, USA</td>
<td>37.5°N</td>
<td>92.5°W</td>
<td>142 m</td>
</tr>
<tr>
<td>Indianapolis, IN</td>
<td>39.5°N</td>
<td>86.1°W</td>
<td>219 m</td>
</tr>
<tr>
<td>Pittsburgh, PA, USA</td>
<td>40.5°N</td>
<td>80.0°W</td>
<td>373 m</td>
</tr>
<tr>
<td>Washington DC, USA</td>
<td>38.9°N</td>
<td>77.0°W</td>
<td>63 m</td>
</tr>
</tbody>
</table>
What are key mechanisms producing 2-stage precipitation propagation pattern?

1. Daytime into nighttime diurnal movement of dryline under control of cross-ridge lee mass fluxes eating away thermal inversion capping mountain boundary layer releasing diurnally propagating line convection, i.e., “lee-side buzz-saw”.

2. Front range nighttime Low Level Jet (LLJ) created by clockwise turning of what was daytime upslope velocity vector until its alignment with mountain ridge axis produces supergeostrophic velocity transport of moisture within internal boundary layer created by formation of nighttime ABL with top below that of remaining daytime ABL downstream from dryline.

3. Transformation of line convection along leading edge of dryline (often represented by thunderstorms and squall lines with storm structures tilted back against mountains) into blob-like Mesoscale Convective System (MCS) fueled by moisture transport from nighttime LLJ which links up with existing jet streak or produces its own jet streak support, continuing precipitation propagation away from mountains -- but now under control of quasi-geostrophic dynamics.


Cordillera de los Andes

Shifting to Central South America Study Area (Cordillera de los Andes), again under prevailing westerlies and using both PR-TMI 2b31 & TMPA-3b42 data, we also find 2-stages of precipitation propagation process similar to what was found over Central N.A. Study Area.

Diurnal Cycle of Central South America Warm Season Rain Rate: PR-TMI 2b31 & TMPA-3b42

**Summertime Diurnal Time - Longitude Sections Averaged Over 15° - 35°S Latitude Zone**

[Based on 6-Month (Nov - Apr) / 8-Year (1998 - 2005) Time Period - Partial Latitude Compositing]

**Stage II: Diurnally Propagating Mountain Slope Flow**

**Stage III: Quasi-geostrophically Propagating MCS**

**Stages II & III: Precipitation Propagation Process over Central S.A. Study Area, during South American Warm Season**

**Underlying Terrain**

<table>
<thead>
<tr>
<th>City</th>
<th>Latitude</th>
<th>Longitude</th>
<th>Elevation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lake Titicaca, PERU</td>
<td>15.8°S</td>
<td>69.7°W</td>
<td>3820 m</td>
</tr>
<tr>
<td>San Pedro de Atacama, CHILE [Atacama Desert]</td>
<td>23.0°S</td>
<td>70.2°W</td>
<td>3430 m</td>
</tr>
<tr>
<td>La Paz, BOLIVIA</td>
<td>16.5°S</td>
<td>66.7°W</td>
<td>4050 m</td>
</tr>
<tr>
<td>Sucre, BOLIVIA</td>
<td>19.0°S</td>
<td>66.3°W</td>
<td>2285 m</td>
</tr>
<tr>
<td>Córdoba, ARGENTINA</td>
<td>31.9°S</td>
<td>60.7°W</td>
<td>379 m</td>
</tr>
<tr>
<td>Lago Argentino, ARGENTINA</td>
<td>35.9°S</td>
<td>62.7°W</td>
<td>24 m</td>
</tr>
<tr>
<td>Asunción, PARAGUAY</td>
<td>25.5°S</td>
<td>56.7°W</td>
<td>57 m</td>
</tr>
<tr>
<td>Montevideo, URUGUAY</td>
<td>33.9°S</td>
<td>51.7°W</td>
<td>31 m</td>
</tr>
<tr>
<td>Porto Alegre, BRAZIL</td>
<td>29.4°S</td>
<td>51.2°W</td>
<td>47 m</td>
</tr>
<tr>
<td>Sào Paulo, BRAZIL</td>
<td>23.4°S</td>
<td>46.7°W</td>
<td>760 m</td>
</tr>
<tr>
<td>Rio de Janeiro, BRAZIL</td>
<td>22.9°S</td>
<td>43.2°W</td>
<td>3 m</td>
</tr>
</tbody>
</table>
North Africa Study Area (Ethiopian Highlands), which unlike previous five study areas is under prevailing easterlies, also exhibits 2-stage -- reversed direction -- precipitation propagation process, but only in terrain sector west of Ethiopian Plateau. Further to west, it is evident that additional complex terrain features regulate diurnal properties of precipitation, but not as 2-stage propagation processes.
Locations of 7 study areas situated over 5 continents (blue-colored grids -- with lighter blue speckled portions indicating coverage by TRMM PR as noted by legend below). Colors used within continental boundaries (color bar legend given below-right) indicate climatological trends in precipitation (% per decade) over 20th century as reported by IPCC-WGI (2001). Note that boundaries of study area 2 (Northern South America) are located in two separate map sectors.
Conclusions

• Space Radar remote sensing provides a variety of new and unprecedented methods to analyze precipitation -- not possible with passive methods of precipitation retrieval.

• It is the responsibility of members of the scientific community to keep the pressure on our space agency sponsors to provide for a continuing and continually improving precipitation radar capability in space.
Thank You