QUAD SPACE WORKING GROUP

TECHNICAL WORKSHOP ON EXTREME PRECIPITATION EVENTS

FEBRUARY 6-10, 2023

THE STEERING COMMITTEE FOR WORKSHOPS ON EXTREME PRECIPITATION EVENTS
Australia (ASA, BOM)
India (IMD, INCOIS, ISRO)
Japan (JAXA, JMA)
United States (NOAA *(Lead)*, NASA, USGS)

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I. Executive Summary

The February 2023 Quad Space Working Group Technical Workshop on Extreme Precipitation Events was an effort under the Quad Space Working Group. The Quad nations are Australia, India, Japan, and the United States. The Quad was established in the wake of the 2004 Indian Ocean Tsunami to coordinate humanitarian assistance and disaster relief, and has since become a leading regional partnership dedicated to advancing a common vision of a free and open Indo-Pacific through practical cooperation on diverse 21st-century challenges.

The focus of the February 2023 Quad Space Working Group Technical Workshop on Extreme Precipitation Events was to discuss extreme precipitation events at the technical level and from the lens of societal benefits. The Workshop explored how the four Quad members' space capabilities and/or capabilities in using space-based Earth observation data might contribute to disaster preparedness and response to extreme precipitation events and the environmental events they exacerbate, as well as how those events impact related transboundary issues. The intended outcome is that through the Quad Space Working Group and the information received and discussed at the February 2023 technical Workshop, the Quad members can strengthen their collective capabilities, as well as potentially help other Indo-Pacific nations develop their capabilities, to prepare for and respond to environmental and natural disasters.

This Workshop was planned by a Steering Committee of members representing multiple agencies from each of the Quad countries. The Workshop was attended by approximately 70 technical subject matter experts and policy representatives from the space, meteorological, and hydrographic agencies from each of the four Quad countries, as well as a couple invited researchers from academia. The Workshop included five sessions, each planned and chaired by a representative of one of the Quad countries. The sessions included presentations and discussions on the following subject areas within the scope of extreme precipitation events:

1. Large scale precipitation systems (e.g., tropical cyclones)
2. Mesoscale precipitation systems
3. Inundation/flooding, coastal erosion and water quality
4. Transboundary issues (e.g., ocean/atmosphere/land changes, cascading hazards)
5. Data integration and applications for societal benefits

The Chairs of sessions 1-4 created background reading and shared it with the participants prior to the Workshop. The background reading addressed the following questions, specific to the topic under discussion in each session. The Workshop participants then discussed these questions and others the session chairs raised specific to the topic in each session, as well as provided useful case studies that demonstrated best practices and challenges. Session five tied the discussions from the first four sessions together and focused the information on a facilitated discussion related to societal benefits.

At the conclusion of the Workshop, the Workshop participants discussed what they viewed as the Workshop outcomes, including the recurring themes raised in the Workshop, and opportunities for Quad collaboration identified during the Workshop. The participants further discussed how each of the identified outcomes and opportunities address one or more of the recurring themes identified during the Workshop. Following the Workshop, the Workshop

Steering Committee further considered the Workshop discussions and came to agreement on the list of Workshop outcomes and opportunities.

The key Workshop outcomes were identified by the Workshop participants and refined by the Steering Committee. The opportunities identified relate to one or more of these key outcomes. (It is important to note that while some of these outcomes and opportunities may seem general in nature, for the purposes this report, each outcome and opportunity outlined below should be read to relate specifically to extreme precipitation events and how to monitor and address extreme precipitation events.)

Summary of the Key Outcomes of the Workshop

1. Identified four overarching themes:
    - Importance of capacity building in the Indo-Pacific region.
    - Importance of timely, accessible open data and open science.
    - Need to discuss how to perform impact assessments over multiple countries.
    - Importance of continuing data gathering to ensure long-term data sets.
2. Need for improving existing models and types of modeling.
3. Need to leverage spatial resolution of Synthetic Aperture Radar (SAR) for improved best track parameters as well as monitoring of land / ocean impacts.
4. Identified important modeling and data assimilation improvement needs.
5. Need to consider spatial and temporal downscaling capabilities tying different observing capabilities together (e.g. blended products, GEO+LEO).
6. Importance of constellation measurements (temporal refresh) for cyclogenesis.
7. Importance of extending the current product data records.

Summary of the Opportunities Identified at the Workshop

A list of opportunities was identified in the Workshop discussions. The Steering Committee refined the language in the opportunities to clarify the intent of each opportunity, including by organizing them by thematic area. These are a list of opportunities the Workshop participants and Steering Committee believes Quad Members could pursue, either individually or through a Quad partnership, to address the key gaps and needs to improve the forecasting of extreme precipitation events, as well as to improve the monitoring and mitigation of the impacts of extreme precipitation events in the Indo-Pacific Region. The opportunities identified relate to one or more of the key Workshop outcomes. Some of the opportunities identified are discreet, specific actions that can be a taken; others are focus on the bigger picture. The opportunities are organized by themes and not in priority order.

Summary Table of Opportunities

The below table sets out potential opportunities for collaboration between Quad nations, arranged by the themes identified in the Workshop. Many items cover multiple thematic areas, and that overlap is indicated in parentheses. This table is not organized with any prioritization. Note that while some of these opportunities may seem general in nature, for the purposes of this report each opportunity outlined below should be read to relate specifically to extreme precipitation events and how to monitor and address extreme precipitation events.

Importance of capacity building in the Indo-Pacific region	Importance of timely, accessible open data and open science	Need to discuss how to perform impact assessments over multiple countries	Importance of continuing data gathering to ensure long-term data sets
• Explore opportunities for **new missions** with instruments to monitor extreme precipitation (also *Long-term Data*) • Provide **mobile applications** to support community-based solutions • Endorse **India's concept note** to move forward to the Quad Space Working Group for formal consideration (also *Open Data* and *Impact Assessments*) • Conduct more **field campaigns** and improve integration of field campaigns with space-based observations (also *Long-term Data*) • Continue to advance and improve **modeling capabilities** to provide accurate, real-time information, especially when a disaster strikes (also *Impact Assessments)*	• Commit to **open science** and **open data** • Commit to providing **relevant, timely, and accessible data** (FAIR principles) • Establish an **integrated portal** of precipitation monitoring capabilities that leverage existing measurements, products, tools, and other capabilities of Quad members • Improve the sharing of technical satellite and environmental data and products in understandable language to non-technical audiences • Provide data in formats that are accessible and usable • **Improve linkages** between the environmental and satellite data providers/scientists and social scientists for hazard communication, as well as for advocates who can represent community needs • Develop agreements between Quad countries for the sharing of satellite and environmental data related to extreme precipitation (also *Capacity Building* and *Long-term Data*) • Ensure **two-way interaction** between end users and algorithm developers, which is always essential to the utility of products.	• Identify, develop, and/or share best practices and case studies for **working with stakeholders and communities** (also *Capacity Building*) • identify, develop, and/or share best practices for the use of space-based observations to **assess coastal vulnerabilities** and **impacts of storms** (e.g., tropical cyclones) from both a flooding and inundation as well as water quality perspective (also *Capacity Building*) • **Work with task teams** with experts from various agencies for different applications, such as: ○ Identifying/developing a **decay model** related to tropical cyclones; ○ targeted improvements **in track and intensity** ○ **hazard modeling** associated with strong winds (gust) and precipitation ○ remote sensing based newer tools and techniques for **damage assessments** (also *Capacity Building* and *Long-term Data*)	• Continue **data gathering to ensure long-term time series of product data records**, with emphasis on extreme precipitation-related data and climatological products • Consider advancements and extensions of current **space-based global observation systems** and the **spatial and temporal observation requirements** from the present instruments (also *Capacity Building*) • Explore new opportunities for **future space-based global observation systems** (also *Capacity Building*)

Concluding Recommendations

This Workshop resulted in robust information sharing among the Quad countries. The Workshop participants identified multiple outcomes and possible opportunities for the Quad partners to pursue through the partnerships under the partnership of the Quad Space Working Group.

As the next steps to follow up on the technical discussions within this Workshop, the Steering Committee recommends the members of Quad Space Working Group:

- Accept this Workshop report; and
- Consider collaborating on the opportunities outlined in this report, with priority focus on the opportunities identified as (1) addressing capacity building in the Indo-Pacific Regions and (2) addressing the importance of timely, accessible, open data and open science.

II. Introduction

<u>The Quad Space Working Group</u>

The February 2023 Quad Space Working Group Technical Workshop on Extreme Precipitation Events was an effort under the Quad Space Working Group. The Quad nations are Australia, India, Japan, and the United States. The Quad was established in the wake of the 2004 Indian Ocean Tsunami to coordinate humanitarian assistance and disaster relief, and has since become a leading regional partnership dedicated to advancing a common vision of a free and open Indo-Pacific through practical cooperation on diverse 21st-century challenges.

The Quad Space Working Group that was established as an outcome of the September 24, 2021, Quad Leaders' Summit, during which the Leaders' indicated, "In space we will identify new collaboration opportunities and share satellite data for peaceful purposes such as monitoring climate change, disaster response and preparedness, sustainable uses of oceans and marine resources, and on responding to challenges in shared domains. We will also consult on rules, norms, guidelines and principles for ensuring the sustainable use of outer space."

The following year, during the May 2022 Quad Leaders' Summit, the Leaders committed the Space Working Group to "...provide capacity building support to countries in the region, including with regards to partnering on using space capabilities to respond to extreme precipitation events." This Workshop is a step in following up on that commitment.

<u>Quad Space Working Group Technical Workshop on Extreme Precipitation Events</u>

Extreme precipitation events are becoming more prominent and devastating in the Indo-Pacific region. The extreme events are increasing in frequency and intensity. Such precipitation events exacerbate the effects from simultaneous environmental events such as extreme weather (e.g., hurricanes and typhoons), floods, sea level rise, and other hydrological disasters, causing economic catastrophes and loss of human life.

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This Workshop met two objectives in the Quad Space Working Group Work Plan, including:

1. Cooperation to utilize space as an enabler to address the climate crisis; and
2. Cooperation to utilize space as an enabler for the sustainable use of oceans and marine resources.

The Quad Space Working Group Technical Workshop on Extreme Precipitation Events was held virtually, February 5-9, 2023 (USA)/February 6-10, 2023 (Australia, India, Japan). The full Workshop agenda is provided in Appendix 1.

This Workshop was planned by a Steering Committee of members representing multiple agencies from each of the Quad countries. The Workshop was attended by approximately 70 technical subject matter experts and policy representatives from the space, meteorological, and hydrographic agencies from each of the four Quad countries, as well as a couple invited researchers from academia. The Workshop included five sessions, each planned and chaired by a representative of one of the Quad countries. The sessions included presentations and discussions on the following subject areas within the scope of extreme precipitation events:

1. Large scale precipitation systems (e.g., tropical cyclones)
2. Mesoscale precipitation systems
3. Inundation/flooding, coastal erosion and water quality
4. Transboundary issues (e.g., ocean/atmosphere/land changes, cascading hazards)
5. Data integration and applications for societal benefits

The Chairs for Sessions 1 - 4 created background reading and shared it with the participants prior to the Workshop. The background reading addressed the following questions, specific to the topic under discussion in each session. (The background reading provided by each Session Chair prior to the Workshop can be found in Appendix 2.)

1. Outline the problem.
2. Identify the key users of data on the issue and the key information requirements. Discuss how to loop this information into what emergency managers need.
3. Consider the problem vs. the Quad Members' capabilities or unique impacts on certain Quad countries of given events (e.g. data, communications, and technology resources).
4. Review current tools and products available and relevant experience and applicability in the Indo-Pacific Region.
5. Explore how to tie into existing mandates and activities from relevant multilateral organizations (e.g., relevant UN groups, World Meteorological Organization, Group on Earth Observations, Coordination Group for Meteorological Satellites, Committee on Earth Observation Satellites)

The Workshop participants then discussed these questions and others the session chairs raised specific to the topic in each session, as well as provided useful case studies that demonstrated best practices and challenges. The participants provided input based on their individual expertise, the background reading, and the presentations provided during each session.

Session five tied the discussions from the first four sessions together and focused the information on a facilitated discussion related to societal benefits. The questions included:

1. What kind of information the Quad countries can bring to the region?
2. How to help the region to use the information to combat their problems
3. How to get feedback from the user community?

To close the Workshop, the participants identified suggested outcomes of the Workshop and potential opportunities for the Quad countries to pursue related to extreme precipitation events.

III. Session Summaries

This section provides a brief summary of the presentations, discussions, and outcomes of each of the five Workshop sessions.

Session 1: Large scale precipitation systems (e.g., tropical cyclones)

Session 1 was chaired by Dr. Atul Varma of the Space Applications Centre of the Indian Space Research Organisation (SAC/ISRO) and Dr. Ananda Kumar Das of the Indian Meteorological Department (IMD). Session 1 included eight presentations focused on various aspects of predicting, monitoring and assessing large scale precipitation events, such as tropical cyclones, and discussing gaps and ways forward to address these gaps. (Please see Appendix 1, Workshop Agenda, for a full review of the questions discussed in the facilitated discussion, and Appendix 2 for the background reading for this session.)

Summary of the Session 1 Presentations

First, the presenters provided information on the present status of tropical cyclone (TC)/typhoon/hurricane forecasts and vulnerability assessments for future plans and gap areas. The presenters noted the following:

- North Indian Ocean - presenters highlighted the following desired actions:
    - Seamless forecast and warning product generation commencing with extended range forecast and followed by medium range, short range and nowcast.
    - High-resolution wind observations and forecasts over oceans.
    - Improved methodology for the probabilistic forecast for exceedance of wind.
    - Filling the gap in observational systems for real-time assessment of the storm location, intensity and structure while the storm lies over the deep sea.
    - Assessment of the impact of TC and vulnerability area from satellite-based observations for the improvement of Impact Based Forecast and Warning services.
- Atlantic and northeast-Pacific Ocean - the following points were discussed:
    - Current hurricane forecast products for the National Hurricane Center (NHC) and Central Pacific Hurricane Center (CPHC).
    - Modeling issues in genesis, track and intensity. Poor genesis forecast continues to be a problem for subtropics and mid-latitudes. Difficulty in predicting intensity. Tilted TC vortices and associated track correction.
    - Major gap areas are surface wind information, optimize operational data collection, rapid intensification process understanding.
    - Research emphasis on Hurricane Forecast Improvement Program (HFIP), NOAA - Ocean and Atmospheric Research and NOAA-National Environmental Satellite, Data, and Information Services.
- Northwest-Pacific Ocean - the following points were discussed:
    - Regional Specialized Meteorological Centre (RSMC)-Tokyo major services and activities via World Meteorological Organisation/Global Telecommunication System (WMO/GTS), online research opportunities.
    - RSMC-Tokyo achievement in remarkable improvement in 5-days TC forecasts.

- Future plan including enhanced horizontal resolution (13 km) in Japan Meteorological Agency's (JMA) global spectral model, and improvements in model physics and data assimilation system.
  - Himawari 8/9 imager operational modes over different target regions of Japan and Australia.
  - JMA Atmospheric Motion Vectors (AMV)-based sea surface winds (ASwinds) product generation and guidance for TC gale wind.
- Southern hemisphere - the following points were discussed:
  - Application of ensemble prediction system for TC forecast.
  - A gap is that warning services are centered on weather systems rather than the hazard.
  - Slow movement towards impact-based forecasts, particularly on vulnerabilities.

There were then presentations on four additional topic areas:

- Advance airborne and satellite observation for understanding genesis, decay, intensification, propagation, and/or structure of cyclones, including:
  - Use of US airborne observations to calibrate the high biases in surface winds from microwave radiometers.
  - Availability of new products from existing satellites, i.e. night time ProxyVis, synthetic passive microwave imagery/precipitation from geostationary satellites; synthetic aperture radar (SAR) observations.
  - Use of Soil Moisture Active Passive (SMAP), Soil Moisture and Ocean Salinity (SMOS), and Advanced Microwave Scanning Radiometer-2 (AMSR) wind speeds in operations.
- Recent advances in theoretical and computational modeling of Tropical Cyclones, including:
  - Forecast Improvement Program of NOAA that has time bound goals.
  - Improvements in Hurricane Weather Research and Forecasting (HWRF), and need for newly developed Advanced Hurricane Analysis and Forecast System (HAFS) in the Unified Forecast System (UFS) framework.
  - Advancements in improving model physics and efforts to assimilate more satellite and field observations.
  - Implementation of nested model system and basin-level forecasts by NOAA.
- Data assimilation for cyclone forecast, including:
  - India's National Centre for Medium Range Weather Forecasting (NCMRWF) numerical weather prediction system (NCUM) for TC forecast generation.
  - Impact of satellite and aircraft data assimilation in TC forecasts.
- Tropical Cyclones in changing climate scenario, and vulnerability assessment, including
  - Global decrease in TC frequency and increase in intense storms, TC induced rainfall and surge.
  - TC genesis locations are shifting towards higher latitudes as favorable conditions are migrating.
  - Regions that were not earlier experiencing intense tropical cyclones are now getting more vulnerable to intense TC.

Summary of the Session 1 Discussions

After the presentations, the Session Chairs facilitated discussions among the presenters and a panel of subject matter experts. The Chairs focused the discussions on the following questions:

- Discussion of the presenters and panel of subject matter experts to address pre-defined questions:
    - Best practice in monitoring of the tropical storms: What are the observing platforms (remote sensing) required to estimate best track parameter (track, intensity and structure) of the tropical cyclonic storms?
    - Are the existing observations over the Asia-Pacific & North Indian Ocean (NIO) regions, sufficient to estimate cyclone best track parameters?
    - What are the bottlenecks to uniformly utilize all satellite observations in different stages (genesis, intensification and landfall/decaying) of the tropical storms? How can these limitations be removed?
    - How present set of observations (conventional and non-conventional) can represent land surface processes for more accurate estimation/forecasting of wind and precipitation after landfall?
    - What are the steps required for uniform best practice of identifying/developing a decay model?
- Discussion of pre-defined questions addressing gaps and opportunities:
    - What are the steps required for the improvement (at least 10-20 %) in genesis and track & landfall forecasts with 10 days and 5 days lead time respectively based on panel discussion?
    - Identifying/developing a decay model.
    - What is required for the early identification of various TC-induced hazards, and generation of multi-hazard maps associated with each land-falling cyclone system for accurate assessment of vulnerability and associated risk?
    - What kind of additional modeling (hazard modeling) efforts are most relevant for the forecasting of hazards associated with strong wind (and/or gust) and heavy precipitation due to tropical cyclones?
    - What tools and techniques can be used for damage assessments of the landscape from remote sensing observations?

Summary of the Session 1 Highlights and Key Points

The discussions in Session 1 of the questions outlined above resulted in the following key points:

- Significant reduction of human deaths due to advancement in TC forecasts in the last decades.
- High-resolution forecast model (like HAFS) is required to improve TC structure and landfall predictions.
- Development of advanced data assimilation scheme and measurement is required.
- Constellation of satellites with instruments such as Advanced microwave radiometers (e.g., Global Precipitation Measurement [GPM] Microwave Imager [GMI], Special Sensor Microwave Imager Sounder [SSMIS], Advanced Microwave Scanning Radiometer for EOS [AMSR-E], etc.) and sounders (e.g., AMSU) with high frequency

channels (e.g., 85, 157 and 165 GHz), and ABI like radiometer to delineate cyclone structure, lightning measurements, Global Navigation Satellite System reflectometry (GNSS)-R, L-band radiometer and SAR wind estimations for intensity forecast are desired.

- New observing instruments such as Space borne W-band Doppler radar for wind structure within cyclones are needed.
- A Task Teams may be formed including experts from various agencies for different applications like identifying/developing a decay model, targeted improvements in track and intensity, hazard modeling associated with strong winds (gust) and precipitation, and remote sensing based newer tools and techniques for damage assessment in next 5-10 years.
- Inclusion of advanced satellite data like SAR surface winds to improve best track parameters.
- Find best practices for how to assess coastal vulnerability and impacts of TCs.
- Assimilate more satellite and ground based data into numerical models to improve predictions.
- Leverage ensemble modeling to improve the forecasts.
- More field campaigns are needed, especially to improve the physics of models.
- More frequent, timely and with greater spatial and temporal resolution, surface wind fields needed to recognize phenomena like secondary wind maxima and eyewall replacement cycles, etc.
- Low Earth Orbit (LEO) + Geosynchronous Equatorial Orbit (GEO) combinations for more downscaling with greater temporal and geographical precision.
- Space based observations from scatterometers, microwave imagers, microwave sounders, SAR and L band radiometer for tropical cyclone applications.
- Constellation of scatterometers will be very useful especially during cyclogenesis and analyzing weak systems.
- Carry out modeling studies to understand how wind shear or other atmospheric oceanic parameters are affecting tropical cyclogenesis and intensification. More space-based observations to validate model simulations.
- Efficient use of existing satellite data or observations system for cyclone studies.
- SAR data can be explored to estimate Rmax and other critical winds like 34, 50 and 64 knots.

Session 2: Mesoscale precipitation systems

Session 2 was chaired by Dr. KUBOTA Takuji of the Japan Aerospace Exploration Agency. Session 2 included four presentations, one from a representative of each of the Quad countries, focused on various aspects of precipitation monitoring, current and planned satellite programs, and discussing gaps and ways forward to address these events. (Please see Appendix 1, Workshop Agenda, for a full review of the questions discussed in the facilitated discussion, and Appendix 2 for the background reading for this session.)

Summary of the Session 2 Presentations

Each presenter provided information on available tools and products for precipitation monitoring, resulting in a review of the current tools and products available. Those tools and products discussed in the presentations included:

- India
  - India National Satellite System (INSAT) series of satellites (INSAT-3D/3DR/3DS) – Visible and Infrared (VIS/IR) Imaging multi-spectral radiometers (ISRO).
  - INSAT-3D/3DR based heavy rain nowcasting, INSAT-3DR Hydro-Estimator Nowcaster (ISRO).
  - Real-time Analysis of Product and Information Dissemination (RAPID) (IMD).
- Japan
  - Himawari-8/-9 (VIS/IR Sensors) (JMA).
  - AMSR Series (Passive Microwave [PMW] Imagers) (JAXA).
  - Tropical Rainfall Measuring Mission (TRMM)/Precipitation Radar (PR), GPM/Duel-Frequency Precipitation Radar (DPR) (Spaceborne precipitation radars) (JAXA).
  - Global Satellite Mapping of Precipitation (GSMaP).
- United States
  - Geostationary Operational Environmental Satellite (GOES series) (VIS/IR Sensors) (NOAA).
  - GMI (PMW Imagers/Sounders) (NASA).
  - SSMIS (PMW Imagers/Sounders) (DoD, NOAA).
  - Advanced Technology Microwave Sounder (ATMS) (PMW Sounders) (NOAA).
  - Rain Rates, Climate Prediction Center (CPC) Morphing technique (CMOPRH-2) (NOAA).
  - Integrated Multi-satellitE Retrievals for GPM (IMERG) (NASA).
  - Global Precipitation Climatology Project (GPCP) (NASA).
- Australia
  - Convective Rainfall Rate based on Cloud Physical Properties (CRRPh).
  - Space-based Weather and Climate Extremes Monitoring (SWCEM), Climate Risk and Early Warning Systems (CREWS), and Global Producing Centers for Long-Range Forecasts (GPC-LRFs).
  - Realtime radar-gauges Rainfall Analysis (RAINFIELDS).
  - Blended real-time Rainfall Analysis (Satellite + Rainfields) (BRAIN), under development.
  - Australian Gridded Climate Dataset (AGCD) rainfall analysis.
  - Studies on using satellite data to enhance AGCD (Research).

Summary of the Session 2 Discussions

After the presentations, the Session Chair facilitated discussions among the presenters and a panel of subject matter experts. The Chair focused the discussions on multiple pre-defined questions. Outlined below are those questions, and some of the missions, products, and/or tools the Workshop participants noted could inform those questions.

- What are gaps between the current tools & products and the requirements from users? What are new sensors we can propose specially catering to extreme precipitation events in the Indo-Pacific region?

- High spatial/temporal variability in convective systems:
  - GEO VIS/IR Sensors (INSAT series, Himawari-10, GOES series).
  - PMW constellation (AMSR3, WSF-M, ATMS).
  - Microsatellites / SmallSats (NASA Time-Resolved Observations of Precipitation structure and storm Intensity with a Constellation of Smallsats [TROPICS], NOAA QuickSounder).
  - Geostationary PMW (PATH/GeoSTAR).
  - Inclined orbit to observe diurnal rainfall variation (Atmosphere Observing System/Precipitation Measuring Mission [AOS/PMM]).
- Vertical humidity information to predict heavy precipitation:
  - GEO hyperspectral IR sounder (Himawari-10, GeoXO Sounder).
- Cloud/precipitation process for better understanding and accurate modeling:
  - Cloud doppler radar (JAXA, Earth Cloud Aerosol and Radiation Explorer Cloud Profiling Radar [EarthCARE/CPR]), Precipitation doppler radar (JAXA, AOS/PMM).
- Lightning and thunderstorm triggers:
  - GEO Lightning sensor (GOES-R series, Proposed INSAT 4th Generation).
- The accuracy vs. timeliness challenge:
  - Users request fast latencies vs more satellite data which becomes available later.
  - Precipitation product latency is important for nowcasting. Efforts to reduce the latency can be helpful to users.
  - An effective approach to reduce latency of LEO products is to use Direct Broadcast (DB) data, such as DBNet.
  - Developing DB capabilities in the Indo-Pacific region may have a significant impact on the use of satellite data in precipitation forecasting/nowcasting in this region.
- Accessibility to the satellite products:
  - Dynamical display of information as a map (vs static images).
  - Mobile-friendly Additional products.
- Stakeholder and public users training:
  - Quad Workshop 2 scheduled for March 2023 and will have training session in addition to the plenary session. (Tackling Extreme Precipitation Events Workshop -Indo-Pacific region, 1-3 March 2023, Online.)
- Growing usage of Artificial Intelligence/Machine Learning (AI/ML) techniques in satellite precipitation algorithms:
  - Continued effort to improve satellite precipitation products using AI/ML.
- More verification of products and dissemination of results back to algorithm providers and to the users:

- What validation methods are required by users?
  - Demand for User Centric interpretable validation metrics.
- What are gaps in integrating among satellite precipitation products and ground-based observations?
  - Spaceborne/ground-based radar synergy:
    - Ground-based radar calibration (BoM).

        - Science in convective systems, orographic precipitation, and algorithms for synergy of both measurements, etc.
    - Different signatures of precipitation in satellite and ground-based data:
        - Satellite sensor estimation biases: pulse-width modulator (PWM) vs IR --> Needs more PMW constellations to more accurate satellite precipitation data.
        - Difficulty in orographic precipitation:
            - Satellite products showed different patterns from ground rain gauges in the Meghalaya Plateau. One solution is a development of the gauge-adjustment satellite product.
        - Scientific research needed to develop and evaluate methodologies to blend multiple sources of data to increase accuracy and reduce latencies.
    - Availability of ground-based observations:
        - Important in a particular area which increases the spatiotemporal heterogeneity of rainfall e.g. topography.
        - Number of stations with long-term reliable records is very limited.
        - Quality control of ground-based observations.
        - Data sharing permissions (open access).
        - Reduced latencies.
        - Real-time data access or the data latency in monitoring and analyses on finer temporal and spatial resolutions (daily, hourly).
    - Mountainous regions remain a major challenge:
        - Sparse gauge coverage at high elevations (difficult to install / maintain).
        - Poor spatial representativeness of high-elevation gauges.
        - Poor radar coverage in complex terrain.
        - Highly complex interactions of wind flow with terrain.
- What are gaps in constructing long-term satellite precipitation products? What are the new sensors?
    - Continuity of the measurements from a constellation of satellite precipitation sensors (such as passive microwave and active radar sensors) for continuous monitoring of precipitation.
        - PMW constellation (AMSR3, Weather Satellite Follow-on Microwave [WSF-M], ATMS).
        - AOS/PMM (Spaceborne precipitation radar) (JAXA).
    - Most products extend to about early 2000s, extension prior to this era is possible but would be based on combining different data sources which introduces extra uncertainty.
        - Spatial resolution changes of sensors.
        - Data Quality Control, Instrument Calibration, Algorithm Evolution.
            - Reprocessing GEO data with improved calibration is also a big scientific and computational task.
        - Challenges:
            - No spaceborne radar before 1998.
            - Sparse PMW in 1990s and no consistent PMW before 1987.

<u>Summary of the Session 2 Highlights and Key Points</u>

The discussions in Session 2 of the questions outlined above resulted in the following key points:

- In the Indo-Pacific Region, many natural hazards are caused by precipitation. Providing timely and accurate information on monitoring of precipitation by satellites helps countries and communities build greater resilience against floods, storms and other hydro-meteorological and climatological hazards and extremes.
- Satellite precipitation products can be used to estimate precipitation in areas where ground-based weather radar and other ground observations are not available. Therefore, satellite precipitation products can contribute to the National Meteorological and Hydrological Services (NMHSs) in the Indo-Pacific region in terms of improving their actual and predictive capabilities for precipitation and other issues.
- Long-term datasets have been constructed from satellite precipitation data and used to detect extreme weather events based on the analysis of climate values, interannual variations and other variables (in, for example, the WMO SWCEM project). Such satellite data sets will contribute to the ability of the NMHSs in the Indo-Pacific to detect extreme precipitation.
- End-to-end warning system will require stakeholder and public users training.
- Science related to satellite derived products needs to improve and more verification of products is needed.
- Ground-based observations availability and the number of stations with long-term reliable records is limited and quality control is lacking.
- Data sharing requires reduced latencies.
- Community should continually improve historical estimates to get the most out of current observations.
- Need better communication between satellite data users and algorithm developers. This would help with verification (e.g., What analysis would help user know how to make the best use of the product/aid developer in making improvements?).
- Good idea to consider a training session on rainfall and nowcasting products for Quad forecasting community, considering the number of products available and their complexities.
- Construction of a portal site focusing on the precipitation monitoring for the Indo-Pacific regions, with the current tools and products available in the Quad members. Would need to be mobile-friendly.
- Opportunity for real-time applications with integration techniques among satellite precipitation products and ground-based instruments for enhancing the precipitation monitoring.
- Opportunity to collect long-term satellite precipitation products in the Quad members, and detection of extreme precipitation using them.

Presentation on India’s Concept Note, “Extreme Weather Events: Space Based Monitoring and Climate Impact”

Prior to the start of Session 3, Dr. Rashmi Sharma and Dr. Nitant Dube from SAC/ISRO provided information on a concept note India provided to the Quad Space Working Group for consideration.

India's vision with this concept note is to use the concept of open science and develop Earth observation applications to aid Indo-Pacific nations for monitoring and sustainable development. The goal is to provide a comprehensive end-to-end satellite-based information on extreme weather, including tropical cyclone, storm surge, swell, precipitation and inundation. The concept note described objectives to each of those events.

India demonstrated the concept by focusing on the Maldives Islands as a case study. India further noted that the example framework supports other partner efforts including Committee on Earth Observation Satellites (CEOS) Coastal Observations Applications Services and Tools (COAST) Initiative, Group on Earth Observations (GEO) Blue Planet Initiative, and the United Nations Ocean Decade. India then outlined an execution plan including a prototyping, rollout, and operational phase, proposing the Maldives Islands for the prototyping phase (but noted it was open to discussing other nations).

India invited Quad countries to participate in the proposal, providing participant to:

- Identify and ensure support for one Indo Pacific nation (preferably a small island nation), which we can include in the list of nations for prototyping phase
- Contribute Satellite and model data for the proposed application
- Participate as Science leads/members under the proposed themes and help in promotion of open science
- Provide Technology stack (Data cubes, Analytics tools, collaboration server) for development and operations of applications
- Participate in Validation and Capacity Development activities
- Provide Infrastructure/support for hosting of Quad applications developed under this proposal.

India indicated the benefits of the proposal in the concept note to both the Indo-Pacific region and the Quad by:

- Enabling economic development, environmental protection and social development in identified Indo Pacific nations to meet Sustainable Development Goals
- Promoting open science for development of Earth Observation applications
- Joint calibration and validation for performance evaluation
- Integrating local data and information for customized applications
- Supporting capacity building in Indo-Pacific region
- Strengthening exchange of scientific knowledge and ideas among Quad nations

The presentation of India's concept note was well received by the Workshop participants, including the Workshop Steering Committee members. The Workshop participants recommended endorsing India's concept note to move forward to the Quad Space Working Group for full consideration.

Session 3: Inundation/flooding, coastal erosion and water quality

Session 3 was chaired by Dr. Stacey Archfield of the United States Geological Survey (USGS). Session 3 included five presentations focused on the topics of flooding and extreme precipitation, modeling flood inundation, effects on water quality, coastal multi-hazard vulnerability assessments, and discussing gaps and ways forward to address these events. This session further included opening remarks from five subject matter expert panelists. (Please see Appendix 1, Workshop Agenda, for a full review of the questions discussed in the facilitated discussion, and Appendix 2 for the background reading for this session.)

Summary of the Session 3 Presentations

The session opened with a summary of the pre-work, reiterating several gaps on the topical area: (1) attribution of precipitation extremes, (2) data needs to assess precipitation extremes, (3) resolving increasing precipitation but multi-directional changes to floods, and (4) quantifying the effects of extreme precipitation on inundation and flooding and in turn on water quality. Presentations from subject-matter experts on these topic areas expanded on these gaps as well as raised additional gaps for consideration.

Dr. Naresh Devineni, City College of New York, USA, presented research on flooding and extreme precipitation in the Quad countries. Dr. Devineni explained that hydrological events and hazards are outpacing other geophysical hazards. Further, Dr. Devineni's work showed that not just intense rainfall is causing extreme flooding in the Quad countries but that low-frequency events coupled with saturated soils can lead to extreme flooding.

David Vallee, NOAA, USA, spoke to the capabilities of the U.S. National Water Model to provide continental scale mapping of flood inundation for emergency services and directing resources during storms and flood events to save life and property.

Dr. Emily Smail, NOAA and the GEO Blue Planet Initiative, provided information on the current state-of-the-science on space-based systems to monitor water quality, including turbidity, chlorophyll-a, surface temperature, macro-debris, salinity, and oil slicks. Dr. Smail pointed to the needs for better integration between water quality and quantity monitoring and integration of socioeconomic parameters with physical, biological, and chemical parameters. Dr. Smail noted that there is already an emphasis on life and property but also a need to address the subsequent cascading events that result from extreme precipitation. Possible existing efforts that could be leverage to address these needs include GEO Blue Planet, GEO AquaWatch, and GeoGLOWS.

Dr. R.S. Mahendra, INCOIS, MoES, India, demonstrated the capabilities of a multi-hazard map and its utility to provide a composite, synthesized overlay of multiple hazards with three-dimensional visualization of inundation with buildings and modeled flow depth, which can be shared through Google Earth. This capability can also provide a socio-economic vulnerability assessment.

Dr. Ulrike Bende-Michl, BOM, Australia, presented a seamless, consistent probabilistic inundation mapping capacity at multiple time scales that also considers extent and depth of the flood. Dr. Bende-Michl noted that further development will need to address the hydrological modeling of soil hydrology, river routing, earth observation, vegetation, and urban modeling.

Summary of the Session 3 Discussions

The presentations were followed by a panel discussion with five panelists representing the Quad countries: Dr. Kosuke Yamamoto, JAXA; Dr. Ulrike Bende-Michl, BOM, Australia; Dr. R.S. Mahendra, INCOIS, MoES, India; Julia Prokopec, USGS, USA; and David R. Vallee, NOAA, USA.

There were four questions asked to each panel member: (1) What is the most pressing gap to fill with respect to inundation, flooding, erosion, and/or water quality in your country? (2) What has been the most significant advancement in recent years for addressing inundation, flooding, erosion, and/or water quality issues in your country? (3) What are the biggest barriers to advancement or gap-filling in your country? (4) What are your thoughts on current initiatives or efforts that could be leveraged to advance or fill gaps in these topical areas?

Summary of the Session 3 Summary and Outcomes

The presentations and discussion have resulted summaries relating to capacities and advancements, identified gaps, barriers to filling gaps, and existing efforts and initiatives.

Capacities and Advancements

Each Quad country has demonstrated and advanced capacities on these topics.

India has developed multi-hazard mapping to provide a composite, synthesized overlay of multiple hazards. India has also innovated methods for vulnerability forecasting and social science integration.

Australia had created a seamless, consistent probabilistic inundation mapping at multiple time scales. Australia has a national data collection effort that provides for a nationally consistent view of the data.

Japan has accumulated long-term data and provides a climate-rainfall watch that provides information of extreme heavy rainfall. Their realizations of flood-forecasting and simulation are based on these observations. It has been an achievement to integrate the composite use of satellites and models and the prediction of the flood risks to support the satellite collection data.

The U.S. provides continental scale mapping of flood inundation through the National Water Model for emergency services and directing resources during storms and flood events to save life and property. The U.S. has also developed methods to remotely-sense discharge information for rivers not accessible by traditional methods to measure due to lack of access.

Identified Gaps

Quad countries identified gaps related to improvements on several topical areas.

For water quality and extreme precipitation, better integration is needed between water quality and quantity monitoring and the coupling of socioeconomic parameters with physical, biological, and chemical parameters. The cascading events that result from extreme precipitation in addition to the immediate catastrophic effects after an extreme event.

Given that there are limits to how to detect to flood risk and make proper evacuation plans in steep areas, the communication of flood risk is a common issue among the countries. Floods caused be caused in the middle of night and warnings could be issued with little time for preparation. It is a sociological question to understand how often to warn the public and communicate risk so that people are not tired of warnings yet prepared for hazardous events. In the aftermath of these events, information is needed at a high level of accuracy to communicate to emergency services and the public.

For these reasons, it is important to improve ground and LiDAR data as well as modeling capabilities. Though remote sensing data is available, we also need consider if our models can consume this data at the resolutions that match our models. Additionally, coupling of our models (coastal, land surface, hydraulics) are critical to filling these gaps. In terms of monitoring, a lack of real-time monitoring is a serious limitation as well as our inability to monitor every river, everywhere. New missions may help with this effort and other technologies are needed to fill this critical gap. Satellite-based monitoring of shoreline change and bathymetry in coastal regions will also be a valuable complement. Finally, the linkage between flooding and inundation (~water quantity) and water quality impacts needs to be better monitored and forecasted.

Barriers to Filling Gaps
Several barriers to filling these gaps were identified. As satellite- and ground-based observations are becoming more sophisticated, it is becoming increasingly difficult to leverage their combined use in a meaningful way due to different temporal and spatial scales, multiple types of sensors, finetuning and downscaling. Access to some of the new sensor data is also difficult and not always free.

Resources are also a barrier, particularly for the maintaining of long-term ground-based networks. The precision required for emergency situations is not available for alternative data collection methods and so there is a barrier to used space-based observations for emergency communications and real-time hazard management. This could be addressed by considering reducing the precision threshold to get as much data as possible out in times of hazard while still maintaining a baseline standard for data quality.

Predicting inundation requires correct rainfall forecasting and that is still a huge modeling barrier. It is still quite possible for a model to miss where flooding actually occurred and to underpredict rainfall for an event. Therefore, providing real-time information has the potential to give wrong or false forecasts. Strides in numerical rainfall prediction are needed; otherwise, inundation predictions are inaccurate.

There are still barriers to sharing information among participating countries. It would be helpful to discuss the specific goals of sharing information instead of blanket sharing agreements so that identified gaps can filled more efficiently. Open access to commercially available would also be beneficial. Some global datasets that are available are difficult to connect to models and sharing of expertise in this would help.

Session 4: Transboundary issues

Session 4 was chaired by Leon Majewski of the Australian Bureau of Meteorology (BOM). Session 4 included five presentations focused on use of satellite and other products in monitoring of extreme precipitation, simulation experiments for hyperspectral infrared sounders on GEO satellites, satellite data assimilation, connecting El Nino Southern Oscillation (ENSO) to landslide impacts, as well as discussing gaps and ways forward to address these events. (Please see Appendix 1, Workshop Agenda, for a full review of the questions discussed in the facilitated discussion, and Appendix 2 for the background reading for this session.)

Summary of the Session 4 Presentations

The session opened with a brief summary of the pre-work and an overview of how the sessions presentations were structured to link observations, the evolution of the observing system, data assimilation techniques, and the application of these elements to identify and assess transboundary processes and issues.

Blair Trewin (BOM, Australia) discussed the ground-based observing system and challenges related to observing and contextualizing extreme precipitation events in the Indo-Pacific and, more generally, the Southern Hemisphere. The lack of data access and/or the high data latency associated with some observations can result in observations of extreme precipitation not being received in time to affect decisions. Careful bias correction of space-based observations of extreme precipitation is needed, accounting for the distribution of ground-based observations.

Dr. Hiromi Owada (JMA, Japan) provided an overview of the observation system simulation experiments performed to assess potential impacts of a hyperspectral infrared sounder in geostationary orbit (GeoHSS) as part of JMA's preparation for Himawari-8/-9 follow-on program. Dr. Owada presented positive results from both global and regional experiments. In one experiment, the simulated GEOHSS observations were shown to improve the prediction, in both time and space, of heavy precipitation. Furthermore, forecast sensitivity observation impact (FSOI) analysis demonstrated that GeoHSS observations are expected to have a large, positive, impact within the instruments field of view.

Dr. Prashant Kumar (ISRO, India) provided a review of data assimilation methods and complexity in covering different ranges in temporal (nowcasts to seasonal scale) and spatial (meters to 100's of kilometers) scales. Dr. Kumar demonstrated the wide array of observations that can be used to improve NWP model characterization of extreme precipitation, and the need to develop advanced data assimilation techniques to benefit from these observations. Dr. Kumar noted the challenge of increasing computational costs associated with this complexity.

Dr. Robert Emberson (NASA, USA) presented a method of assessing landslide susceptibility using space-based observations of extreme precipitation in conjunction with climate-scale variability (El Niño–Southern Oscillation) and known population data. The Landslide Hazard Assessment Situational Awareness (LHASA) model provides a real-time, global, assessment of landslide hazard. Analysis of LHASA output, enabled by the increasingly long record of space-based Earth Observations, has shown that ENSO correlates with extremes in precipitation, driving landslides. Dr. Emberson demonstrated the global impact of the space-based observing system.

Dr. Tim Cowan (University of Southern Queensland, Australia, and BOM, Australia) demonstrated the value of developing tailored products and communication channels for regional communities and industries. Dr. Cowan presented the impact of the Madden Julian Oscillation on extreme precipitation and the negative impact on the cattle industry in Queensland, Australia in 2019. Improvements in observation system and model physics have resulted in an information source that, in combination with community consultation, will improve the preparedness and resilience of livestock producers across northern Australia.

Summary of the Session 4 Discussions

After the presentations, the Session Chair facilitated discussion with the presenters and the audience.

The panel discussed the role of the World Meteorological Organization (WMO) and regional meteorological agencies in championing the open access to observations of precipitation from the ground-based network. It was noted that improvements in data sharing, through the WMO's framework, could result in improved real-time products and warnings. It was also noted that there are barriers to data sharing and that these should be acknowledged when consulting with potential data providers.

It was noted that Non-Governmental Organizations (NGO's) also play a role in improving how small nations/states prepare for emergencies and disasters.

In response to an audience question, it was noted that products such as those presented by Dr. Emberson and Dr. Cowan may need to be tailored to adequately represent local conditions. This can be achieved if observations are available in the region of interest.

In response to another audience question, high-quality long-term space-based precipitation products were listed and discussed. Dr. George Huffman discussed some of the recent advances in these products. In addition, other observation types (e.g. Synthetic Aperture Radar) that can assist in flood assessment were discussed.

Summary of the Session 4 Highlights and Key Points

- Importance of combination of observations and satellite precipitation data sets
    - There will always be gaps
    - Need to be aware of limitations
    - Need to continue sharing observations
- Understanding the impact of new missions
    - Both sensors and mission types
    - Growth of commercial sector
- Improvements in models
    - Convective scale models; seasonal models and forecasts
    - Need for reanalysis

    - Assimilation of new and different observation types
    - Effective use of Ensemble Prediction (EPS)
    - Need Observing System Simulation Experiments (OSSE) and others at convective scale (and assimilation of high-resolution radar observations)
        - 1-2km scale – high computational cost, but we think it's worth it
        - Role of these observations in particular weather scenarios
- Real world impacts
    - Disaster mitigation is a priority
    - Impact assessment and the benefits of remote sensing need to be captured
- Key groups - university sector, WMO, Group on Earth Observations, non-governmental organization (NGOs), NMHS, Coordination Group for Meteorological Satellites (CGMS), International Precipitation Working Group (IPWG).
- A challenge with transnational work is the different needs depending on agency/region.
- Consider including a broader group of people – Do not have representation from the research agencies that provide observations and support field experiments in the Pacific.
- Need high resolution rainfall product - downscaling requirement.
- Data quality is a great challenge.
- Need for engagement with Indo-Pacific region populations.
    - Need to determine topics that could benefit the region - need to communicate and get the information out to the affected populations.
    - Use existing access methods.
    - Common approach from Quad nations.

Session 5: Data integration and applications for societal benefits

Session 5 was chaired by Dr. Paul DiGiacomo of the United States National Oceanic and Atmospheric Administration (NOAA) National Environmental Satellite, Data and Information Service (NESDIS). Session 5 included a presentation recapping the discussions and information obtained during sessions 1-4, as well as four presentations outlining one case study per country demonstrating how a real-world extreme even impacted society and how each country responded. The Chair then facilitated a discussion among the meeting participants. (Please see Appendix 1, Workshop Agenda, for a full review of the questions discussed in the facilitated discussion, and Appendix 2 for the background reading for this session.)

Summary of the Session 5 Presentations

The session opened with a case study from each of the four Quad countries. The case studies demonstrated how a real-world extreme event impacted society and how each country responded before, during, and after the event.

Judith Landsberg (BOM, Australia) provided a case study on "Using satellite views of the recent Western Australia floods to derive impact information". Landsberg described how the Australian Climate Services provided information to inform emergency services during flooding events from Tropical Storm Ellie. A key transit route was cut off limiting access to a 400km area with a low population density, requiring supplies to be delivered by helicopter. BOM used data from Himawari 8 (Japan) and a commercial service and a point database to determine how many were affected. In this case, BOM discovered that the quickest and most accurate images were from the commercial service, but obtaining those images was very expensive. Further, while the information was extremely valuable to Australia's response in this event, the contract with the commercial company complicated what data could be released.

Surya Parkash (National Institute of Disaster Management, India) provided a case study on "Achieving zero casualties from cyclones in India." Parkash noted that India has 10% of worlds cyclones and heavy casualties in the past. Parkash described how data has been used to develop a forecast and model system, reducing deaths dramatically during recent cyclones. The key focus has been on information sharing and dissemination. Lessons learned included that impacts lessened due to early satellite forecasting of cyclone landfall, which enabled the forecasters to inform residents and allow for evacuations.

Kotaro Bessho (JMA, Japan) provided a case study on "Risk Reduction of heavy rain in Japan." Bessho outlined how yearly disasters caused by heavy precipitation resulted in damage from landslides and floods and led to loss of life. Bessho outlined the need for accurate water vapor observations, improved prediction system, and improved probability information. JMA upgraded their observation system and switched to Himawari 9 data, using a supercomputer which resulted in a better prediction system. Bessho also outlined further datasets JMA uses and combined with data sets from JAXA's missions, which led to better predictions. The results were shared with local governments allowing local communities better information in which to respond to extreme precipitation events.

Karen Ryberg (USGS, U.S.) provided a case study on "Red River Flooding Events." The Red River flows across USA-Canada border and has a long flood events, of which USGS has over 200 years of records. The repeated and episodic flooding events have worsened over time, leading to extensive flood damage to various metropolitan areas in the U.S. and Canada. Infrastructure installation exacerbated the impacts of the flooding events. Ryberg explained that diversion tactics are underway, as well as efforts to monitor water quality and quantity, of such artificial diversion, to better understand these interventions in the future.

Summary of the Session 5 Discussions

After the presentations, the Session Chair facilitated discussions among the presenters the full Workshop participants. The Chair focused the discussions on the following questions:

- What kind of usable information the Quad countries can bring to the region?
- How can we to address the complexity looking down and across different synergistic effects?
- What are the challenges for determining what is fit-for-purpose for stakeholders in terms of events (science offerings vs. translating it into what users' desire)?
- How can we get feedback from the user community?
- How do we incorporate that user feedback into our products?
- How do we deal with storing the huge amounts of data we are all now accumulating?
- What are best practices and lessons learned that integrate social science and environmental science?
- How do we address technology transfer to build capacity? How do we distill information, since we are now bringing the users to the data, not the other way around?

Summary of the Session 5 Highlights and Key Points

The discussions in Session 5 of the questions outlined above resulted in the following key points. Governments, agencies, and other data providers should:

- Strive for, and optimize, open science and open access to data.
- Assemble best practices and lessons learned from their responses to various extreme precipitation events, and communicate how to apply those practices and lessons to responses to events in other regions, as applicable.
- Work together through the Quad to implement the pilot proposals outlined in India's concept note on "Extreme Weather Events: Space Based Monitoring and Climate Impact".
- Gather relevant and timely data in format that is usable by the individuals and communities that need the data. Use plain language for the common user to understand and deliver information in native languages.
- Involve social scientists, non-governmental organizations, and community advocates to create the link between the data providers and the communities that need the information.
- Consider the development of mobile applications to more easily and quickly deliver information to users. This is especially important for smaller and less accessible communities.
- Communicate expected emergency actions for people to take during extreme precipitation events.

IV. Outcomes and Opportunities

At the conclusion of the Workshop, the Workshop participants discussed what they viewed as the Workshop outcomes, including the recurring themes raised in the Workshop, and opportunities for Quad collaboration identified during the Workshop. The participants further discussed how each of the identified outcomes and opportunities address one or more of the recurring themes identified during the Workshop. Following the Workshop, the Workshop Steering Committee further considered the Workshop discussions and came to agreement on the list of Workshop Outcomes and Opportunities.

It is important to note that while some of these outcomes and opportunities may seem general in nature, for the purposes this report, each outcome and opportunity outlined below should be read to relate specifically to extreme precipitation events and how to monitor and address extreme precipitation events. For example, when noted that one outcome of the Workshop was the identification of the importance of timely, accessible open data and open science, that should be read to refer specifically to data and science related to the issue of monitoring and mitigating extreme precipitation events.

Key Workshop Outcomes

The key outcomes of the Workshop are as follows. These key outcomes were identified in the Workshop and refined by the Steering Committee while considering the Workshop discussions and developing this report. The opportunities identified in the following subsection relate to one or more of these key outcomes.

Summary of the Key Outcomes

1. Identified four overarching themes:
    - Importance of capacity building in the Indo-Pacific region.
    - Importance of timely, accessible open data and open science.
    - Need to discuss how to perform impact assessments over multiple countries.
    - Importance of continuing data gathering to ensure long-term data sets.

2. Need for improving existing models and types of modeling.

3. Need to leverage spatial resolution of Synthetic Aperture Radar (SAR) for improved best track parameters as well as monitoring of land / ocean impacts.

4. Identified important modeling and data assimilation improvement needs.

5. Need to consider spatial and temporal downscaling capabilities tying different observing capabilities together (e.g. blended products, GEO+LEO).

6. Importance of constellation measurements (temporal refresh) for cyclogenesis.

7. Importance of extending the current product data records.

Further Explanation of the Key Outcomes

Four Overarching Themes

Throughout the Workshop four themes were frequently and readily apparent in the presentations and discussions. These were the importance of capacity building in the Indo-Pacific region; the importance of timely, accessible open data and open science; the need to discuss how to perform impact assessments over multiple countries; and the importance of continuing data gathering to ensure long-term data sets. As the Workshop participants discussed all of the information gathered throughout the Workshop in the final session, the participants highlighted the four recurrent themes. The Steering Committee then determined the most effective way to present the opportunities raised during the Workshop was to organize them under these four overarching themes. (The opportunities will be discussed in the following subsection.)

- Importance of Capacity Building in the Indo-Pacific region: Building capacity is key to any new initiative for the long term. In order to build long term capacity, we need to have a clear understanding of the gaps or problems, as well as identify the resources needed to build the capacity, such as the experts, data, information, and infrastructure. There was a lot of discussion at the Workshop about the importance of training and communication in order to establish the needed capacity. By using these Workshops to identify the gaps and problems that the Quad members and nations in the Indo-Pacific region all face is in itself one way to build capacity. The Workshop also discussed many other ways to build capacity, and these are all outlined in the following subsection describing opportunities for the Quad Space Working Group to consider working on together and/or the Quad members individually move forward in addressing extreme precipitation events.

- Importance of timely, accessible open data and open science: Timely, accessible and open data is critical for hazard preparedness and disaster response. The Workshop participants discussed this topic at length, noting not only the critical importance of providing timely, accessible and open data, but also providing information via the means of the user receiving the data. For example, users do not all have the same technologies to receive important information needed to respond to disasters. Understanding what technologies, or lack thereof, the users have access to will help the Quad members provide open access information in the form needed by the users.

- Need to discuss how to perform impact assessments over multiple countries: Impact assessments are an important tool for emergency managers to assess the vulnerability and risk of extreme precipitation events on landscapes and human populations. The Workshop participants noted multiple times that response to extreme precipitation events could be improved if impact assessments had a baseline standard by which to perform them consistently across countries and regions. In this way, the impact assessments could translate advances to the real world and allow nations to quantify and qualify the benefits of remote sensing asset, while using these data in disaster mitigation.

- Importance of continuing data gathering to ensure long-term data sets: The importance of extending current product data records was raised in discussions under multiple sessions. Emphasis was placed on climatological products and historical data records, as these data are essential in providing a baseline by which the effects of climate change can be measured. The more robust and long-term the data set, the more they can inform and improve models for forecasting extreme precipitation events; thereby, providing more reliable information to governments and organizations responding to and mitigating the impacts of extreme precipitation events and the disasters they can create.

<u>Need for improving existing models and types of modeling</u>

The need to improve various modeling efforts was raised in multiple sessions, including sessions 1 and 3. Many specific types of modeling were recommended, depending on the specific topic under discussion. Participants discussed the need to improve modeling to forecasts when a storm may make landfall and the impacts on the landscape that it might have (e.g., rockslides, flooding, etc.), decay, and hazard modeling, as well as modeling improvements needed both in terms of deterministic forecast shortcomings (resolution, positional accuracy, better quantitative prediction forecasts) to better utilization and communication of ensemble/probabilistic information. The need to improve modeling was also discussed in terms of modeling as gap in multiple areas (e.g., Genesis, intensity and track are all areas for improvement, need for modeling at the municipal level using high resolution). It was clear that the work on the issue of extreme precipitation events would benefit from more detailed discussions focused on what types of models need improvements, which existing models to focus on, and how to look to creating future models. Improved modeling and forecasting efforts are also required to assess the attendant biological, biogeochemical and ecological impacts of extreme precipitation events.

<u>Need to leverage spatial resolution of Synthetic Aperture Radar (SAR) for improved best track parameters and assessments of land / ocean impacts</u>

Synthetic Aperture Radar (SAR) satellites are important tools for monitoring weather-related hazards as they have the ability to see an area day or night, in rain, clouds, or sunshine. For this reason, throughout the Workshop the participants recognized the importance of SAR in improving the monitoring extreme precipitation events. Specific applications discussed included using SAR imaging to improve radiometer training to get more information that improve estimates of winds and winds products, and using SAR for space-based water quality monitoring, such as to detect oil and storm runoff. Currently, many of the Quad countries have SAR capabilities on their satellites, and there was some discussion at the Workshop of also leveraging SAR data from commercial companies. SAR was high on the list of data the participants recommend the Quad consider exploiting on existing, new, and future missions. SAR observations are also essential for improved monitoring of flooding and inundation events in coastal zones as well as attendant water quality impacts, to be coupled with equally high-resolution satellite optical (e.g., aquatic color) measurements

<u>Identified important modeling and data assimilation improvement needs</u>

In addition to discussing the need to improve modeling (as discussed above), there was also extensive discussion on identifying specific modeling and data assimilation needs as well as extensive discussion on the challenges in present data assimilation efforts. Examples of the specific needs identified included, but were not limited to: assimilating more and disparate data; leveraging data for model physics improvement; idealized studies to further understand linkages between atmospheric and ocean parameters; and cyclogenesis and intensification. Specific to data assimilation, another key point that was raised repeatedly was not only the need for more data assimilation to inform model development of conditions, but the fact that computing needs to improve in order to expand data assimilation techniques. Further, data assimilation requires a lot of human and time resources. The participants discussed successful data assimilation efforts (such as through India NCMWRF systems used for global and regional forecasting), then focused discussion on highlighting challenges in present satellite data assimilation efforts. These challenges include data amount, observation error correlations, all-sky variances requirements, assimilating high resolution observation at convective-scale, the desire to move to particle filter, and modeling of model error. There was acknowledgement that more teamwork and the use of ensemble methodology would help with data assimilation, but there was also repeated calls for more resources for data assimilation efforts.

<u>Need to consider spatial and temporal downscaling capabilities tying different observing capabilities together (e.g. blended products, GEO+LEO)</u>
The Workshop participants highlighted the need to consider spatial and temporal downscaling capabilities by tying different observing capabilities together. The participants noted this is an efficient way to infer important high-resolution information from tying multiple sources of low-resolution information from different observing capabilities together to get fuller or better resolution data. Examples discussed include the use and creation of blended products or by joining data from GEO and LEO data together. The Workshop participants noted that better shared information between Quad members, as well as to regional partners, would speed the ability of partners to improve downscaling capabilities, leading to improved information and data. This would require increasing and improving data access to and by Quad members. One specific need discussed was the need for high resolution rainfall product, which would require downscaling. The Workshop participant welcomed a presentation related to this need on Australia BOM's efforts to develop a blended real-time rainfall analysis (BRAIN) which will estimate in real-time with rainfall accumulations.

<u>Importance of constellation measurements (temporal refresh) for cyclogenesis</u>
Beyond new satellites, the participants discussed the value in maintaining satellite constellation continuity. For example, a constellation of scatterometers would be really helpful to increase frequency of data. The Workshop participants highlighted that a significant gap that needs to be addressed is the continuity of measurements from a constellation of satellite precipitation sensors for continuous monitoring of precipitation and measurements for cyclogenesis. The participants further outlined a sensor wish list including high spatio-temporal resolution observations constellation of cloud/rain radar, lightning sensors (GEO), and the need for more passive microwave (PMW) constellations for more accurate satellite precipitation data.

<u>Importance of extending the current product data records</u>
As discussed under the first outcome above, the importance of extending current product data records was raised in discussions under multiple sessions. Emphasis was placed on climatological products and historical data records, as these data are essential in providing a baseline by which the effects of climate change can be measured. Most products extend to about the early 2000s. Extension prior to this era is possible but would be based on combining different data sources which introduces extra uncertainty; however, this is important to strengthen existing products and models as extending and advancing historical data records will enable long-term time series. This would allow for the ability to get daily and/or sub-monthly variability out of long-term data records, among other things. One example discussed at the

Workshop was the importance of extending data records to prior to the NASA/JAXA joint Tropical Rainfall Measuring Mission (TRMM), which is an important data set for the monitoring of mesoscale precipitation systems in the Indo-Pacific region. Another example discussed was NASA's Landslide Hazard Assessment Situational Awareness (LHASA) model, which allows for the generating the seasonality of landslide hazards, amongst other factors, and allows for layering reported global landslide fatalities in the model to analyze impacts for people in the location of landslides. The results currently indicate impacts associated with El Nino and its effects on rainfall patterns relates to landslide patterns around the world; however, the current records used in the model only extend back to 2001. Extending this product data record would result in a more robust tool for the use in predicting the impacts of extreme precipitation events in the region.

Opportunities Identified at the Workshop

This section describes the key opportunities identified at the Workshop, outlined by the thematic areas described in the discussion of the Workshop outcomes above. These opportunities were identified in the Workshop discussions and refined by the Steering Committee while developing this Workshop report. These are a list of opportunities the Steering Committee believes Quad Members could pursue, either individually or through a Quad partnership, to address the key gaps and needs to improve the forecasting extreme precipitation events, as well as to improve the monitoring and mitigation of the impacts of extreme precipitation events in the Indo-Pacific Region. The opportunities identified in this subsection relate to one or more of the key outcomes described above. Some of the opportunities identified are discreet, specific actions that can be a taken; others are focus on the bigger pictures.

The list of opportunities is first presented in table format for ease of reference, followed by elaboration on the description and intent of each opportunity. The opportunities discussed in this section are organized by themes and not in priority order.

Summary Table of Opportunities

The below table sets out potential opportunities for collaboration between Quad nations, arranged by the themes identified in the Workshop. Many items cover multiple thematic areas, and that overlap is indicated in parentheses. This table is not organized with any prioritization. Note that while some of these opportunities may seem general in nature, for the purposes of this report each opportunity outlined below should be read to relate specifically to extreme precipitation events and how to monitor and address extreme precipitation events.

Importance of capacity building in the Indo-Pacific region	Importance of timely, accessible open data and open science	Need to discuss how to perform impact assessments over multiple countries	Importance of continuing data gathering to ensure long-term data sets
● Explore opportunities for **new missions** with instruments to monitor extreme precipitation (also *Long-term Data*) ● Provide **mobile applications** to support community-based solutions ● Endorse **India's concept note** to move forward to the Quad Space Working Group for formal consideration (also *Open Data* and *Impact Assessments*) ● Conduct more **field campaigns** and improve integration of field campaigns with space-based observations (also *Long-term Data*) ● Continue to advance and improve **modeling capabilities** to provide accurate, real-time information, especially when a disaster strikes (also *Impact Assessments)*	● Commit to **open science** and **open data** ● Commit to providing **relevant, timely, and accessible data** (FAIR principles) ● Establish an **integrated portal** of precipitation monitoring capabilities that leverage existing measurements, products, tools, and other capabilities of Quad members ● Improve the sharing of technical satellite and environmental data and products in understandable language to non-technical audiences ● Provide data in formats that are accessible and usable ● **Improve linkages** between the environmental and satellite data providers/scientists and social scientists for hazard communication, as well as for advocates who can represent community needs ● Develop agreements between Quad countries for the sharing of satellite and environmental data related to extreme precipitation (also *Capacity Building* and *Long-term Data*) ● Ensure **two-way interaction** between end users and algorithm developers, which is always essential to the utility of products.	● Identify, develop, and/or share best practices and case studies for **working with stakeholders and communities** (also *Capacity Building*) ● identify, develop, and/or share best practices for the use of space-based observations to **assess coastal vulnerabilities** and **impacts of storms** (e.g., tropical cyclones) from both a flooding and inundation as well as water quality perspective (also *Capacity Building*) ● **Work with task teams** with experts from various agencies for different applications, such as: ○ Identifying/developing a **decay model** related to tropical cyclones; ○ targeted improvements **in track and intensity** ○ **hazard modeling** associated with strong winds (gust) and precipitation ○ remote sensing based newer tools and techniques for **damage assessments** (also *Capacity Building* and *Long-term Data*)	● Continue **data gathering to ensure long-term time series of product data records**, with emphasis on extreme precipitation-related data and climatological products ● Consider advancements and extensions of current **space-based global observation systems** and the **spatial and temporal observation requirements** from the present instruments (also *Capacity Building*) ● Explore new opportunities for **future space-based global observation systems** (also *Capacity Building*)

Further Explanation of the Opportunities

The potential opportunities for collaboration between Quad nations discussed in this section are arranged by the themes identified in the Workshop; however, many items cover multiple thematic areas. In those cases, that overlap is indicated in parentheses. Recall that while some of these opportunities discussed below may seem general in nature, for the purposes of this report each opportunity discussed should be read to relate specifically to extreme precipitation events and how to forecast, monitor, and/or mitigate extreme precipitation events.

<u>Opportunities related to the "Importance of capacity building in the Indo-Pacific region"</u>

The Quad Leaders have placed an emphasis on the importance of capacity building in the region. For example, during the May 2022 Quad Leaders' Summit, the Quad Leaders committed the Quad Space Working Group to "...provide capacity building support to countries in the region, including with regards to partnering on using space capabilities to respond to extreme precipitation events."

The Workshop participants in turn also placed significant emphasis throughout all discussions of the Workshop on the importance of capacity building in the Indi-Pacific region. Participants repeatedly noted in order to fully monitor and mitigate extreme precipitation events and their impacts in the Indo-Pacific region, then all of the recommendations for data and modeling improvements, etc., need to apply not only to the Quad members themselves, but also need to be shared with other users in the region, including small island developing nations. Further, that the Quad can help those users build their capacity to respond to extreme precipitation events. Some specific opportunities discussed related to this topic include (although some of these opportunities also apply to one or more of the other overarching themes identified at the Workshop):

- <u>Explore opportunities for new missions with instruments to monitor extreme precipitation (also Long-term Data):</u> The discussion on exploring opportunities for new missions arose during session 3. Various missions were mentioned (e.g., SWOT, SMOS, PACE, ALOS, SAR (Sentinel, NISAR, commercial), high to very-high resolution optical), but the main point was that the Quad countries could consider exploring where to partner on new missions or build on one another's missions in order to expand the available data for use in monitoring and responding to extreme precipitation events. This would also add to longer-term datasets, which are important in ensuring continued improvement and expansion of the responses to extreme precipitation events.

- <u>Provide mobile applications to support community-based solutions</u>: The Workshop participants discussed the importance of mobile applications (i.e., mobile/cell phone "apps") in getting information directly to individuals and communities. The mobile applications can be used to provide real-time warning of hazards, as well as general information for the community to access to make informed decisions about preparing for, monitoring, and mitigating extreme precipitation events.

- Endorse India's concept note to move forward to the Quad Space Working Group for formal consideration (also Open Data and Impact Assessments): The Workshop participants agreed with the potential benefits to the work of the Quad Space Working Group that India outlined in their concept note, "Extreme Weather Events: Space Based Monitoring and Climate Impact". The participants viewed the proposals in the concept note as further opportunities for the Quad to further work together to address extreme precipitation events and therefore listed it as an opportunity out of this Workshop for the Quad Space Working Group to further consider the proposals in the concept note and discussion whether and how to work together on those proposals in the future.

- Conduct more field campaigns and improve integration of field campaigns with space-based observations (also Long-term Data): The Workshop participants discussed importance of more field campaigns using space-based observations, especially those field campaigns focused on improvising the physics of models, to help the Quad members improve space-based observations informing the forecasting, monitoring and mitigating of extreme precipitation events. An opportunity for Quad member agencies would be to work together to conduct more joint field campaigns to improve our individual space-based observations of extreme precipitation events, as well as our overall Quad capabilities in this arena. Assessments of biological, biogeochemical and ecological impacts of extreme precipitation events are also crucial, particularly to support space-based water quality monitoring efforts.

- Continue to advance and improve modeling capabilities to provide accurate, real-time information, especially when a disaster strikes (also Impact Assessments): During the Workshop, representatives in multiple agencies from each of the Quad countries shared information on models they have created, are working to create, and those they are working to improve. The participants identified an opportunity for the Quad members to continue to work to advance and improve the modeling capabilities to provide accurate, real-time information when disaster strikes. The opportunity here is for both the Quad members to individually work to improve their models, as well as to work with Quad partners to create joint models. The types of models discussed for the Quad members to continue to advance and improve included advancements and improvements for: models needed for forecasting when a storm may make landfall and the impacts on the landscape that it might have (e.g., rockslides, flooding, etc.); decay modeling; hazard modeling; models needed to aid in identifying deterministic forecast shortcomings (resolution, positional accuracy, better quantitative prediction forecasts); models aimed at better utilization and communication of ensemble/probabilistic information; models focused on intensity and track; and high resolution modeling for use at the municipal level using high resolution. An opportunity for the Quad on this issue is for the technical experts from the Quad member agencies to participate in detailed discussions focused on what types of models need improvements, which existing models to focus on first, and how to look to creating future models.

Opportunities related to the "Importance of timely, accessible open data and open science": The Workshop participants placed significant emphasis throughout all discussions of the Workshop on the importance of timely and accessible open data and open science. This emphasis moves beyond the need to improve the data and modeling, but to then providing that information to the people that need it most to prepare and respond to extreme precipitation events. The opportunities outlined below are ways in which the Quad and the Quad members could move towards providing more timely, accessible, and usable data to the users and communities in the Indo-Pacific region. Some specific opportunities discussed related to this topic include (although some of these opportunities also apply to one or more of the other overarching themes identified at the Workshop):

- Commit to open science and open data: One way of progressing towards the overarching Workshop theme of the importance of timely and accessible open data and open science, highlighted as a Workshop outcome in the previous section, is for each of the Quad nations to commit to open science and open data. Therefore, an opportunity identified at the Workshop for the Quad members to consider is for each to make a commitment to open science and open data.

- Commit to providing relevant, timely, and accessible data (FAIR principles):–Similar to committing to open science and open data, the Quad members could take that one step further and committee to not only providing open data, but providing relevant, timely, and accessible data. One way to achieve this, is for each of the Quad members to agree to the FAIR principle of data: findability, accessibility, interoperability, and reusability (FAIR).

- Establish an integrated portal of precipitation monitoring capabilities that leverage existing measurements, products, tools, and other capabilities of Quad members: The Quad members each have their own websites and portals for disseminating satellite and environmental data related to extreme precipitation events. The Workshop participants discussed the idea of integrating each of the Quad members satellite and environmental data and precipitation monitoring capabilities into one portal, to improve on the data accessibility to all users in the Indo-Pacific region. This could include construction of a portal site focusing on the precipitation monitoring for the Indo-Pacific regions, with the current tools and products available in the Quad members. The purpose of this would be to enable small-island nations and least developed nations one site or portal to access to obtain the necessary data, instead of spending time looking around at multiple sites from multiple countries. While this would make data more easily accessible, the Workshop participants recognized that implementing this as an opportunity would require significant resources (time, personnel, and funding) and would need to be carefully designed to satisfy the real needs for such coordinated access to data.

- Improve the sharing of technical satellite and environmental data and products in understandable language to non-technical audiences: As satellite and environmental data, information, and products are often described with technical language that is not understandable to a non-technical audience (which include most users and communities that need to be warned about coming extreme precipitation events), the Workshop participants placed a lot of emphasis on not only needing to improve the data and modeling, but also then providing how that information is communicated to the people and communities that need it most to prepare and respond to extreme precipitation events. One important aspect of this issue is to provide data and information in a language that is understandable to the specific user.

- Provide data in formats that are accessible and usable: Data from different satellite instruments and different data products are often provided in a variety of formats and levels of processing. Further, different data providers and scientists provide that data in various formats. Therefore, another example of providing timely and accessible data is to ensure the users are receiving the data in a format that is usable. Each user will have different technical capabilities, thereby impacting the format of the data they need in order for it to be usable in their specific circumstance. Some specific ideas discussed to implement this opportunity were: making data and information available in formats that all can use; providing machine readable data; providing analysis-ready data, or data where very little processing required; and creating cloud storefronts to data and information portals with visual tools that can be easily understood equally by a scientist or a person with no training or expertise in satellite imagery.

- Improve linkages between the environmental and satellite data providers/scientists and social scientists for hazard communication, as well as for advocates who can represent community needs: To be most effective in ensuring all potentially impacted communities receive the necessary data and information, it is important to focus on how to most efficiently provide that information to all the different types of users. To address this question, the Workshop participants noted the importance of establishing connections between the data providers/scientists and the social scientist who can help craft the messaging, as well as linking those individuals to community advocates who can help get the messaging and information out to the communities and individuals who need it most. Some specific ideas discussed on improving linkages between the data providers and users were to rely heavily on social scientists to help craft messaging around the data/information to ensure the important aspects of the messaging will be understood by the communities who need to respond. Further, in cases where there may be a lack of trust between communities and the data providers, creating partnerships between the data providers and community advocates who are trusted within the communities could improve the chances the message is trusted by the communities.

- Develop agreements between Quad countries for the sharing of satellite and environmental data related to extreme precipitation (also Capacity Building and Long-term Data): Workshop participants discussed the opportunity for Quad members to work better in partnership if Quad agency partners enter into data sharing agreements, with the goal of building capacity across the globe to address the current global climate crisis. Entering into data sharing agreements could speed up the ability of each Quad member to share not only its own data with stakeholders who need it, but also share data from partner Quad agencies. These agreements could cover the sharing of satellite and environmental data related to extreme precipitation events, including, but certainly not limited to, flood inundation data. While this would make it easier for each Quad member agency to share data with users, and easy for users to obtain data from all the Quad countries even if they only approach one Quad member agency, the Workshop participants recognized that implementing this as an opportunity would require consideration of data and other security issues, as well as the consideration of the different laws and policies as appropriate for different countries and agencies.

- Ensure two-way interaction between end users and algorithm developers, which is always essential to the utility of products: The Workshop participants highlighted the value of obtaining user input during the development of products and algorithms, both to the users and the Quad members agencies developing the algorithms for products aimed at monitoring and mitigating extreme precipitation events. Ensuring two-way interaction between the end users and the algorithm developers will ensure that the products created and data received by users who need them to respond to extreme precipitation events will be the products and data that each user most needs for their specific situations. Workshop participants noted that to move forward on this opportunity, it would require including metrics that are user-centric and user-interpretable in validation quantification and qualification, as well as developing verification approaches and apply these approaches to ongoing refinements of current methods as well as to new and emerging methods (i.e., AI/ML, downscaling, modeling, and data assimilation).

Opportunities related to the "Need to discuss how to perform impact assessments over multiple countries"

The Workshop participants place significant emphasis throughout the Workshop on the need for impact assessments, especially those that can be performed or applied to multiple countries or regions. Impact assessments are an important tool for emergency managers to assess the vulnerability and risk of extreme precipitation events on landscapes and human populations. The Workshop participants noted multiple times that response to extreme precipitation events could be improved if impact assessments had a baseline standard by which to perform them consistently across countries and regions. In this way, the impact assessments could translate advances to the real world and allow nations to quantify and qualify the benefits of remote sensing asset, while using these data in disaster mitigation. Some specific opportunities discussed related to this topic include (although some of these opportunities also apply to one or more of the other overarching themes identified at the Workshop):

- Identify, develop, and/or share best practices and case studies for working with stakeholders and communities (also Capacity Building): During session 5 of the Workshop, each Quad country presented a case study to demonstrate how a real-world extreme event impacted their society and how each country responded before, during, and after the event. The speakers provided information on what worked and what did not, as well as what lessons were learned. An important component of the information provided in these case studies was how each country or agency not used the available satellite and other data to forecast and monitor the extreme precipitation event in question, but also how that information was communicated to the stakeholders and communities impacted by the event. The lessons learned, as communicated by the speaker presenting the case study, showed that asking the right questions and tailoring the outreach to the specific stakeholders and communities impacted by the event, can not only lead to a better response by communities to the information provided by the government or agency, but also help the decision makers respond to events. Therefore, the Workshop participants identified the importance of identifying, developing and/or sharing best practices and case studies for working with stakeholders and communities so that other governments or agencies in the Indo-Pacific might incorporate some of these practices in their future impact assessments and responses to extreme precipitation events. A first step in implementing this opportunity could be to review the existing studies related to working with communities to develop user requirements for proposed initiatives, such as studies performed by CEOS, WMO, and Digital Earth Pacific, to identify where more detail may be required.

- Identify, develop, and/or share best practices for the use of space-based observations to assess coastal vulnerabilities and impacts of storms from both a flooding and inundation as well as water quality perspective (e.g., tropical cyclones) (also Capacity Building): The Workshop participants noted the existence of many models and tools based on space-based observations that the Quad member agencies have made available and are used in various parts of the world. However, the utility of the products from those spaced based observations to a coastal area in question depends in large part on the ability to get the information to the community and provide it in a language or format that is usable to the community. Further, the information needs to be specific enough to speak to each, individual coastal region and nuances of each storm since the vulnerabilities of coastal areas, both to the coastal landscapes as well as the human populations who reside in those communities, is large and varied depending on the specifics of the coastline in question (e.g., flat, below sea level, mountainous), the location and design of human settlements (e.g., village high on hill, city below sea level), as well as the specifics of each individual storm (e.g., wind speed, wind direction). This information can both help coastal communities prepare for potential future storms, as well as respond in real time to specific storms forecasted to impact the area. Therefore, the Workshop participants saw it as an opportunity for the Quad to identify, develop and/or share some best practices for the use of space-based observations to assess coastal vulnerabilities and impact to storms.

- Work with task teams with experts from various agencies for different applications, such as identifying/developing a decay model related to tropical cyclones, targeted improvements in track and intensity, hazard modeling associated with strong winds (gust) and precipitation, and remote sensing based newer tools and techniques for damage assessments (also Capacity Building and Long-term Data): As has been discussed in the explanations for previous opportunities described in this subsection, as well as the key Workshop outcomes identified in the previous subsection, the Quad members have a vast array of capabilities related to space-based observations for extreme weather events; however, there is also many areas that could use improvement. The participants noted the significant advance the group has in working together, given the capabilities of each of the Quad members. To that end, one opportunity identified by the Workshop participants was for the Quad member agencies to create several task teams of subject matter experts from the relevant agencies in each Quad member nation focused on the topics the Workshop participants deemed most important to address first. Those included task teams focused on:
    - Identifying and/or developing a decay model related to tropical cyclones;
    - Focused on targeted improvements in track and intensity;
    - Hazard modeling associated with strong winds (gust) and precipitation; and
    - Remote sensing-based newer tools and techniques for damage assessment.

Opportunities related to "Importance of continuing data gathering to ensure long-term data sets"
The Workshop participants place significant emphasis throughout the Workshop on the

importance of continuing data gathering to ensure long-term data sets. Emphasis was placed on climatological products and historical data records, as these data are essential in providing a baseline by which the effects of climate change can be measured. The more robust and long-term the data set, the more they can inform and improve models for forecasting extreme precipitation events; thereby, providing more reliable information to governments and organizations responding to and mitigating the impacts of extreme precipitation events and the disasters they can create. Some specific opportunities discussed related to this topic include (although some of these opportunities also apply to one or more of the other overarching themes identified at the Workshop):

- Continue data gathering to ensure long-term time series of product data records, with emphasis on extreme precipitation-related data and climatological products: The Workshop participants viewed the continued gathering of data to ensure long-term time series of product data records as an opportunity for the Quad members. The Workshop participants emphasized Quad members first focus on the opportunity to build these long-term time series and data records for extreme precipitation-related data and climatological products, as these data are essential in providing a baseline by which the effects of climate change can be measured and can assist the Quad members in continuing to improve their monitoring and mitigation of extreme precipitation events. One example discussed at the Workshop was the importance of extending data records prior to the NASA/JAXA joint Tropical Rainfall Measuring Mission (TRMM), which is an important data set for the monitoring of mesoscale precipitation systems in the Indo-Pacific region. Extending this product data record would result in a more robust tool for the use in predicting the impacts of extreme precipitation events in the region

- Consider advancements and extensions of current space-based global observation systems and the spatial and temporal observation requirements from the present instruments (also *Capacity Building*): The Workshop participants discussed the general opportunity for Quad members to continue to invest in advancing and extending their space based global observation systems as well as the spatial and temporal observation requirements from the present instruments. Extending and advancing each Quad member's space-based observation systems and instruments relevant to forecasting and monitoring extreme precipitation events, and the impacts of those events, will continue the data record and provide additional strength to the information and data obtained by those systems and instruments.

- Explore opportunities for new, future space-based global observation systems (also *Capacity Building*): As with the previous bullet, the Workshop participants discussed the general opportunity for Quad members to consider opportunities for new, future space-based global observation systems. These systems could include new and refined instruments that can help members strengthen their observations. By potentially working together with other Quad members on missions, the Quad can expand both its individual member's capabilities as well as strengthen the Quad partnership, be it through joint missions, instrument ride shares on a partner country's mission, or through ground station support.

V. Concluding Recommendations

As the information in the previous sections show, this Workshop resulted in robust information sharing among the Quad countries. The Workshop participants identified multiple outcomes and possible opportunities for the Quad partners to pursue through the partnerships under the partnership of the Quad Space Working Group.

As the next steps to follow up on the technical discussions within this Workshop, the Steering Committee **recommends** the members of Quad Space Working Group:

- Accept this Workshop report; and
- Consider collaborating on the opportunities outlined in section IV of this report, with priority focus on the opportunities identified as (1) addressing capacity building in the Indo-Pacific Regions and (2) addressing the importance of timely, accessible, open data and open science.

VI. Appendices

Agenda: Quad Space Working Group Technical Workshop on Extreme Precipitation Events

Quad Space Working Group Technical Workshop on Extreme Precipitation Events
February 5-9, 2023 USA/February 6-10, 2023, Australia, India, Japan

What is the Quad: This Workshop is an effort under the Quad Space Working Group. The Quad nations are Australia, India, Japan, and the United States. The Quad was established in the wake of the 2004 Indian Ocean Tsunami to coordinate humanitarian assistance and disaster relief, and has since become a leading regional partnership dedicated to advancing a common vision of a free and open Indo-Pacific through practical cooperation on diverse 21st-century challenges. With six leader-level working groups—on COVID-19 Response and Global Health Security, Climate, Critical and Emerging Technologies, Cyber, Space, and Infrastructure—the Quad is building habits of cooperation among our four countries that will support a more peaceful and prosperous Indo-Pacific. For additional background, please see the May 24, 2022, Quad Leaders' Joint Statement.

Workshop Focus: Discuss Extreme Precipitation Events from the lens of societal benefits. Explore how the Quad members' space capabilities can contribute to disaster preparedness and response to extreme precipitation events and the environmental events they exacerbate, as well as how they impact related transboundary issues. This Workshop could set the stage for more focused Workshops or training on disaster preparedness and response with countries in the Indo-Pacific Region. A technical Workshop examining extreme precipitation events meets the objectives under both Line of Effort 1 and Line of Effort 2 in the Quad Space Working Group Work Plan. Through the Quad Space Working Group and this Technical Workshop, we can strengthen our collective capabilities, as well as help other Indo-Pacific nations develop their capabilities, to prepare for and respond to environmental and natural disasters.

Pre-Work Drafted by Session Chairs (shared with participants one week before the Workshop):

- Understanding the Problem
  - Review existing reports and information.
  - Who are the key players and what they are researching?
  - What are previous recommendations and assessments.
- Who are the key users and what are the key information requirements?
  - Loop this into what emergency managers need
- Consider the problem vs. the Quad Members' capabilities or unique impacts on certain Quad countries of given events.
- Review current tools and products available and relevant experience and applicability in the Indo-Pacific Region.
- Explore how we can tie into existing mandates and activities from relevant multilateral organizations (e.g., UN, WMO, GEO, CEOS)

Objectives for Workshop Outcome:

- Create Recommendations for the Space Working Group Principal's consideration
  - Recommendations based on what we can do *now* with current capabilities and resources of each of the Quad members;
  - Aspirational recommendations, e.g., recommendations for things we could do if we had additional resources, etc.
- Report of the Workshop, format To Be Determined

Workshop Dates & Times: Five sessions over five days:

- United States: Sunday, February 5 - Thursday, February 9, starting at 8 PM (2000) EST
- Australia: Monday, February 6-Friday, February 10, start at 1200 AEDT
- India: Monday, February 6-Friday, February 10, start at 0630 IST
- Japan: Monday, February 6-Friday, February 10, start at 1000 JST

WebEx Information – same for all sessions:
https://nesdisia.webex.com/nesdisia/j.php?MTID=m0c06b79532749d5769c430d9a2bdfe0c
Meeting number (access code): 2764 818 5225
Meeting password: BGyc37Tdnk2 (24923783 from video systems)

Please review the "Technical Guidance & Meeting Protocols" document for additional options for joining the WebEx, as well as other guidance for speakers to share screens and what to do in the event of technical difficulties.

Session 1: Large scale precipitation systems (e.g., tropical cyclones)

Sunday, February 5, 2000 EST/ Monday, February 6, 0630 IST; 1000 JST; 1200 AEDT
Session Duration: 4 Hours

Welcome (*30 minutes*)

A. Keynote Welcome: Stephen Volz, NOAA NESDIS Assistant Administrator, USA
B. Workshop Facilitator Introduce Schedule: Melissa Andersen Garcia, NOAA, USA

Session 1 (*3 hours*)

Session Chairs: Atul Varma, SAC/ISRO, India; and Ananda Kumar Das, IMD, India

A. Chair report discussing Present capabilities to forecast Tropical Cyclones: present status, Gap areas in terms of modeling and observations (data), way forward to address these problems (15 minutes)

B. Presentations (1 hour 20 minutes)
   i. Present status of cyclone/Typhoon/Hurricane forecast and vulnerability assessment future plans and gap areas:
      - Indian Ocean Region: Ananda Kumar Das, IMD, India
      - Atlantic and northeast-Pacific Ocean: John Knaff, NOAA, USA
      - Northwest-Pacific Ocean: Kotaro BESSHO, JMA, Japan
      - Southern hemisphere: Adam Conroy, BOM, Australia
   ii. Advance airborne and Satellite observation for understanding genesis/ decay/intensification/ propagation/structure of cyclones: John Knaff, NOAA, USA
   iii. Recent advances in theoretical and computations modeling of Tropical Cyclones: Vijaya Tallapragada, NOAA, USA
   iv. Data assimilation for cyclone forecast: John George, NCMRWF, MoES, India
   v. Tropical Cyclones in changing climate scenario, and vulnerability assessment: Neeru Jaiswal, SAC/ISRO, India

C. Chair-facilitated discussion of the presenters and panel of subject matter experts to address pre-defined questions (30 minutes)
   i. Best practice in Monitoring of the tropical storms: What are the observing platforms (remote-sensing) required to estimate best track parameter (track, intensity and structure) of the tropical cyclonic storms?
      - Whether the existing observations over the Asia-Pacific & North Indian Ocean (NIO) regions are sufficient for estimation of the best track parameters?
      - What are the bottlenecks to utilize uniformly all satellite observations in different stages (genesis, intensification and landfall/decaying) of the tropical storms? How can be these limitations removed?
   ii. Best Practice for the forecasting of tropical storms in case of General forecasting: What are best practices for cyclone forecasts over Asia-Pacific & NIO regions for QUAD member nations?
      - Whether present practice of forecasting (including modeling) of tropical cyclones are utilizing satellite observations optimally with available scientific tools/techniques?

- How present set of observations (conventional and non-conventional) can represent land surface processes for more accurate estimation/forecasting of wind and precipitation after landfall?
- What are the steps required for uniform best practice of identifying/developing a decay model?

D. Chair-facilitated group discussion of pre-defined questions addressing gaps and opportunities (45 minutes)
   i. What kind of improvements projected in the estimation of best track parameters during the next 5 years based on panel discussion? (A Task Team may be formed)
   ii. What are the steps required for the improvement (at least 10-20 %) in genesis and track & landfall forecasts with 10 days and 5 days lead time respectively based on panel discussion? (A Task Team may be formed)
   iii. A Task Team may be formed for identifying/developing a decay model?
   iv. What is required for the Early identification of cyclone induced various hazard, and generation of multi-hazard map associated to each land-falling cyclone system for accurate assessment of vulnerability and associated risk?
      - What kind of additional modeling (hazard modeling) efforts are most relevant for the forecasting of hazards associated with strong wind (and/or gust) and heavy precipitation due to tropical cyclones? (Task Team may be formed)
      - What kinds of tools and techniques based on remotely sensed observing platforms are necessarily be utilized for the damage assessment in land is caused by different kinds of hazards? (Task Team may be formed)

E. Summary of key points, actions and next steps (10 minutes)

Close

Session 2: Mesoscale precipitation systems, including precipitation, thunderstorms, orographic precipitation and cloudburst, in monsoon season

Monday, February 6, 2000 EST/ Tuesday, February 7, 0630 IST; 1000 JST; 1200 AEDT
Session Duration: 3.25 Hours

Welcome back; Overview of today's schedule (5 *minutes*): Melissa Andersen Garcia, NOAA, USA

Session 2 (*3 hours*)
Session Chair: Takuji KUBOTA, JAXA, Japan

A. Chair presents introduction of topic and results of pre-work (30 minutes)

B. Presentations (1 hour 20 minutes)
   i. Strategies for satellite based nowcasting of convective storms: Advancements and Gap areas: Bipasha Paul Shukla, SAC/ISRO, India
   ii. Himawari Follow-on Program: Yasuhiko Sumida, JMA, Japan
   iii. Precipitation Monitoring in the US: Status and Remaining Gaps: Bob Kuligowski, NOAA, USA
   iv. Precipitation Monitoring in the Australia: Observations, Nowcasting and Remaining Gaps: Carlos Velasco-Forero, BOM, Australia

C. Chair-facilitated discussion of the presenters and panel of subject matter experts to address pre-defined questions (30 minutes)
   i. Summary proposed by Session chair for presentations related to the pre-defined questions from respective countries in Session 2B.
   ii. Comments & discussions to the proposed summary from presenters in Session 2B.

   Questions for discussion
   i. What are gaps between the current tools & products and the requirements from users?
   ii. What are gaps in integrating among satellite precipitation products and ground-based observations?
      - What are the experiences in your country?
   iii. What are gaps in constructing long-term satellite precipitation products?
      - What are the experiences in your country?
   iv. What are new sensors we can propose specially catering to extreme precipitation events in the Indo-Pacific region?

D. Chair-facilitated group discussion of pre-defined questions addressing gaps and opportunities (30min)
   i. Comments & discussions to the proposed summary from participants.

E. Summary of key points, actions and next steps (10 minutes)

Close

<u>Session 3: Inundation/flooding, coastal erosion, water quality</u>

Tuesday, February 7, 2000 EST/ Wednesday, February 8, 0630 IST; 1000 JST; 1200 AEDT
Session Duration: 4 Hours

<u>Welcome back; Overview of today's schedule</u> (*5 minutes*): Melissa Andersen Garcia, NOAA, USA

<u>Presentation on India's 2022 Concept Note, "Extreme Weather Events: Space Based Monitoring and Climate Impact"</u> (*30 minutes*): Rashmi Sharma and Nitant Dube, SAC/ISRO

<u>Session 3</u> (*3 hours*)
Session Chair: Stacey Archfield, USGS, United States

A. Chair presents introduction of topic and results of pre-work (10 minutes)

B. Presentations (1 hour)
   i. Flooding and Extreme Precipitation: Naresh Devini, City College of New York, USA
   ii. Modeling Flood Inundation in the United States: David R. Vallee, NOAA, USA
   iii. Effects on Water Quality: Emily Smail, NOAA, USA; GEO Blue Planet Initiative
   iv. Coastal Multi-hazard Vulnerability Assessment: Perspectives of INCOIS: R.S. Mahendra, INCOIS, MoES, India
   v. Modeling flood inundation in Australia – a seamless perspective: Ulrike Bende-Michl, BOM, Australia

C. Chair-facilitated discussion of the presenters and panel of subject matter experts to address pre-defined questions (1 hour)
   i. Panel member opening remarks**:**
      - Kosuke Yamamoto, JAXA, Japan
      - Ulrike Bende-Michl, BOM, Australia
      - R.S. Mahendra, INCOIS and KHV Durga Rao, NRSC, India
      - Julia Prokopec, USGS, and David R. Vallee, NOAA, USA
   ii. Panel discussion with questions
      - What is the most pressing gap to fill with respect to inundation, flooding, erosion, and/or water quality in your country?
      - What has been the most significant advancement in recent years for addressing inundation, flooding, erosion, and/or water quality issues in your country?
      - What are the biggest barriers to advancement or gap-filling in your country?
      - What are your thoughts on current initiatives or efforts that could be leveraged to advance or fill gaps in these topical areas?

D. Chair-facilitated group discussion of pre-defined questions addressing gaps and opportunities (40 minutes)

E. Summary of key points, actions and next steps (10 minutes)

Close

Session 4: Transboundary issues (e.g., ocean/atmosphere changes, numerical weather prediction, cascading hazards/environmental impacts/phenomena)

Wednesday, February 8, 2000 EST/ Thursday, February 9, 0630 IST; 1000 JST; 1200 AEDT

Session Duration: 3.25 Hours

Welcome back; Overview of today's schedule (*5 minutes)*: Melissa Andersen Garcia, NOAA, USA

Session 4 (*3 hours)*

Session Chair: Leon Majewski, BOM, Australia

A. Chair presents introduction of topic and results of pre-work (10 minute)

B. Presentations (1 hour 30 minutes)
   i. Potential use of satellite and reanalysis products in regional monitoring of extreme precipitation, Blair Trewin, BOM, Australia
   ii. Observation system simulation experiments for a hyperspectral infrared sounder onboard a geostationary satellite: Hiromi OWADA, JMA, Japan
   iii. Advances in satellite data assimilation to improve extreme precipitation events: Prashant Kumar, ISRO, India
   iv. Connecting ENSO to Landslide Impacts: Robert Emberson, NASA, USA
   v. Extreme rainfall in northern Australia: the 2019 Queensland floods and the MJO: Tim Cowan, BOM, Australia

C. Chair-facilitated discussion of the presenters and panel of subject matter experts to address pre-defined questions (20 minutes) -- General Q&A linked to the presentations

D. Chair-facilitated group discussion of pre-defined questions addressing gaps and opportunities (45 minutes hour)
   i. Current status
      - What are the impacts of transboundary processes on the region at large?
      - How does the space segment contribute to observing these?
      - How can improved modeling of transboundary processes be used in Indo-Pacific?
   ii. Research
      - What research, experiments, and/or observations are occurring or required to improve our understanding?
      - How do we support vital ground- and ship-based experiments?
      - How will the future space segment contribute upcoming missions & related OSSEs?
      - What tools/products could enhance our understanding and decision making?
   iii. Engagement
      - How does the space segment better engage with the coupled model / seasonal prediction community?
      - How can we better share our knowledge with the Indo-Pacific region?
      - What avenues for engagement are there with existing organisations?
      - What lessons have been learned from past engagements?

E. Summary of key points, actions and next steps (15 minutes)

Close

Session 5: Data Integration and Applications for Societal Benefits

Thursday, February 9, 2000 EST/ Friday, February 10, 0630 IST; 1000 JST; 1200 AEDT
Session Duration: 4 Hours

Welcome back; Overview of today's schedule (*5 minutes)*: Melissa Andersen Garcia, NOAA, USA

Session 5 (*2.5 hours*)
Session Chair: Paul DiGiacomo, NOAA, USA

A. Chair presents introduction of topic (10 minutes)

B. Recap of Sessions 1-4 (10 minutes): Will McCarty, NASA, USA
    i. Session leads distill the information from sessions 1-4 and provide to the speaker of this session to include in the recap.
    ii. Include where we all agree who the target users are and key gaps based on the conversation we've had in the previous sessions.

C. Country case studies: Demonstrate how a real-world extreme event impacted society and how each country responded before, during, and after the event. What worked and what did not? What were the lessons learned that we can share? (20 minutes)
    i. Using satellite views of the recent Western Australia floods to derive impact information, Judith Landsberg, BOM, Australia
    ii. Achieving the Zero Casualty against Cyclones, Surya Prakash, MHA, India
    iii. Japan's effort for risk reduction of heavy precipitation: Kotaro BESSHO, JMA, Japan
    iv. Red River Flooding Events, Karen Ryberg, USGS, USA

D. Chair-facilitated Discussion (1 hour 30 minutes)
    i. What kind of information the Quad countries can bring to the region?
    ii. How to help the region to use the information to combat their problems?
    iii. How to get feedback from the user community?

E. Summary of key points, actions and next steps (20 minutes)

Actions and Next Steps from throughout the Workshop *(1.5 hours)*
Facilitator: Melissa Andersen Garcia, NOAA, USA

A. Recommendations to leadership based on what we can do *now* with current capabilities and resources of each of the Quad members;
B. Aspirational recommendations, e.g., recommendations for things we could do if we had additional resources, etc.
C. Discuss format and timeline for report of the Workshop

Close Workshop

Sessions 1-4 Background Reading Provided in Advance of the Workshop

Session 1: Large scale precipitation systems (e.g., tropical cyclones)

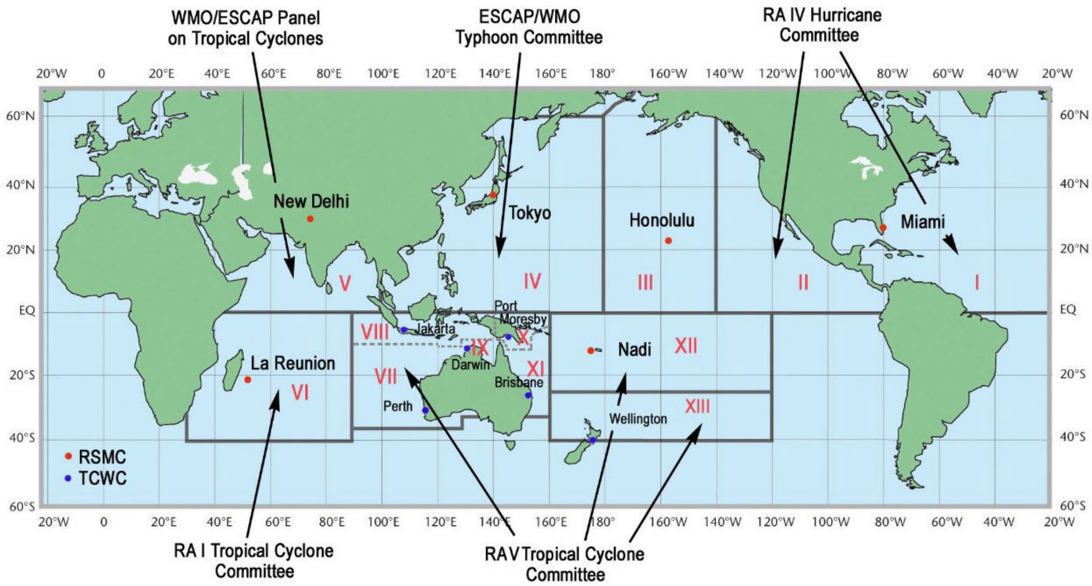
1. Introduction

The large-scale precipitation systems (LPTs) represent the organized weather systems that persist for many days before their dissipation. These systems include Tropical Cyclones, Western Disturbances, Easterly Waves, Monsoonal systems (e.g., Monsoon Lows & Depressions, Mid-Tropospheric Cyclones, Monsoon Trough, etc.), etc. Among all these systems, tropical cyclones are the most devastating multi-hazard weather systems. Tropical cyclones (TCs) develop over the open ocean under favorable atmospheric and oceanic conditions (Gray, 1975), and cause huge damage and destruction when they approach towards the land due to heavy rainfall, strong winds and storm surges associated with them. Remote sensing observations from the Low-Earth Orbit (LEO) or Geosynchronous Equatorial Orbit (GEO) constellation of satellites offer a huge potential for monitoring and prediction of these weather systems. Long-term satellite data and climate records help in studying the climate impact on their formation and intensification, and that in turn may support in developing mitigation strategies (Gray, 1975). The adverse effects associated with these systems can be contained by issuing timely and accurate early warning, and by adopting effective prevention and mitigation strategies and measures.

Accurate early warning of TCs is of paramount importance, particularly for coastal regions where landfall affects a large population and causes a huge damage. The space-based and the ground-based observations that include weather satellites, land-based surface and upper air observations, Doppler Weather Radars (DWRs), ocean buoys and ship measurements play pivotal role and make huge impact in cyclone forecast. Over last few years, the advancements in observational network and numerical modeling simulations with better understanding of cyclone dynamics resulted in significant improvements in cyclone forecast accuracy. As these cyclonic systems form over the oceans with sparsely available surface observations, satellites play an important role in real-time monitoring from genesis to dissipation.

2. Global Status of Tropical Cyclone Forecast:

Tropical cyclone forecast system includes forecasting of its various elements like cyclogenesis, track, intensity, wind structure, rainfall, storm surge, inundation, etc. Various approaches involving dynamical, statistical, hybrid, ensemble and artificial intelligences (AI) modeling are commonly employed for their forecast. To minimize the loss of life and damage to property due to tropical cyclones, World Meteorological Organization (WMO) has established national and regionally coordinated system under the Tropical Cyclone Programme (TCP). Worldwide Regional Specialized Meteorological Centers (RSMCs) and Tropical Cyclone Warning Centers (TCWCs) participating under WMO tropical cyclone warning programme (shown in the Figure 1) are entrusted to keep a watch on the formation of cyclones in the area under their warning authority. These centers also provide forecast guidance to National Meteorological and Hydrological Services (NMHSs) in different time scales, e.g., seasonal, weekly, 5-day and 2-day outlooks, and real-time forecasts up to a week for each cyclonic system. Different agencies utilize different approach to generate the forecast of the cyclones in their respective ocean basins. In the presence of an active cyclone, the respective RSMC/TCWC provides warning in terms of text and graphical displays for different stages of the cyclone. The advance cyclogenesis forecast for an extended range is produced to indicate the potential tropical cyclone activity in the next 1-2 weeks. Track forecasts are usually controlled by large-scale weather features, which are simulated using the numerical/statistical models. Intensity forecasts are more challenging as intensity change is controlled by the cyclone's environment (upper ocean conditions, vertical wind shear etc.) and internal structure as well as the possibility of interactions with land. The numerical models are also used to predict the rainfall patterns and wind structure within a cyclonic system. For storm surge prediction specific models are used that account for central pressure, storm size, cyclone track, angle of approach, radius of



maximum winds, and of the ocean bathymetry near the coastline.

Figure 1: Worldwide Tropical Cyclone Warning Centers and their regions. These regions are I (Atlantic), II (Eastern Pacific), III (Central Pacific), IV (Northwest Pacific), V (North Indian Ocean), VI (South West Indian Ocean), VII-XI (South west Pacific and South West Indian Ocean), XII-XIII (South Pacific). This figure is taken from WMO site (https://community.wmo.int/activity-areas/tropical-cyclone-programme-tcp).

2.1 Tropical cyclone Forecast in the North Indian Ocean

Regional Specialized Meteorological Centre (RSMC), India Meteorological Department (IMD), New Delhi is responsible to generate the warnings for Tropical cyclones formed in the North Indian Ocean (NIO). IMD utilizes an advanced modeling system along with in-situ and satellite-based observations for the surveillance and forecast of TCs. The coastal radar data from various places at the east and west coast of India is utilized to decipher the cyclone structural parameters near the coast. Observations from meteorological satellites are used to unravel various cyclone features. Both surface and satellite observations are assimilated in numerical models to produce the best possible cyclone forecasts.

IMD uses an array of global and regional models including IMD-GFS, GEFS, NCUM, NEPS, WRF and HWRF models within MOES as well as NCEP-GFS, ECMWF and KMA models etc. from other global modeling centers for track and intensity prediction of tropical cyclones over

NIO. Various dynamical-statistical models e.g., Genesis Potential Index, Multi-Model Ensemble (MME), Rapid Intensification (RI) Index and decay model etc. are also utilized on real time basis in the forecasting of tropical cyclonic disturbances. The forecasts are provided with 120 hours forecasts from the stage of deep depression.

The official cyclone track forecast errors of RSMC IMD New Delhi for TCs forming in the north Indian Ocean during last 5 years (2017 to 2021) with 24, 48 and 72 hours of lead-time are 73 km, 106 km and 144 km respectively (pl. see, https://rsmcnewdelhi.imd.gov.in/track-forecast.hph). The official intensity forecast errors (Root Mean Square Error-RMSE) of IMD RSMC New Delhi for TCs of NIO in recent 5 years with 24, 48 and 72-hours lead-time are 9.7, 13.9 and 17.0 knots, respectively (please see, https://rsmcnewdelhi.imd.gov.in/intensity-forecast.hph). Similarly, in recent years, there is significant improvement in cyclone landfall errors (see https://rsmcnewdelhi.imd.gov.in/landfall-forecast.hph).

2.2 Tropical cyclone Forecast in the Atlantic and northeast-Pacific Ocean

The National Hurricane Centre (NHC) generated official forecasts for the cyclones forming in the North Atlantic and East Pacific Basins. Their forecast errors and its trends for the last 20 years are reported in the NHC forecast verification reports. The intensity forecast error in last 5 years with 24-hour lead-time is 7-10 knot. The cyclone track error in last 5 years with 24- hour lead-time is less than 50 km (please see, https://nhc.noaa.gov/verification/verify5.shtml). There is continuous improvement in cyclone track and intensity predictions over last 20 years. It is observed (please see, https://nhc.noaa.gov/verification/verify5.shtml) that the improvement in track forecast accuracy has slowed down in the recent years, possibly suggesting that forecasts may be near to their limits in accuracy owing to chaotic nature of the atmosphere processes.

An inter-comparison of all available best models for tropical cyclone showed that no one model can consistently outperform the official NHC forecast. Studies show that for TC track forecast, the GFS model was the best model in 2021, followed by the European model. For intensity forecast almost all days HMON model performed better than all other models (pl see, https://nhc.noaa.gov/modelsummary.shtml).

2.3 Tropical cyclone Forecast in the northwest-Pacific Ocean

With the help of statistical models, statistical- dynamic models, and dynamic models, TC intensity forecasts covering up to 120 h are routinely issued at the three major operational centers that are responsible for TC monitoring and prediction over the western North Pacific (WNP). These include the Joint Typhoon Warning Center (JTWC), Regional Specialized Meteorological Center Tokyo-Typhoon Center (RSMC- Tokyo), and China Meteorological Administration (CMA) (Huang et al., 2021). The root mean square error (RMSE) of intensity forecast of maximum wind speed provided by RSMC-Tokyo for 24, 48, 72, 96 and 120 hours lead-time is 5.0, 6.5, 6.9, 7.6 and 8.2 m/s, respectively. The annual mean operational track forecast error for 24, 48, 72, 96 and 120 hours is 87, 157, 225, 261 and 264 km, respectively (please see, https://www.jma.go.jp/jma/jma-eng/jma-center/rsmc-hp-pub-eg/AnnualReport/2021/Text/Text2021.pdf).

2.4 Tropical cyclone Forecast in the Southern hemisphere

During the recent years, relatively high incidence of tropical cyclones is observed in South pacific and South East Indian Ocean. The Australian bureau of meteorology is responsible for tropical cyclone monitoring in the area of south of equator between 90-160° E. The Bureau's responsibility is shared by three TC warning centers viz., Perth, and Brisbane. The southwest Indian Ocean is the responsibility of RSMC La Reunion. JTWC also make forecasts every 12- h in the Southern Hemisphere. The annual official mean track forecast error of RSMC Nadi during the year 2020 was 190 km for 24 hours lead-time. JTWC reported track errors of 76, 124, 183, 229 and 270 km at 24, 48, 72, 96, and 120 h in the 2020-2021 cyclone season.

3. Present Challenges

The tropical cyclones are associated with heavy rainfall, strong winds, thunderstorms, lightning and high storm surges near the coast, which causes huge loss of lives and properties. The existing computational facilities, observational networks and scientific understanding have made it possible to provide the reasonably accurate forecast of these systems with sufficient lead prediction time. However, still there is a need to improve the tropical cyclone forecast system to provide more precise track, intensity and landfall information. *Cyclone intensity forecast is the most challenging task because it depends upon the least known interaction among convective systems embedded in the core of the storm, the surrounding environment and complex energy exchange processes between atmosphere and ocean.* The real-time cyclone centre and intensity analysis is carried out using both subjective Dvorak (Dvorak 1984) and advanced Dvorak techniques (Olander and Velden, 2019), which is essentially as cloud pattern recognition technique that utilizes optical and thermal infrared images from geostationary satellites.

The Figure 2 suggests different stages of cyclone prediction and monitoring, and impact assessment. The first stage is the prediction of cyclogenesis - cyclone formation. The prediction may be realised using a dynamical model (Halperin et al., 2013), or using model derived fields of the environmental parameters in Genesis Potential Parameter (GPP) (Kotal et al., 2019), or by observing surface wind patterns in wind scatterometer measurements. Scatterometer derived wind fields are effectively used to predict tropical cyclogenesis 1-4 days prior to cyclone formation in the North-Indian Oceans (Jaiswal and Kishtawal, 2011). Recent years have demonstrated that global models and global ensemble systems can be used to anticipate tropical cyclone formation using both direct and statistical-dynamical approaches. The lead-time for the forecast of cyclogenesis is important for some regions like North Indian Ocean and Australian regions where cyclones often form close to the landmass. Prior to the cyclone formation, a warm ocean, and corresponding high positive anomaly in Tropical Cyclone Heat Potential (TCHP) make the oceanic conditions favorable for cyclogenesis, TCHP can be calculated using the temperature and salinity profiles from satellite observations or using these fields derived from an ocean model (e.g., Modified version of Modular Ocean Model-3, MVMOM3, Mandal et. al., 2020). *However, it may be desired to predict the cyclogenesis with all satellite and model based indicators with 7-10 days lead-time.*

The second stage is about cyclone monitoring and pre-landfall forecast. The various cyclone features, meteorological parameters and processes that need to be examined includes precise centre of the eye location, storm size, wind structure, maximum intensity, rapid intensification/decay, track including recurving and cyclone-topography interaction, tornadoes forecast, storm surge and coastal inundation. Proper positioning of the TC low-level center is important for determining initial motion and initiating track model guidance. A horizontal resolution of 1-2 km in IR image and 500 m in visible image may be desired for resolving and capturing tropical cyclone inner-core/eye-wall convective-scale processes as well as the interactions with the large-scale processes, which is critical for improving track, intensity, rainfall and size predictions. For resolving, convective-scale processes, nested (may be a nest within a nest) model grid is necessary. HWRF has capability of moving nests following the storm; such nests may be interactive and may have capability to follow the cyclone for several days located in any parts of the globe. These moving high-resolution nests also resolve terrain at coast, more importantly hilly coastal terrain, at a high resolution for better simulation of storm-terrain interaction. Wind warnings are issued for 1, 3, or 10 -minute mean sustained surface (10 m) winds, depending on warning center.

Radius of Maximum Winds (R_{max}) is one of the most critical parameters that determines the tropical cyclone wind structure. The precise value of R_{max} helps identifying regions of severe winds, but precise measurements for R_{max} remain elusive in most cases. This, however, does not provides information on wind gusts. Wind gusts cause maximum impact to inland structures and turn airborne debris into deadly missiles after the landfall, but *forecast guidance of wind gusts from dynamical models is not commonly known*. *There is need to further examine the possibility of providing wind gusts forecast and gusts hazard mapping. Rapid intensification (RI) remains a significant forecast challenge for both the model guidance and forecasters.* RI is generally refers to a 30-kt or more increase in intensity over a 24 hr period, which corresponds closely to the 95th percentile. Various features of a tropical cyclonic system spans over multiple spatial scales – while the entire system is a synoptic scale phenomenon, the embedded rain bands and vortices within the eyewall are mesoscale, and turbulence in the inner core region is a microscale. *The ability to analyse these processes in multiple spatial scales and the interaction between these scales is necessary for accurate TC intensity and structure predictions* (Marks et al. 1998). Satellite observations and derived products, such as images in optical and microwave regimes of the E-M spectrum, cloud motion vectors, Radar scatterometer winds, intense wind measurements from L-band microwave radiometer, cross- polarized synthetic aperture radars, and CYGNESS constellation with each of the constellation members equipped with GNSS reflectivity measuring radiometer, provide information on the characteristics of the tropical cyclone wind structure (Knaff et al. 2021), which are vital in assessing environmental controls on TC track and intensity. Challenging is the fact that while remote sensing provides vital information about the surface winds, these observations are both too course and less frequent than needed in operations. *With need for high-resolution simulations, there is parallel need to develop improved physical parameterization procedures and advanced data assimilation schemes.*

The coastal inundation by rain, and extreme waves and surge is another topic of paramount importance. This topic is being discussed in the Workshop in "India's concept note", and hence is not included here.

The third stage is on loss assessment of marine and terrestrial ecosystem. This may be carried out aftermath analysis. Here the observations, particularly satellite based observations, play the primary role. This phase is important because it helps taking the corrective measurements to restore normalcy, and for assessing and compensating the losses. The change in ocean biological productivity can be assessed with chlorophyll images from space-borne Ocean Color Monitor (OCM). A radially available daily multi-sensor merged chlorophyll product at 4 km resolution, GlobColor (pl. see, https://www.globcolour.info/), can be utilized for this study. Flooded area over land is detectable using remote sensing measurements from different satellite-borne instruments such as synthetic aperture radar (SAR), radar Scatterometer, microwave radiometer, and infrared and visible band imagers. However, the SAR observations (for example, Sentineal-1A SAR), due to their high spatial resolution and all-weather capabilities, are most appropriate to map the inundated regions at few meter (~10 m) resolution.

SAR with its all-weather observation capabilities is effectively used for crop identification and crop planting area statistics, crop and cropland parameter extraction and crop yield estimation. Polarimetric SAR measurements provide information on classification and segmentation of vegetation types and phenology and forest/non-forest classification. On the other hand, at optical wavelengths, Normalized Difference Vegetation Index (NDVI) measured using near infrared (NIR) and red wavelength bands, is a good indicator of vegetation density and health. Using SAR and NDVI measurements, it is possible to map the affected areas of agricultural patches (Varma et al., 2023). The NDVI data can be used to demarcate active agricultural area using pre-defined threshold and forest mask (Global annual forest Mask derived from Landsat observation at 30 m resolution (Hansen et al., 2013)). SAR, NDVI and its maximum value composites during pre- and post-cyclone periods can help identifying probable agriculture affected area in different damage classes, such as, low, moderate and high. In addition, pre-and post-cyclone SAR polarimetric parameters such as entropy, anisotropy and alpha and Eigen value/Eigen vector decomposition (Pottier and Cloude, 1996) can also be used for areas of probable damage with three classes for agriculture. NDVI anomaly from long-term mean helps assessing damage over coastal forest especially mangroves (Varma et al., 2023).

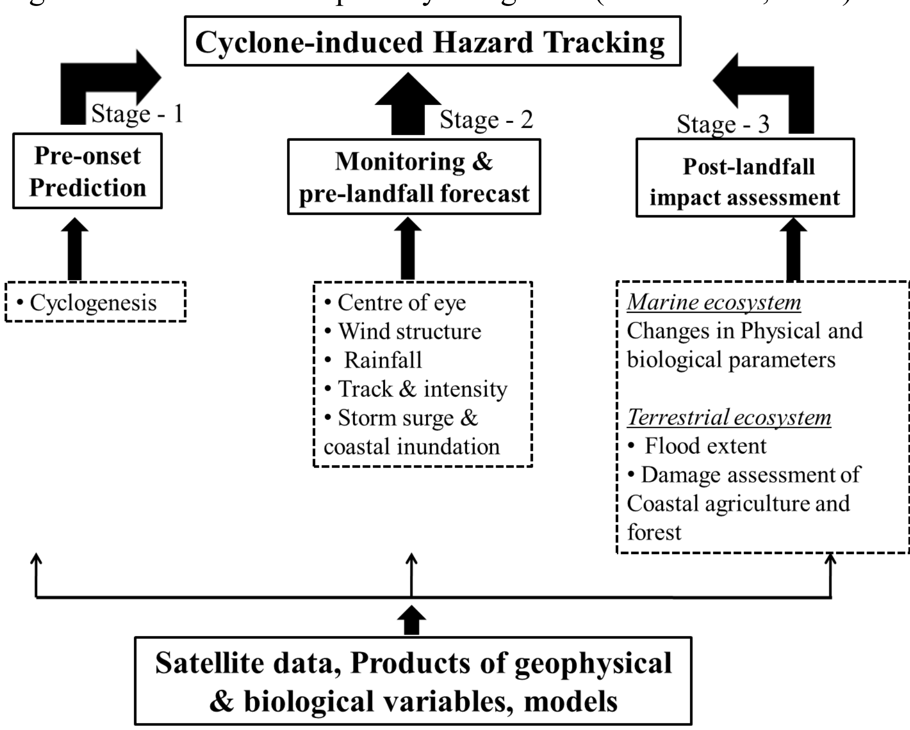


Figure 2: Schematic representation of three-stage tracking of cyclone-induced hazard (Reproduced from Varma et al., 2023)

4. Way Forward

Cyclone research is intended to provide improved forecast and products to save lives, assess and minimize the damage, helping victims and rebuilding the damaged infrastructure. It is thus necessary to use our collective knowledge and strength for the advancement of research in these areas. Keeping the objectives of cyclone research in mind, we may put our efforts in following areas where improvement is desired:

- Improvements in cyclogenesis forecast to 7-10 days.
- Improvements in cyclone intensity and wind structure forecasts with particular emphasis on improving forecasts of rapid intensification and providing forecasts of the expansion of the wind field, and of the radius of maximum wind.
- Development of a model for inland wind gusts forecast.
- Improvements in accuracy of track prediction and landfall by about 10%-20% in next 5 years.
- Better understanding of recurving and cyclone-land topography interaction.
- Better understanding of land surface process to improve the parameterization scheme in numerical models to simulate the post landfall characteristics of tropical cyclones.
- Identifying/developing a decay model to estimate the cyclone inland penetration track, intensity and precipitation.
- Impact based High-resolution rainfall forecast, particularly extreme precipitation, in terms of amount and distribution, through advanced data assimilation, microphysics representation, improved resolution in numerical models, and adopting ensemble quantitative precipitation forecast techniques.
- To help the decision makers in early preparedness of evacuation and releasing the impact based hazard warnings, generation of hazard map associated to each land-falling cyclone system for accurate assessment of vulnerability and risk associated with it.
- Better understanding of convective cores in eye-wall and cloud bands to understand and predict the tornadoes associated with a hurricane/typhoon.

In order to achieve above objectives, it is necessary to have improved models, observation systems and data assimilation methods as listed below:

- A more advanced high-resolution hurricane/cyclone forecast model (e.g., HAFS).
- Improvements in the model physics, and development of advance data assimilation techniques like feature data assimilation, assimilation of visible measurement, etc.
- Frequent wind measurements from space-borne Radar Scatterometer possibly from a constellation of satellites.
- Space-borne observing systems and advance retrieval algorithms for measuring high winds such as L-band radiometer (e.g., SMOS) and GNSS reflectometry (e.g., CYGNESS).
- Synthetic aperture cross-polarized wind speeds to provide occasional high-resolution ground truth for other space borne observations.
- Advanced Imager like (ABI) on board geostationary platform providing continuous observations with rapid scan capability to examine the fast changing characteristics of the

cyclone structure.

- Constellation of advanced microwave radiometers (e.g., GMI, SSMIS, AMSRE, etc.) and sounders (e.g., AMSU) with high frequency channels (e.g., 85, 157 and 165 GHz) to delineate cyclone structure.
- Strengthen the DWR (including duel pole) systems, particularly along the coast for monitoring precipitation distribution.
- Lightning measurements from ground/space sensors.
- Sensitivity study of inputs on target skill prediction for defining future sensors, and their development.
- Survey of forecasters to assess their needs.

It is also necessary to disseminate forecast and related products in a simple format and timely manner to concerned stakeholders in QUAD countries. It is also desired to support the small island nations who are highly vulnerable to cyclone related disasters, and lack capabilities to have their own cyclone forecast and product generation.

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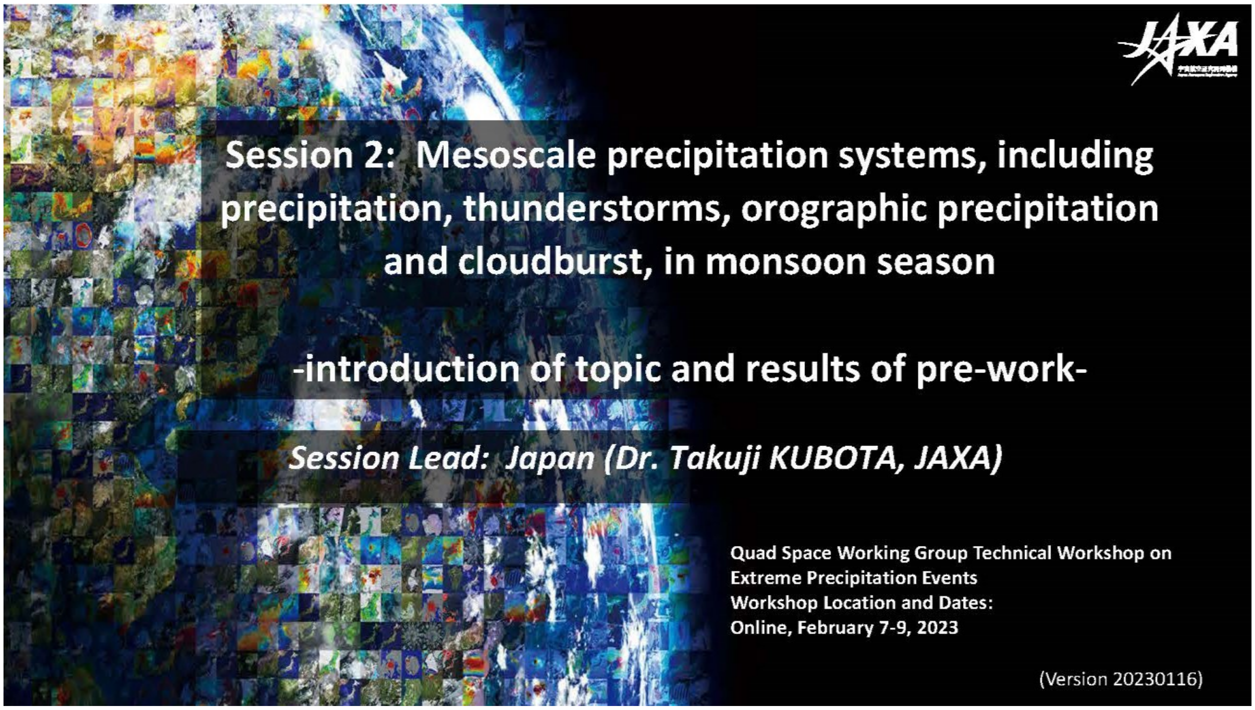
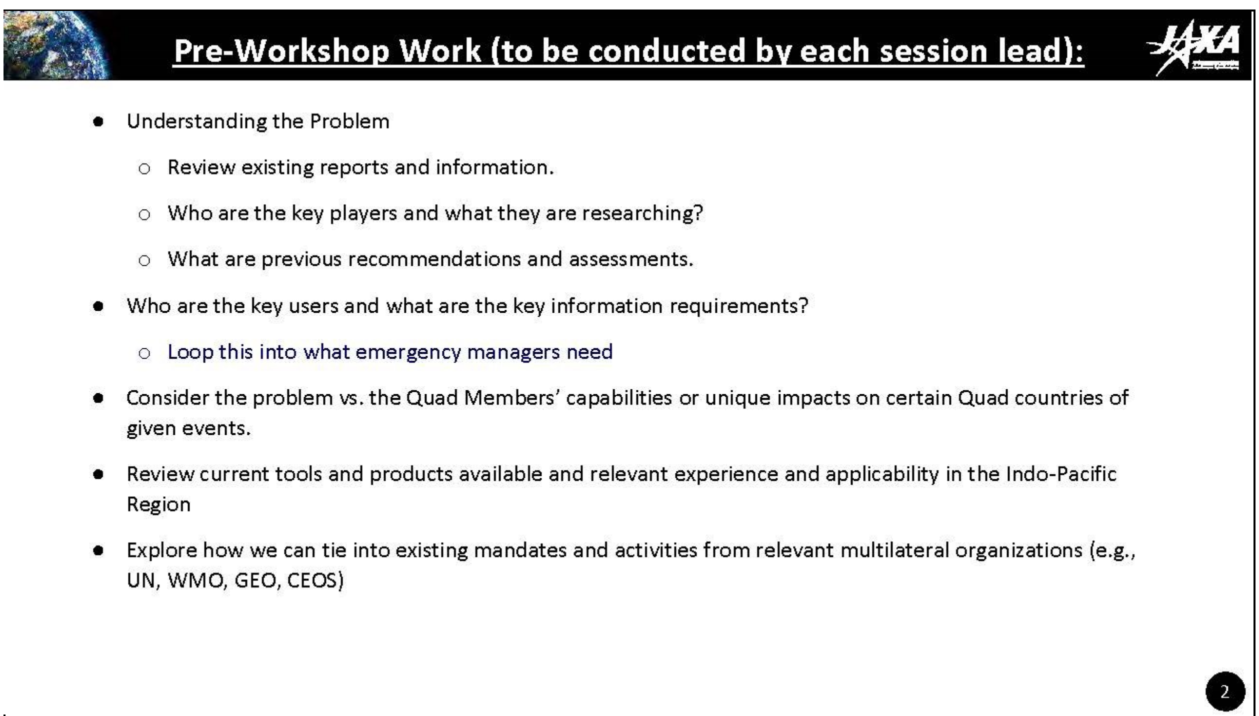
Session 2: Mesoscale precipitation systems

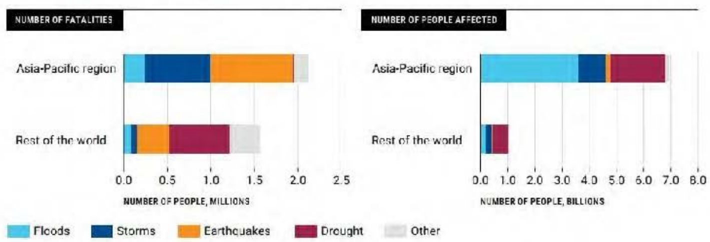




Understanding the Problem
Review existing reports and information

- Since 1970, Asia and the Pacific has accounted for 57 per cent of global fatalities from disasters and 87 per cent of the global population that has been affected by natural hazards.
- Between 1970 and 2020, natural hazards in Asia and the Pacific affected 6.9 billion people and killed more than 2 million, that is 41,373 lives per year.

FIGURE 1-1 Number of fatalities and people affected in the Asia-Pacific region and the rest of the world, 1970–2020



Source: Data from EM-DAT – The International Disaster Database. Available at https://www.emdat.be/ (accessed on 4 May 2021).

Floods and Stroms are more frequent and have high impacts.

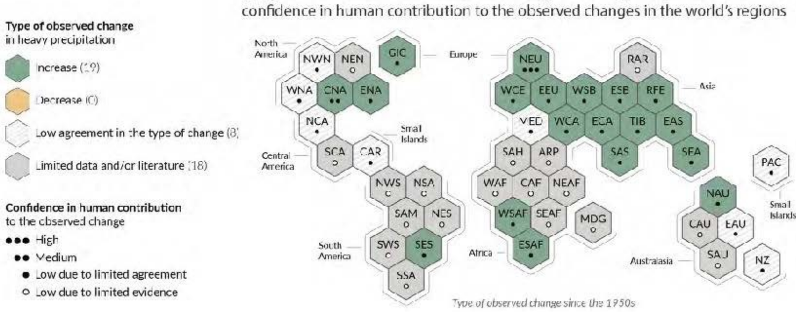
United Nations (UN) Economic and Social Commission for Asia and the Pacific (ESCAP)
Asia-Pacific Disaster Report 2021
https://www.unescap.org/kp/2021/asia-pacific-disaster-report-2021

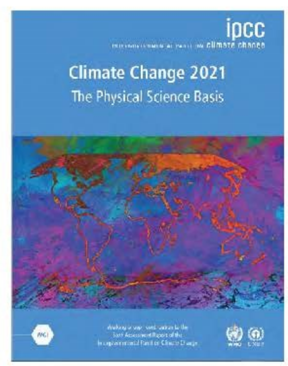
3

Understanding the Problem
Review existing reports and information

- The IPCC AR6 WG1 report (2021)
  - Human-induced climate change is already affecting many weather and climate extremes in every region across the globe.
  - Evidence of observed changes in extremes such as heatwaves, **heavy precipitation**, droughts, and tropical cyclones, and, in particular, their attribution to human influence, has strengthened since AR5.

(b) Synthesis of assessment of observed change in **heavy precipitation** and confidence in human contribution to the observed changes in the world's regions



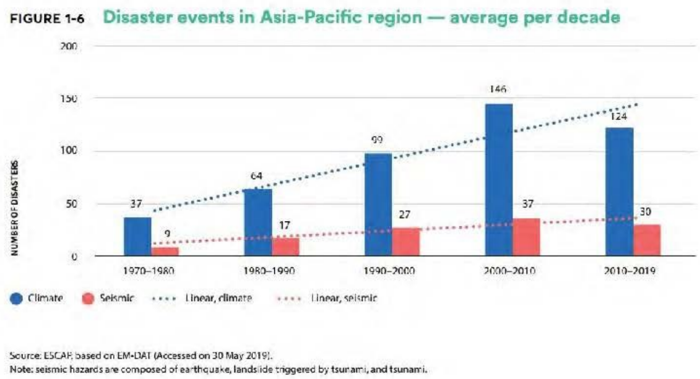


IPCC AR6 WG1 report:
Climate Change 2021: The Physical Science Basis
https://www.ipcc.ch/report/ar6/wg1/

4

Understanding the Problem
Review existing reports and information

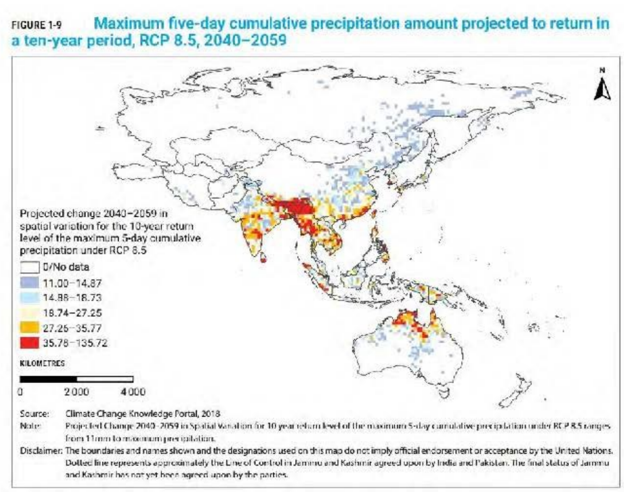
- The ESCAP Asia-Pacific Disaster Report 2019 noted recent developments and diagnostic analysis suggest a series of **major trends in disaster risk in Asia and the Pacific**.
  - The overall number of disasters is on an upward trend, largely toward an increase in the number of climate-related events and the related environmental degradation.
  - The report also noted, despite the increasing number of disasters, the fatalities have been reduced, largely on disaster caused by climate-related events.



https://www.unescap.org/publications/asia-pacific-disaster-report-2019

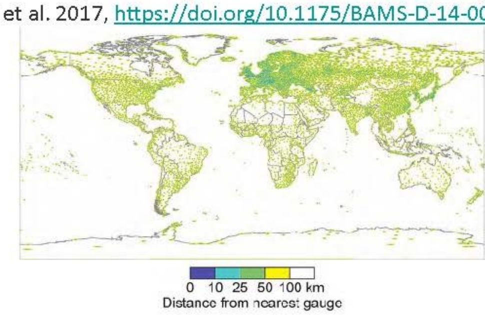
Understanding the Problem
Review existing reports and information

- The ESCAP Asia-Pacific Disaster Report 2021 noted the risks of the flood will be greater in lower-latitude regions.
- The right figure shows the maximum five-day cumulative precipitation amount projected to return in a ten-year period for the period 2040–2059 under RCP 8.5 (worst-case scenario).
  - The 'return period', which is the frequency with which the maximum cumulative precipitation over five consecutive days is likely to return during a ten-year period.
- More precipitation does not necessarily lead to more floods, but the risks can increase, especially in flood-prone countries, such as Bangladesh and India, in coastal areas in South-East Asia and in the Pacific small island developing States.

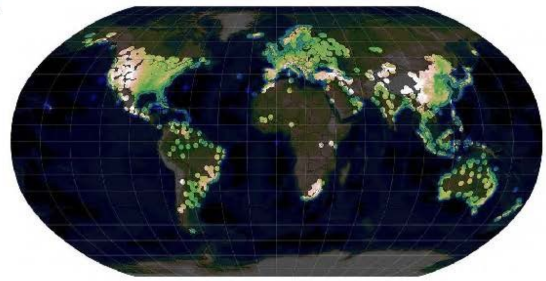


Who are the key users and what are the key information requirements?

A map showing the distance to nearest GTS gauge, typical of 3-hourly/daily measurements available in near–real time; blank areas in the figure are beyond 100 km from the nearest gauge. (Kidd et al. 2017, https://doi.org/10.1175/BAMS-D-14-00283.1)



A map of weather radar coverage in the world (Saltikoff et al. 2019, https://doi.org/10.1175/BAMS-D-18-0166.1)



- **The distribution of rain gauges across the globe is limited**: over land their distribution and density is variable, while over oceans very few gauges exist and where measurements are made, they may not adequately reflect the rainfall amounts of the broader area (Kidd et al. 2017).
- The ground weather radar networks are now covering a majority of the densely populated areas of the world. **Unfortunately, a lot of the older radar data have been lost, and not all of them are archived even today** (Saltikoff et al. 2019).

7

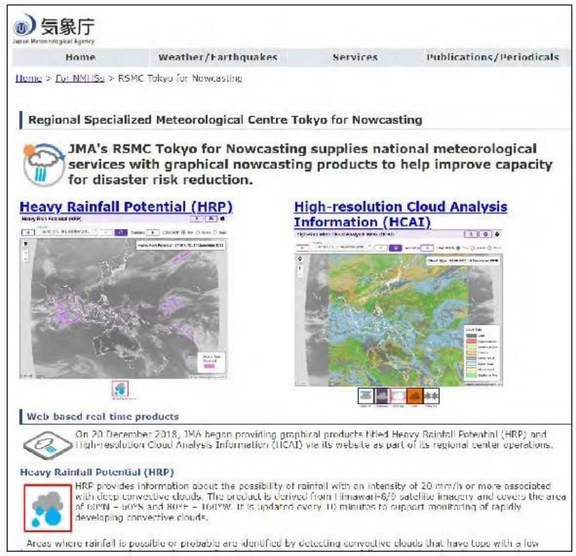
Who are the key players and what they are researching? What are previous recommendations and assessments

- In the Indo-Pacific Region, many natural hazards are caused by precipitation. Providing **timely and accurate information on monitoring of precipitation by satellites** helps countries and communities build greater resilience against floods, storms and other hydro-meteorological and climatological hazards and extremes.
- Satellite precipitation products can be used to estimate **precipitation in areas where ground-based weather radar and other ground observations are not available**. Therefore, satellite precipitation products can contribute to the NMHSs in the Indo-Pacific region in terms of improving their actual and predictive capabilities for precipitation and other issues.
- **Long-term datasets have been constructed from satellite precipitation data** and used to detect extreme weather events based on the analysis of climate values, interannual variations and other variables (in, for example, the WMO SWCEM project). Such satellite data sets will contribute to the ability of the NMHSs in the Indo-Pacific to detect extreme precipitation.

8

- Japan Meteorological Agency (JMA) 's Regional Specialized Meteorological Centre Tokyo for Nowcasting (RSMC) Tokyo for Nowcasting supplies **national meteorological services with graphical nowcasting products to help improve capacity for disaster risk reduction**.
  - Heavy Rainfall Potential (HRP) derived from Himawar-8/9
  - High-resolution Cloud Analysis Information (HCAI) derived from Himawar-8/9

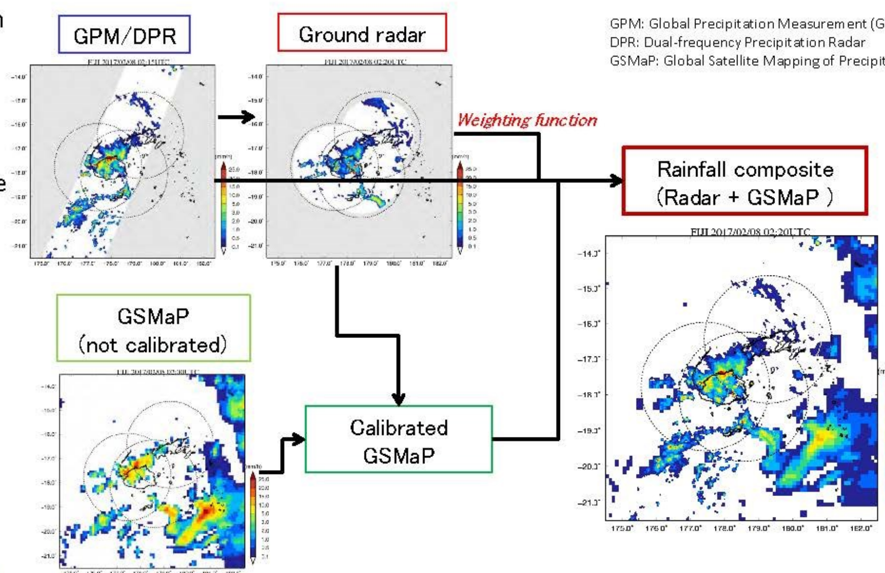
  etc.
- JAXA and JMA have been collaborating toward the utilization of JAXA's satellite precipitation product (GSMaP) data in the issuance of warnings by the **National Meteorological and Hydrological Services** in Asia and Pacific region through the RSMC Tokyo for Nowcasting.



https://www.jma.go.jp/jma/jma-eng/jma-center/nowcasting/

- JAXA studied integration techniques among **satellite precipitation products and ground-based radars** in Fiji.
- These techniques can be helpful for **enhancing the precipitation monitoring**, because it allows seamless monitoring from the ground-based radar's observation range to satellite observation areas.

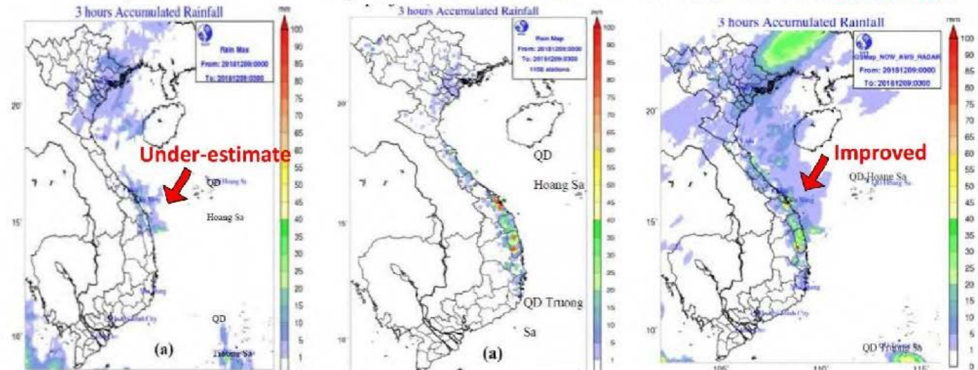
GPM: Global Precipitation Measurement (GPM)
DPR: Dual-frequency Precipitation Radar
GSMaP: Global Satellite Mapping of Precipitation



Kubota et al. (2022)
https://doi.org/10.1109/IGARSS46834.2022.9884078

- **VietNam Meteorological and Hydrological Administration (VNMHA) uses GSMaP data for quantitative precipitation estimation (QPE), leading to improve the under-estimation.**

Precipitation analysis by VNMHA | RainGauge precipitation by automated weather stations | Modified precipitation analysis using AWS and radars with GSMaP data



00-03UTC, December 9, 2018 | **00-03UTC, December 9, 2018** | **00-03UTC, December 9, 2018**

Saito et al. 2020, Heavy rainfall in central Viet Nam in December 2018 and modification of precipitation analysis at VNMHA. VN. J. Hydrometeorol., https://doi.org/10.36335/VNJHM.2020(5).65-79

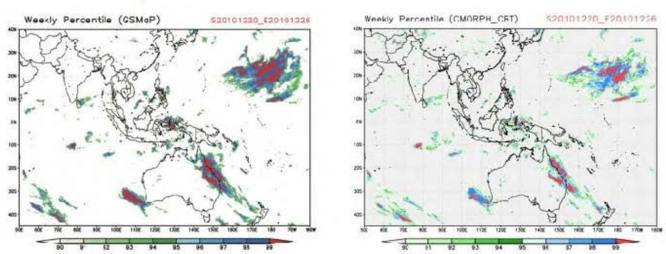
11

Who are the key players and what they are researching?
What are previous recommendations and assessments

- The **JAXA** and the National Oceanic and Atmospheric Administration, Climate Prediction Center (**NOAA/CPC**) have provided **satellite precipitation data** and products such as Global Satellite Mapping of Precipitation (**GSMaP**) and CPC Morphing Technique (**CMORPH**) in the WMO Space- based Weather and Climate Extremes Monitoring (**SWCEM**) project.
  - An "extreme rainfall" event is defined as occurring when mean rainfall for a specified period is higher than a certain percentile threshold, for example in the 90th to 99th percentile.
  - In the project, statistics for daily, pentad and weekly extreme precipitation (90th to 99th percentiles) are provided by the GSMaP and the CMOPRH with about 20-yr accumulation.

JAXA GSMaP (left) and CPC / NOAA CMORPH (right) weekly rainfall percentiles for 20-26 December 2010.

The areas of rainfall above the 95th percentile shown in both the GSMaP and the CMORPH analyses maps corresponded to the "very much above average" rainfall deciles derived from Bureau of Meteorology (BoM) rain gauge observations.



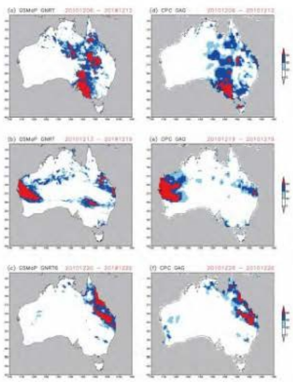
Kuleshov et al. 2020, *WMO Bulletin*.
https://public.wmo.int/en/resources/bulletin/wmo-space-based-weather-and-climate-extremes-monitoring-demonstration-project

12

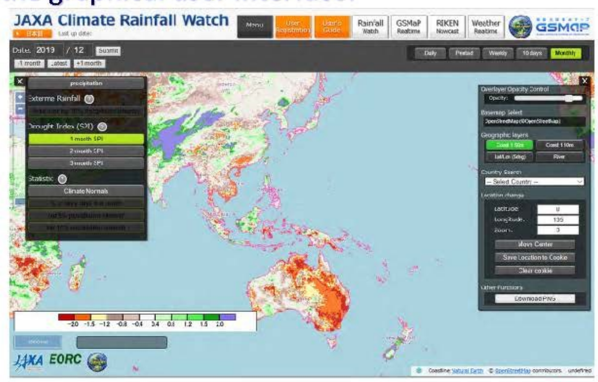
Who are the key players and what they are researching?
What are previous recommendations and assessments

- The JAXA evaluated usefulness of satellite precipitation extremes monitoring in the East Asia and Western Pacific region (Tashima et al. 2020). And the JAXA has operated our homepage "JAXA Climate Rainfall Watch" since Mar. 2020, which shows the heavy rainfall indices with the graphical user interface.

Weekly percentiles over land in Australia. derived from (left) JAXA's GSMaP and (right) NOAA/CPC rain gauges. Areas above R90p are colored.



Tashima et al. (2020, IEEE JSTARS) https://doi.org/10.1109/JSTARS.2020.3014881.



Displaying accumulated rainfall in some temporal scale (daily, pentad, weekly, 10-days and monthly) and 20-year climate normal.

https://sharaku.eorc.jaxa.jp/GSMaP_CLM/index.htm

13

Consider the problem vs. the Quad Members' capabilities or unique impacts on certain Quad countries of given events

Country	Japan	US	India	Australia
Satellite products	• Himawari-8/9 (JMA) • GSMaP (JAXA) • JMA-JAXA Joint product (planned in the RMSC-Tokyo Nowcasting)	• Global Hydro-Estimator (NOAA) • Enterprise Rain Rates (SCaMPR) (NOAA) • Climate Prediction Center (CPC) CMORPH2 (NOAA) • Integrated Multi-satellitE Retrievals for GPM (IMERG) (NASA)	• RAPID (Real-time Analysis of Product and Information Dissemination) • System for Thunderstorm Observation, Prediction and Monitoring (STORM) (IMD) • Rainfall Nowcasting using INSAT-3D/3DR Hydroestimator product (ISRO)	• Satellite Nowcasting System (CPRPh) (BoM) • Blended radar-gauges rainfall (BoM) • BRAIN: Blended real-time Rainfall Analysis (BoM)

- Recommendations based on what we can do now with current capabilities of each of the Quad members;
  - →Construction of a portal site focusing on the precipitation monitoring for the Indo-Pacific regions, with the current tools and products available in the Quad members.
- Aspirational recommendations, e.g., recommendations for things we could do if we had additional resources, etc.
  - → Integration techniques among satellite precipitation products and ground-based instruments for enhancing the precipitation monitoring
  - → Collection of long-term satellite precipitation products in the Quad members, and detection of extreme precipitation using them.

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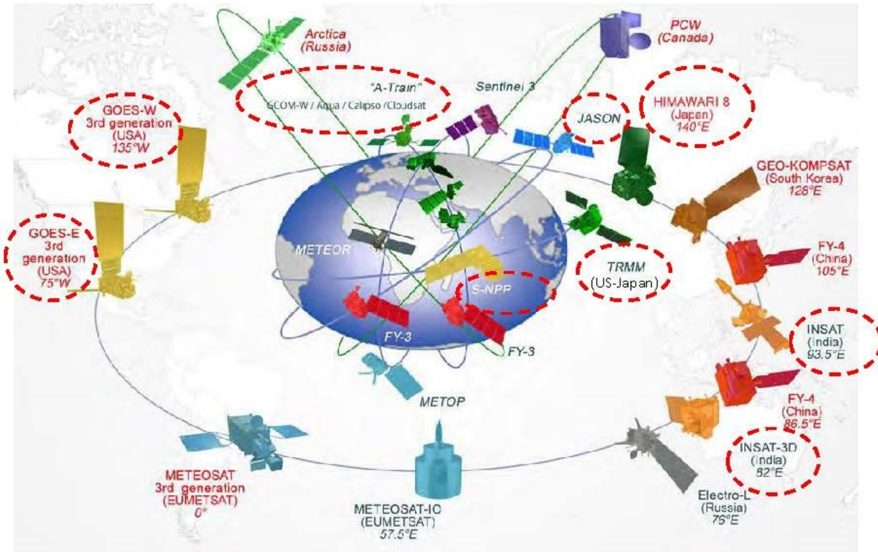
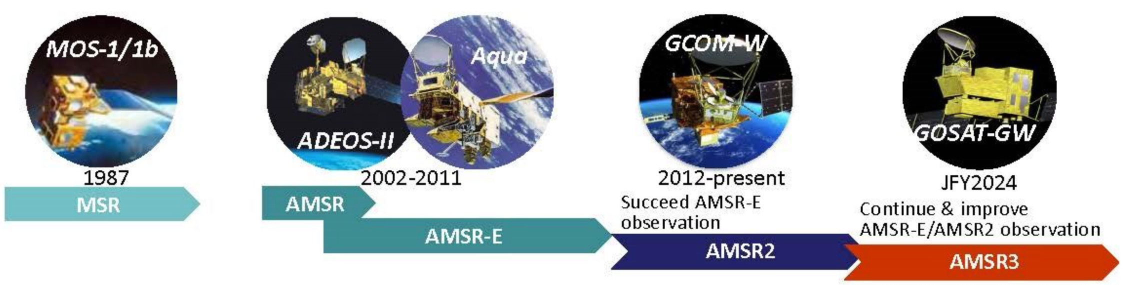
Dashed circles:
Satellite missions by the Quad members listed in the WMO illustration.
(not cover all satellite missions)

https://community.wmo.int/activity-areas/wmo-space-programme-wsp/global-planning



JAXA

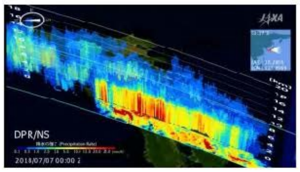
- Space-borne passive microwave radiometer (PMW) has big advantages in observation of water-related parameters inside clouds or in sea and land surface through clouds, and the PMW has been used in precipitation retrievals.
- JAXA has developed and operated a series of passive microwave imager, called the Advanced Microwave Scanning Radiometer (AMSR) series. The AMSR series has a ~2m diameter size real aperture antenna that enables observation with high-spatial resolution among the previous passive microwave imagers.



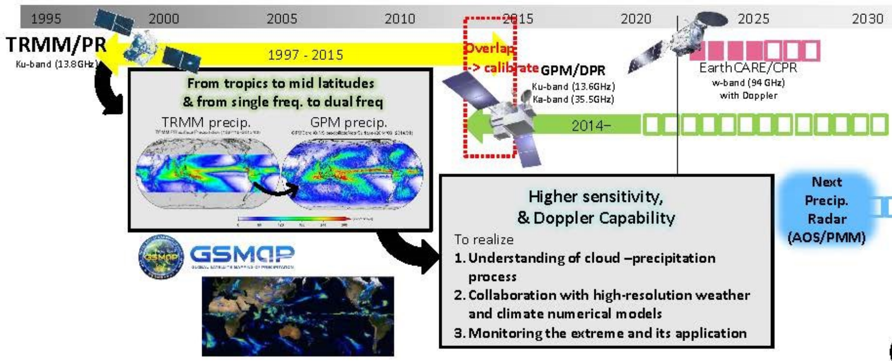
Review current tools and products available and relevant experience and applicability in the Indo-Pacific Region

JAXA

- Spaceborne precipitation radar can provide unique information such as 3-D precipitation measurement. JAXA has large heritage of the TRMM/PR and GPM/DPR, and the data record of spaceborne precipitation radars is more than 20 years.
- JAXA is planning the Precipitation Measuring Mission (PMM) for the Spacecraft carrying the Ku-band Doppler Precipitation Radar, with participation of NASA's AOS constellation.
  - Our targets for the next generation precipitation radar will be Doppler Observations, Higher sensitivity measurements with scanning capability.



GPM/DPR 3D precipitation on 00UTC 7th July 2018: heavy rainfall in July 2018, causing serious damage in western part of Japan.



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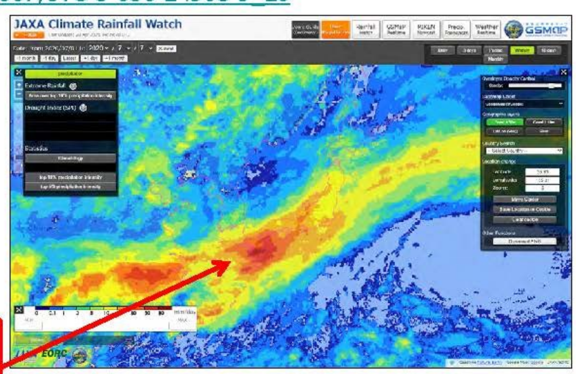
Review current tools and products available and relevant experience and applicability in the Indo-Pacific Region

JAXA

- Global Satellite Mapping of Precipitation (GSMaP) is the Japanese GPM product, and a multi-satellite precipitation product from a blended Passive Microwave radiometer(PMW)-IR algorithm.
  - A review paper of GPM-GSMaP V03 & V04 was published: Kubota et al. (2020). https://doi.org/10.1007/978-3-030-24568-9_20



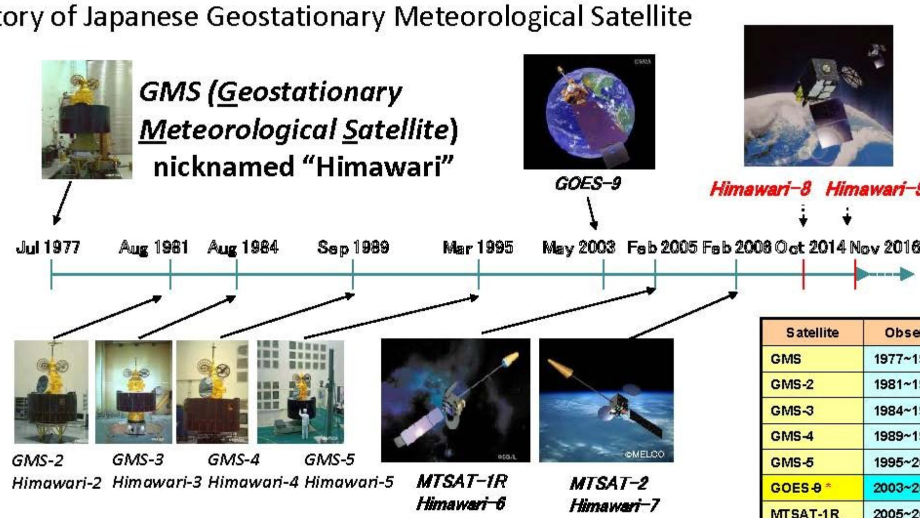
Extreme heavy rainfall in Kyushu, Japan for weekly precipitation (July 1-7, 2020)

- Graphical User Interface of the "JAXA Climate Rainfall Watch" website (https://sharaku.eorc.jaxa.jp/GSMaP_CLM/)
- Displaying accumulated rainfall in some temporal scale (daily, pentad, weekly, 10-days and monthly), indices related to extreme heavy rainfall and drought.

18

JMA

- History of Japanese Geostationary Meteorological Satellite



Satellite	Observation period
GMS	1977~1981
GMS-2	1981~1984
GMS-3	1984~1989
GMS-4	1989~1995
GMS-5	1995~2003
GOES-9 *	2003~2005 *
MTSAT-1R	2005~2010
MTSAT-2	2010~2015
Himawari-8	2015~2022
Himawari-9	2022~2029

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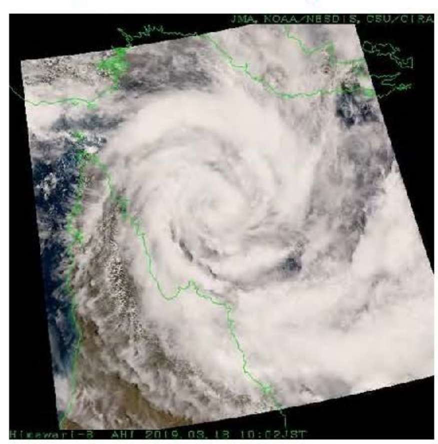
Review current tools and products available and relevant experience
and applicability in the Indo-Pacific Region

JMA

- HimawariRequest was started from January 2018 in cooperation with Bureau of Meteorology (BoM), Australia.
- International service for NMHSs in Himawari-8/-9 coverage area to request Target Area observation (***1,000 x 1,000 km area every 2.5 minutes***).
- JMA expects this service to support ***disaster risk reduction activities in the Asia Oceania*** region.
- Status as of 11 Nov. 2022
  - Registration: **22** NMHSs
  - **148** requests for TC, volcanic eruption, wild fires, etc.



HimawariRequest from BoM
on 13-19 Mar. 2019

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Japan

- JAXA's Space-borne passive microwave radiometers (AMSR Series)
- JAXA's Space-borne precipitation radars (TRMM/PR, GPM/DPR, AOS/PMM)
- Global Satellite Mapping of Precipitation (GSMaP)
  - JAXA Global Rainfall Watch: https://sharaku.eorc.jaxa.jp/GSMaP/
- JMA Himawari 8/9: https://www.data.jma.go.jp/mscweb/en/index.html
  - ✓ HimawariRequest
  - ✓ Products
    - Heavy Rainfall Potential (HRP)
    - High-resolution Cloud Analysis Information (HCAI)
- RSMC Tokyo for Nowcasting: https://www.jma.go.jp/jma/jma-eng/jma-center/nowcasting/

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Review current tools and products available and relevant experience
and applicability in the Indo-Pacific Region

NOAA

- Global Hydro-Estimator (to be replaced by Enterprise rain rates in 2023)--global estimates of instantaneous rain rate / accumulations of 1-7 days on a 4-km (0.02 deg) lat / lon grid with a latency of < 1 hour
- Global Hydro-Estimator: https://www.ospo.noaa.gov/Products/atmosphere/ghe/index.html
- Enterprise Rain Rates (SCaMPR): https://www.star.nesdis.noaa.gov/smcd/emb/ff/SCaMPR.php
- Climate Prediction Center (CPC) CMORPH2: more accurate estimates (they directly use microwave data) but with significantly longer latency: https://rammb.cira.colostate.edu/training/visit/quick_guides/CMORPH2_Quick_Guide_v1.pdf
- Gridded quantitative precipitation forecasts from the NWS Weather Prediction Center: https://www.wpc.ncep.noaa.gov/#page=qpf
- Excessive Rainfall Outlooks from the NWS Weather Prediction Center: https://www.wpc.ncep.noaa.gov/#page=ero
  - (these forecasts are initial guidance to be used by the individual NWS Weather Forecast Offices to determine whether to set up flash flood watches and which areas to focus on).

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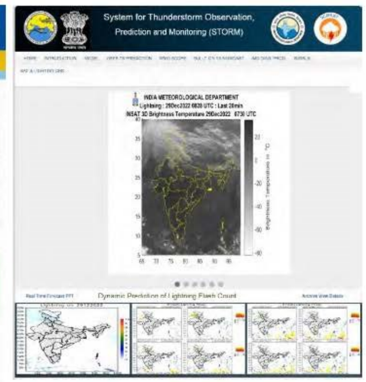
Review current tools and products available and relevant experience and applicability in the Indo-Pacific Region

IMD/MoES, India

- RAPID (Real-time Analysis of Product and Information Dissemination): https://rapid.imd.gov.in/r2v/
- Quantitative Precipitation Forecast (Sub-basin scale for India): https://mausam.imd.gov.in/responsive/quantPrecipForecast.php
- Nowcast (Districtwise/Stationwise for India): https://mausam.imd.gov.in/
- Warnings (Sub-divisionwise/Districtwise for India): https://mausam.imd.gov.in/
- Thunderstorm prediction (India): https://srf.tropmet.res.in/srf/ts_prediction_system/index.php
- Flash Flood Warning bulletins (India/South Asia): https://mausam.imd.gov.in/responsive/flashFloodBulletin.php

https://rapid.imd.gov.in/r2v/

https://mausam.imd.gov.in/

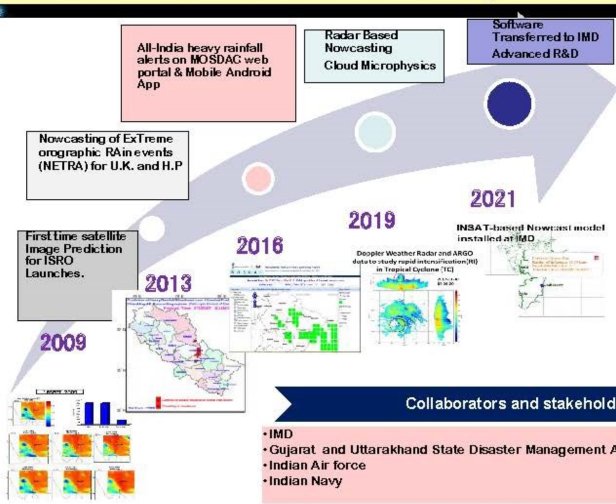


https://srf.tropmet.res.in/srf/ts_prediction_system/index.php

23

Evolution of Satellite based Heavy Rainfall prediction (SAC, ISRO, INDIA)

ISRO



MAJOR FUTURE PLANS

METHODS
- BLENDING
- DEEP LEARNING

DATA
- SYNERGISTIC DATA USAGE

PRODUCTS
- LIGHTNING NOWCAST
- THUNDERSTORM ALERT

Collaborators and stakeholders
- IMD
- Gujarat and Uttarakhand State Disaster Management Authority
- Indian Air force
- Indian Navy

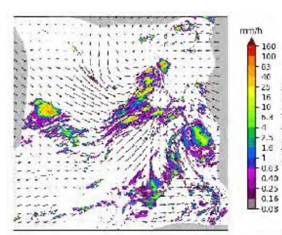
APPLICATIONS	DATA	MODELS	PRODUCTS
• Extreme events • Rescue operations, • Aviation industries • Event Management, • Daily planning	• Satellite data: • INSAT-3D/3DR • GPM –DPR • TRMM,CLOUDSAT • EARTHCARE (future) Radar data	• In-house developed models based on • Machine learning, • Optical Flow, • Probabilistic • Statistical	• All India Heavy Rainfall Alerts • Cloud burst Potential alerts (Uttarakhand Himachal Pradesh)

Future Next generation INSAT satellites will have major applications in nowcasting of severe weather

- *Shukla et al. (2011, DOI:10.1109/LGRS.2010.2060311)*
- *Shukla et al. (2012, DOI:10.1109/JSTARS.2011.2170661)*
- *Shukla et al. (2014., DOI:10.1109/TGRS.2013.2280094)*
- *Shukla et al (2017, DOI: 10.1109/JSTARS.2017.2655105)*

NEW DEVELOPMENTS

Rainfall Nowcasting using INSAT-3D/3DR Hydroestimator product

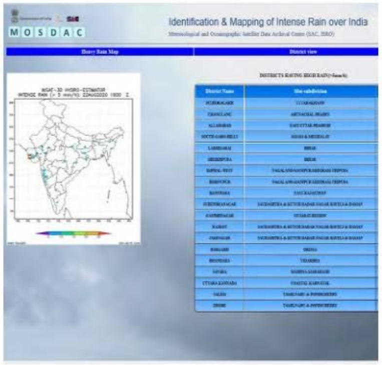


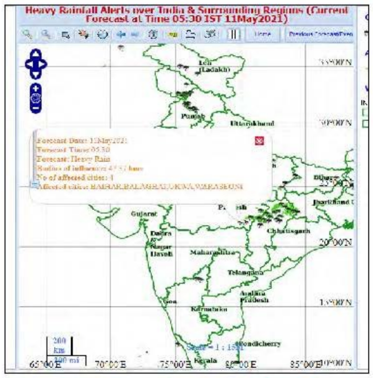
Current Tools and Products Available (ISRO, INDIA)

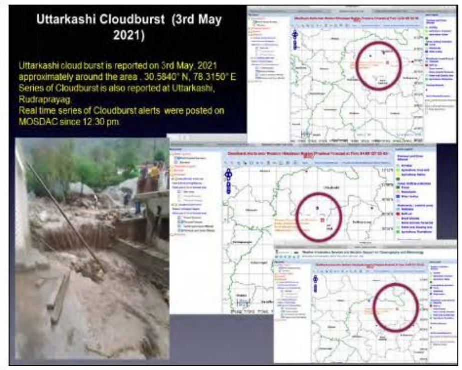
ISRO

REAL TIME SATELLITE BASED HEAVY RAINFALL / CLOUDBURST ALERTS USING SAC NOWCAST MODEL

INSAT-3D/3DR Intense Rain Observation	Alerts over India and surrounding region	Cloudburst Potential Alerts (Western Himalaya)







https://www.mosdac.gov.in/heavyrain/ https://mosdac.gov.in/afs/state

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Current tools and products available (The Bureau, Australia)

BoM

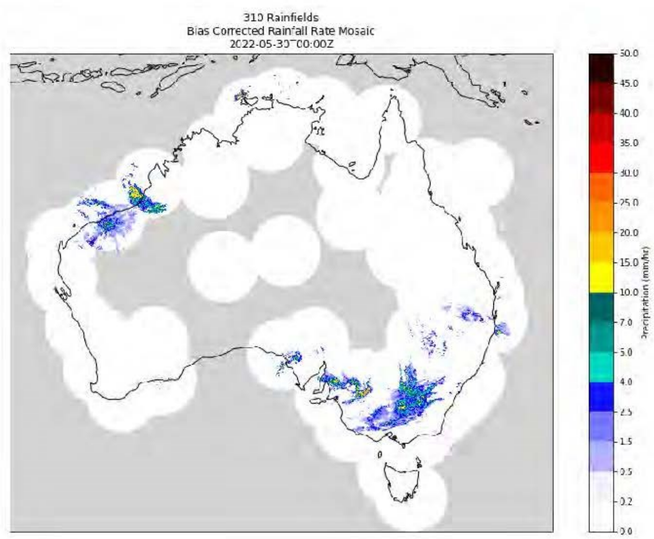
Rainfields (Radar Rainfall)

- 77+ Radar Rainfall Estimates
- Updates every 5 minutes, Spatial Resolution 1km
- Quality controlled volume scans (QC added to the volume scan data)
- Surface radar reflectivity for single and multi-radar domains
- Instantaneous rain rate (used for accumulations and nowcasts)
- Rainfall accumulations (5 min to 24 h)
- Limited to Australia extents

- Blended radar-gauges rainfall grids (reduced extent)
- 2000+ real-time rain gauges
- Real-time verification (using up to 6K daily gauges)

- Website, Mobile App and FTP
- http://reg.bom.gov.au/catalogue/rainfields_user_guide.pdf

- Rainfall Nowcasting 0-90 min (STEPS)



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BoM

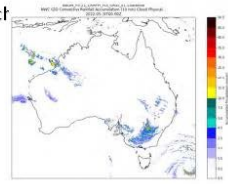
Satellite Nowcasting System

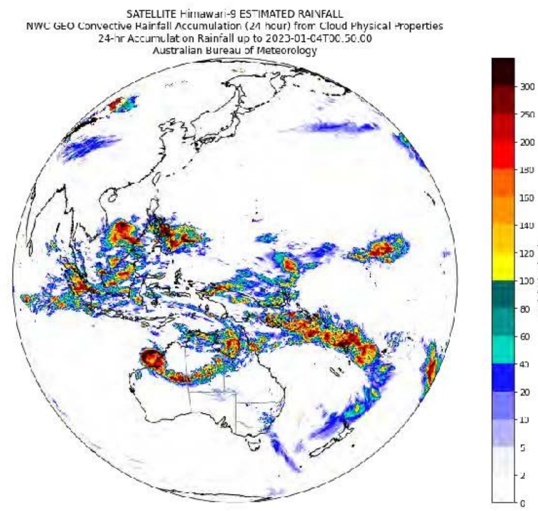
- Himawari 8/9
- EUMETSAT NWC SAF algorithm (link)
- Convective Rainfall Rate based on Cloud Physical Properties (CRRPh)

- Updates every 5 minutes, Spatial Resolution 1km
- Quality controlled (QC added to scan data)
- Instantaneous rain rate (used for accumulations)
- Rainfall accumulations (10 min, 1hr, 24hr)
- Uses lightning strikes information

- Real-time verification (against gauges and radar)

- Full disk coverage
- Special subset to matc… …jection





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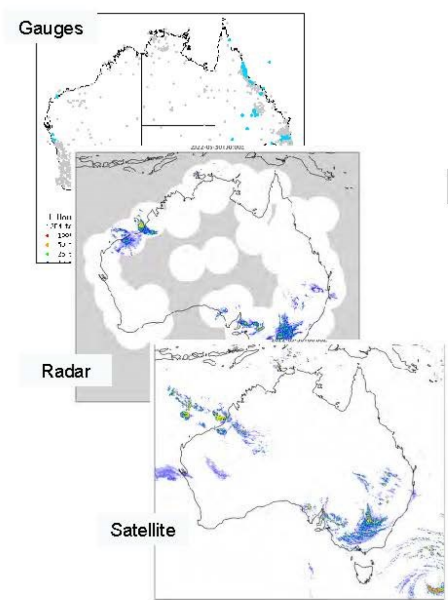
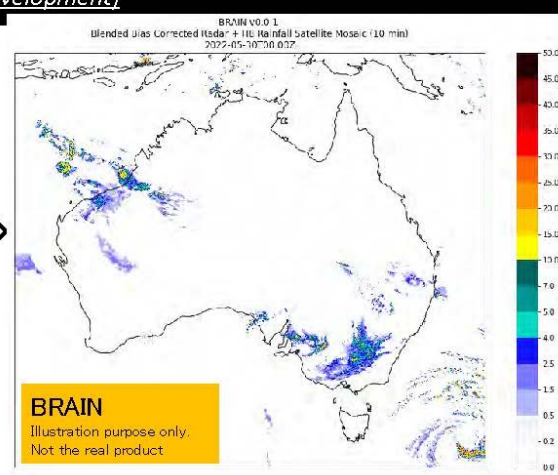
BoM





- Blending Radar and Satellite Rainfall estimates in real time
- First Version: Rainfall accumulations (1hr) during 2024
- Later: sub-hourly Rainfall accumulations (10-15min) by 2025
- Real-time verification
- To be based on https://doi.org/10.4225/08/594eb78c96025

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Explore how we can tie into existing mandates and activities from relevant multilateral organizations (e.g., UN, WMO, GEO, CEOS)

- The following existing mandates and activities can be tied.
  - World Meteorological Organization (WMO)
    - The WMO promoted the Space-based Weather and Climate Extremes Monitoring (SWCEM) project. In the SWCEM, the JAXA and the NOAA/CPC have provided the satellite precipitation data, and the WMO Steering Group for the SWCEM has been chaired by Dr. Yuriy Kuleshov (BoM).
  - United Nations (UN) Economic and Social Commission for Asia and the Pacific (ESCAP)
    - The ESCAP serves as In Asia and Pacific regions, UNESCAP is working with member States to enhance capacities of developing countries in Pacific regions to better use space-based observations and GIS for strengthening disaster risk modeling, assessment, monitoring and early warning.
    - The ESCAP/WMO Typhoon Committee has already a long history of more than fifty years and has been an example followed by countries of other regions affected by tropical cyclones.

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Explore how we can tie into existing mandates and activities from relevant multilateral organizations (e.g., UN, WMO, GEO, CEOS)

- The following existing mandates and activities can be tied.
  - AOGEO (Asia-Oceania Group on Earth Observations)
    - Synergies can be expected with GEO's Regional Initiative in Asia-Oceania (AOGEO), which promotes regional cooperation on Earth observations in support of sustainable development.
  - International Precipitation Working Group (IPWG) of the Coordination Group for Meteorological Satellites (CGMS)
    - The IPWG provides a forum for operational and research users of satellite precipitation measurements to exchange information on methods for measuring precipitation and the impact of space borne precipitation measurements in numerical weather and hydrometeorological prediction and climate studies.
  - Precipitation Virtual Constellation (P-VC) of Committee on Earth Observation Satellites (CEOS)
    - The P-VC of the CEOS exists to sustain and enhance a systematic capability to observe and measure global precipitation.

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Pre-defined Questions in Session 2

1. Based upon the current tools and products available in the Quad members, enhancing the precipitation monitoring can be promoted for the Indo-Pacific regions in some ways (for example, a portal site). What are gaps between the current tools & products and the requirements from users?
2. What are gaps in integrating among satellite precipitation products and ground-based observations?
   - What are experiences in your country?
     - ✓ Issues in real-time data access, …
3. What are gaps in constructing long-term satellite precipitation products?
   - What are experiences in your country?
     - ✓ Issues in calibration, availabilities during old periods, …
4. What are new sensors we can propose specially catering to extreme precipitation events in the Indo-Pacific region ?

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Session 3: Inundation/flooding, coastal erosion and water quality

1. Understanding the Problem: Links between extreme precipitation and inundation, flooding, coastal erosion, and effects on water quality

> "According to the [US] National Oceanic and Atmospheric Administration, 14 weather and climate disasters 32 cost 91 billion USD in 2018 (NOAA NCEI, 2019). Asia Pacific and Oceania has been 38 particularly impacted by typhoon and flooding (China, India, the Philippines) resulting in economic 39 losses of 58 billion USD, 2000–2017, and combination of flooding typhoon and drought totalling 89 40 billion USD in 2018 (inclusive of loss by private insurers and government sponsored programs (Aon 41 Benfield UCL Hazard Research Centre 2019)."
>
> *[p. 15-66, L37-41, IPCC (2021)]*

Changes in extreme precipitation: Recent global analysis of trends in precipitations (Sun et al., 2021; Papalexiou and Montanari, 2019) show that in general extreme precipitation is increasing in magnitude, duration, and frequency of events. Globally, most regions of the world have a larger number of stations with positive trends than negative for frequency and magnitude of events (Papalexiou and Montanari, 2019). For countries in the Quadrilateral Security Dialogue (Quad), these recent studies can be examined in detail for their regional outcomes, except for India which appears has a data gap in many of these global studies (Sun et al., 2021; Papalexiou and Montanari, 2019).

In recent studies that used gauged observations, regions containing the Quad countries show that extreme precipitation has increased in many more locations than where it has decreased (Sun et al., 2021). A notable divergence from this observation is in southern Australian where a decrease in the magnitude and frequency of extreme precipitation has been observed (Sun et al., 2021; Papalexiou and Montanari, 2019). Rainfall has also decreased in parts of the Pacific islands poleward of 20° latitude in both hemispheres (eastern Pacific and southern Pacific subtropics) (IPCC, 2021). This drying trend will continue in the coming decades, except in parts of western and equatorial Pacific (IPCC, 2021). In the Western Indian Ocean islands, declining trends in rainfall have also been observed over the past 50-60 years (IPCC, 2021).

For future climate, there high confidence (IPCC, 2021) that heavy rainfall events will increase in the western tropical Pacific at 2°C global warming and above; however, higher evapotranspiration under a warming climate either amplifies or partially offsets respectively the effect of decreases or increases in rainfall resulting in increased aridity in parts of the Pacific. This offset is reported to have medium confidence at 2°C global warming and above (IPCC, 2021). In the United States, extreme precipitation is expected to increase across the country with the largest increases expected in the northeast United States (USGCRP, 2017).

Linking extreme precipitation to extreme flooding: While extreme precipitation has generally increased at the global scale, changes to floods has not been consistently observed (Sharma et al., 2018). In fact, IPCC (2014) states that there "low confidence that anthropogenic climate change has affected the frequency and magnitude of fluvial floods on a global scale" and that because of human activities on catchments, the attribution of detected changes in floods to climate change is much more difficult. In the United States, the National Climate Assessment (USGCRP, 2017) recently synthesized flood change studies and states with medium confidence that "detectable changes in some classes of flood frequency have occurred in parts of the United States and are a mix of increases and decreases….formal attribution approaches have not established a significant connection of increased riverine flooding to human-induced climate change, and the timing of any emergence of a future detectable anthropogenic change in flooding is unclear."

Extreme precipitation and inundation: For this topic, we use the definition of 'inundation' proposed by Flick et al. (2012) to describe an area that was once dry and is now permanently submerged or drowned. Inundation can arise from long-duration inland extreme precipitation events, such as atmospheric rivers or long-duration hurricane events. Sweet et al. (2022) point to increases in coastal inundation due to storm surge but also from global and regional sea level rise, resulting in increased so-called "sunny-day" flooding.

2. **Member Capabilities: Existing tools and products**

The following is a compilation of potential tools and products that could be leveraged by the Quad to address identified gaps. It would be one goal of the session to discuss the potential of these tools and products, as well as identify other potential capabilities.

Southeast Asia Flash Flood Guidance System (SeAFFGS): The SeAFFGS will improve early warnings for a major natural hazard, which accounts for a significant portion of the lives lost and property damages due to flooding in the region. SeAFFGS has been developed under the project "Building Resilience to High-Impact Hydrometeorological Events through Strengthening Multi-Hazard Early Warning Systems (MHEWS) in Small Island Developing States (SIDS) and Southeast Asia (SEA)", which is funded by the Government of Canada (Environment and Climate Change Canada – ECCC), and implemented by the World Meteorological Organization and the Hydrologic Research Center (HRC), while National Oceanic and Atmospheric Administration (NOAA) is a satellite data provider into the System.

Wave-driven Flood-forecasting on Reef-lined Coasts Early warning system (WaveFoRCE): *WaveFoRCE* will provide all communities with forecasts of marine flooding, every 200 metres along every coral reef-lined coast in the world. It will also provide historic flood information and the ability to run what-if scenarios that utilize sea level and wave information. With this information, communities can prepare for imminent and future flood events in an informed manner. The Wave-driven Flood-forecasting on Reef-lined Coasts Early warning system (WaveFoRCE) project is a joint initiative of the National Oceanic and Atmospheric Administration (NOAA), the United States Geological Survey (USGS) and Deltares, and includes a number of other organisations such as GEO Blue Planet, ReefSense, the Commonwealth Science and Industrial Research Organisation (CSIRO) and the Pacific Community (SPC).

ASEAN Risk Monitor and Disaster Management Review (ARMOR), June 2022 Report, Leveraging Artificial Intelligence for Enhanced Flood Emergency Response, *Amidst COVID-19 Pandemic (AHA Centre, 2022):* This report illustrates how the UN Satellite Centre's (UNOSAT) FloodAI programme can provide up-to-date imagery of flood-prone areas. This would allow decision makers to optimise the response to flooding in a much shorter timeframe than through human-based analysis and reduce the loss of life and mitigating damage.

Kumamoto Initiative for Water (4th Asia-Pacific Water Summit):

The Kumamoto Initiative, announced as Japan's contribution to water issues at the 4th Asia-Pacific Water Summit attended by 49 countries in the Asia-Pacific region, declares Japan's contribution to filling gaps of observation data and to governance (systems, human resources, and capacity) as part of its efforts to promote both climate change adaptation and mitigation measures. Under this initiative, Japan is contributing to the Asia-Pacific region by providing satellite data (JMA geostationary meteorological satellite (Himawari), the Advanced Land Observing Satellite 2 (ALOS-2), the Global Precipitation Measurement (GPM) core satellite, etc.) and hydrological simulation data and technologies (Flood Analysis System (IFAS), Global Flood Alert System (GFAS), Today's Earth (Global Terrestrial Hydrological Simulation System), etc.) which can be utilized for the water-related risk monitoring.

3. Gaps and Needs

There are several identified knowledge gaps that currently exist in these topical areas. Another goal of the session would be to discuss how to address existing gaps or identify other gaps.

Gap -- Attribution of precipitation extremes: The IPCC (2021) provides a summary table (TS.5) of confidence for a set of climatic impacts and the potential drivers of these impacts. However, regions in the Quad have medium to low confidence in the observed and future direction of change, and none have high or medium confidence in the attribution evidence for these changes. Sun et al. (2021) point out that the causes of precipitation variation not well understood due to a lack of understanding related to the association between large-scale circulation anomalies, aerosols, and changes in non-greenhouse gases. Further investigation is needed. These factors may be contributing to the weakening of extreme precipitation in the western US and parts of Australia. In northern China, Sun et al. (2021) reference that the decline in Asian monsoonal circulation strength relation to aerosols is a potential explanation for this decrease. Atmospheric circulation changes and low-frequency modes of variability may potentially explain changes in Australian precipitation (Sun et al., 2021).

Gap -- Data needs to assess precipitation extremes: It is important to note that uncertainties in precipitation extremes is higher where there is poor coverage, including Australasia due to sparse station coverage and non-representative spatial sampling (Sun et al., 2021). Sun et al. (2021) also notes that regional-scale detection of trends becomes more difficult due to signal-to-noise issues, although there is confidence in the observation that there is an intensification of extreme precipitation in the US and Asia and a decreasing trend in extreme precipitation in southern Australia. According to Sun et al. (2021), the "vast majority" of stations are in midlatitudes of Northern Hemisphere; whereas the tropical, subtropical, and midlatitude southern hemisphere are less well sampled. Sun et al. (2021) suggest an "urgent need" to improve data collection in these areas.

Other challenges exist with observation networks and precipitation products. Precipitation measurements taken at different locations are difficult to homogenize due to spatial and temporal variability (Sun et al., 2021). Furthermore, gridded products that assimilate radar satellite and observations use interpolation and, therefore, may exhibit bias in variance depending on the approaches used to infill records (Papalexiou and Montanari, 2019). Some precipitation products are typically too short in length to perform long-term trend analysis (Papalexiou and Montanari, 2019).

The IPCC (2021) specifically comments on Small Island regions in the Pacific, which have precipitation trends that vary spatially and seasonally. The IPCC (2021) notes that the climate of Small Islands has and will continue to change in diverse ways, making the construction of climate information for Small Islands challenging due to lack of observations and high-resolution climate projections, as well as the representation and understanding of key modes of variability and their interplay with trends.

Gap – Resolving increasing precipitation but multi-directional changes to floods: Sharma et al. (2018) hypothesize the potential knowledge gaps that contribute to the apparent mismatch between generally increases in precipitation, but both increases and decreases in floods worldwide. They (Sharma et al., 2018) outline specific areas of research focus that could resolve these questions, including: (a) increased focus on the changes to antecedent conditions and their relation between precipitation events and flooding; (b) changes to the proportion and persistence of storms that are generated by different causal mechanisms, (c) how catchment size and shape affect attenuation of the precipitation signal, (d) the role of snow and snow volume in flood generation, and (e) the role of land cover in flooding, and its interaction with other climatic factors.

Gap - Extreme precipitation and inundation: Gaps remain related to the mapping of current and future flooded (dry areas which become temporarily wet according to Flick et al. (2012)) and inundated areas.

4. Leveraging existing mandates and working groups

Lastly, this section compiles a list of potential existing mandates and working groups that may be potential collaborators or partners in addressing identified gaps and/or have additional capabilities. Another goal of the session would be to discuss how to leverage other existing mandates and working groups and/or how to engage those entities below.

Asia-Pacific Regional Space Agency Forum (APRSAF) Satellite Applications for Societal Benefit Working Group: This working group aims to promote and facilitate the utilization of space-based systems including Earth observation satellites and navigation satellites combined with ground-based information, to contribute to global agendas by solving a broad range of common social issues in the region, especially in the field of disaster management, climate change matters, and environmental concerns. The Working Group leverages two existing initiatives - the Sentinel-Asia and Space Applications For Environment: SAFE - and will explore potential application in other new domains for societal benefit.

GEO Blue Planet: The GEO Blue Planet functions as a network of ocean and coastal-observers, social scientists and end-user representatives from a variety of stakeholder groups, including international and regional organizations, NGOs, national institutes, universities and government agencies.

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Session 4: Transboundary Issues

Ocean/atmosphere changes, numerical weather prediction, cascading hazards/environmental impacts/phenomena

Overview of Transboundary Processes

Transboundary processes may be considered as events or impacts that cross geographical boundaries or as interactions/phenomena/processes that cross ocean/atmosphere/land surface boundaries.

- Geographical: Across national boundaries and how satellite observations could be used to alleviate them (e.g., water usage and water law/regulations of large rivers or water bodies from one country to another), and
- Processes: Across meteorological and physical boundaries from the earth systems science perspective where there is a relationship between atmospheric dynamics and land surface processes or ocean dynamics. In this direction, satellite observations coupled with in situ data collection would be used to demonstrate if one system or phenomenon affects another.

The main goals of this session are to explore how observations from the space segment are, or could be, used to improve estimates of extreme precipitation resulting from ocean/atmosphere/land surface interactions, and identify cascading phenomena that include links to extreme precipitation. Understanding of these interactions can result in (targeting of) improvements in coupled ocean/atmosphere models (Figure 1) and or seasonal prediction models since some of the phenomena are at longer time scales. Such improvements could contribute to an improved understanding of the impacts of extreme precipitation across geographical boundaries. As such, this session should be considered as focussing on processes.

Processes and their effects may be linked. For example, the cascading phenomena for an Australian case that has interactions across multiple temporal and spatial scales and multiple meteorological boundaries: periods of drought that enhance dust storms; periods of extreme heat that enhance bushfires; extended (or repeated) La Niña periods where heavy rain can saturate the land surface and result in (repeated) widespread flooding.

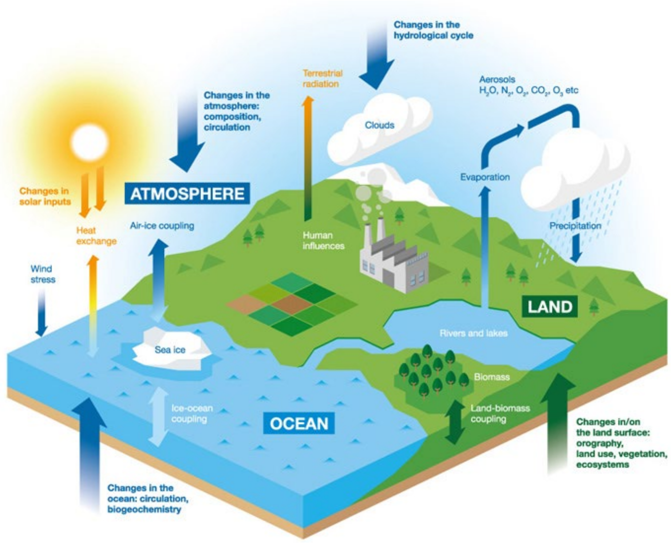

Figure 1. Schematic of how the ocean, atmosphere and land are coupled (ECMWF, 2018)

Other examples are the use of Satellite Precipitation Estimates to assess climate variability in the Indo – Pacific region, such as variability of extreme precipitation in South America (Giraldo et al 2022), changes in Tropical Cyclone rain rates over the western North Pacific (Tu et al, 2022), the Impact of El-Niño and La-Niña on the Pre-Monsoon Convective Systems over Eastern India (Sahu et al, 2022), Identification of Sensitive Vegetation Regions in Indonesia (Arjasakusuma et al, 2018) and global connections between El Niño and landslides impacts (Emberson, et al 2021, Figure 2), among many others.

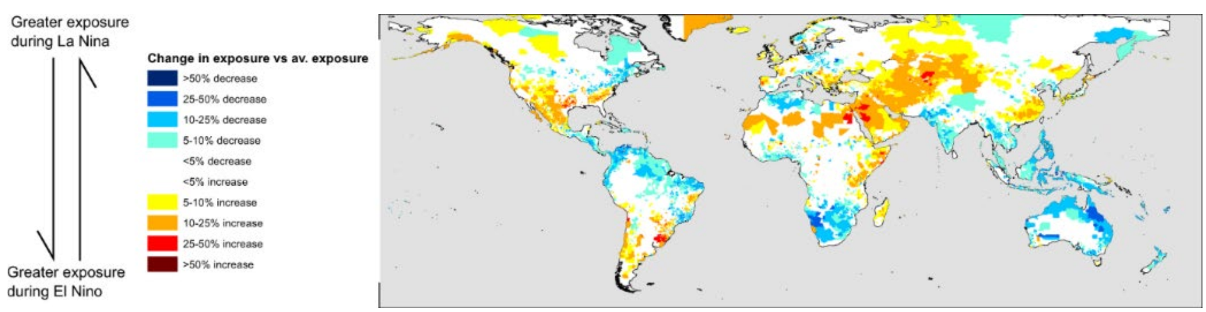

Figure 2. Relative change in exposure for a unit change in Multi-variate El Nino Southern Oscillation (ENSO) index value (Emberson, 2021)

Atmospheric rivers (narrow, elongated corridors of concentrated moisture transport) that interact with topography and can deposit significant amounts of precipitation in relatively short periods of time leading to flooding and mudslides (GHRC). Atmospheric rivers can be observed using satellites (Guan, 2015) and are particularly important for rainfall over East Asia and South Asia: Liang (2021) shows that up to 68% of the extreme precipitation amount over East Asia is connected to atmospheric rivers; Park (2021) perform similar studies over eastern China, Korea and Japan. Harada (2017) and Guo (2021) demonstrate that atmospheric rivers are associated with the Boreal Summer Intra-Seasonal Oscillation (BSISO).

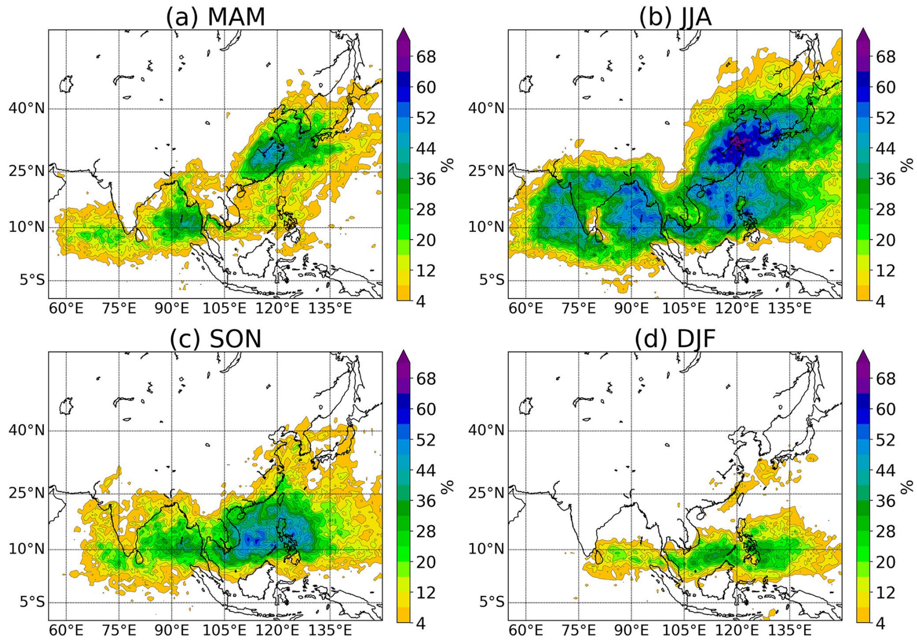

Figure 3. figure showing contribution of Atmospheric Rivers for different seasons to the seasonal accumulation of extreme precipitation (6-hourly precipitation >99th percentile maximum values): (a) MAM, (b) JJA, (c) SON, (d) DJF (Liang, 2020)

Research

There are many aspects to research on extreme precipitation related to transboundary processes. Much of the research focuses on the processes and their affects. This research is generally conducted by those affected by the process, or those wishing

Other aspects of research include satellite missions and sensors, algorithm development, validation campaigns, field campaigns, data assimilation for numerical weather models, and seasonal prediction. Much of this research is driven by national meteorological agencies and their downstream consumers (e.g. Governments, emergency management etc).

Regional monitoring of extreme precipitation

Monitoring of climate extremes, and changes in those extremes, at regional and global scale using conventional instrumental data has been a major challenge. Global data sets used in assessment of these extremes typically have good coverage in most of North America and Europe, Russia, east Asia, Australia and New Zealand, but very limited coverage elsewhere.

Remotely sensed data sets have the potential to provide alternative forms of information for use in regional and global analyses. There are a number of satellite-based data sets for monitoring of precipitation at multi-day and monthly timescales, and a WMO pilot project that uses satellite data to monitor monthly and multi-month precipitation anomalies in the Pacific and southeast Asia, but applications to extremes are more limited to date.

For this work to advance, a number of open issues would need to be addressed, including potential biases of individual datasets and their capacity to resolve extremes on smaller spatial scales.

Space-based estimates of precipitation

Sensors / Missions / Products

Session 2 of this Workshop provides a detailed overview of available sensors, missions and products that contribute to our understanding of extreme precipitation. The satellite constellation referred to in Session 2 is shown in Figure 4, while Table 1 provides an overview of the precipitation products available to each Quad nation.

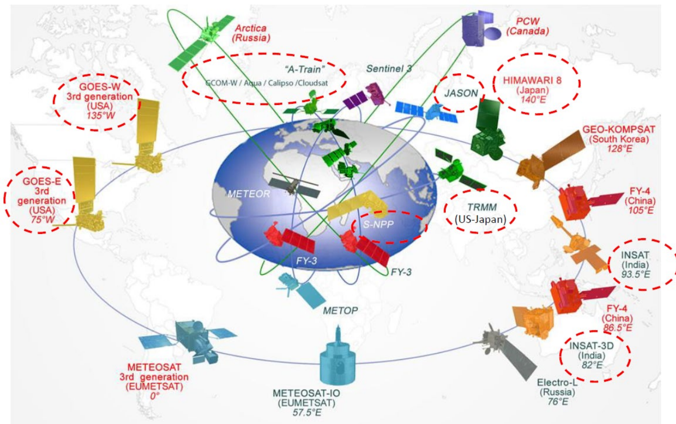

Figure 4. Major satellites that contribute to WMO Global Observing System (WMO). Quad missions highlighted.

Table 1. Overview of some derived precipitation products by Quad members.

Japan	US	India	Australia
• Himawari-8/9 (JMA) • GSMaP (JAXA) • JMA-JAXA Joint product (planned in the RMSC-Tokyo Nowcasting)	• Global Hydro-Estimator (NOAA) • Enterprise Rain Rates (SCaMPR) (NOAA) • Climate Prediction Center (CPC) CMORPH2 (NOAA) • Integrated Multi-satellitE Retrievals for GPM (IMERG) (NASA)	• RAPID (Real-time Analysis of Product and Information Dissemination) • System for Thunderstorm Observation, Prediction and Monitoring (STORM) (IMD) • Rainfall Nowcasting using INSAT-3D/3DR Hydroestimator product (ISRO)	• Satellite Nowcasting System (CPRPh) (BoM) • Blended radar-gauges rainfall (BoM) • BRAIN: Blended real-time Rainfall Analysis (BoM)

Precipitation Algorithms

The CGMS/WMO International Precipitation Working Group (IPWG) focuses the scientific community on operational and research satellite based quantitative precipitation measurement issues and challenges. It provides a forum for operational and research users of satellite precipitation measurements to exchange information on methods for measuring precipitation and the impact of space borne precipitation measurements in numerical weather and hydrometeorological prediction and climate studies (IPWG, 2023). IPWG is global in focus but includes contributions from the Indo-Pacific region.

IPWG hosts a Workshop every 1-2 years, providing opportunities for scientists to present on recent scientific advances in precipitation, particularly estimates from the space segment. IPWG members focus on quantitative precipitation algorithms and their validation, providing guidance and recommendations, including on the importance of the measurements and estimation of extreme precipitation.

IPWG provides a mechanism to transfer knowledge of processes that affect precipitation and methods to account for these processes (Figure 5). IPWG is also an important forum to connect researchers to field campaigns that capture observations for processes studies (including transboundary processes).

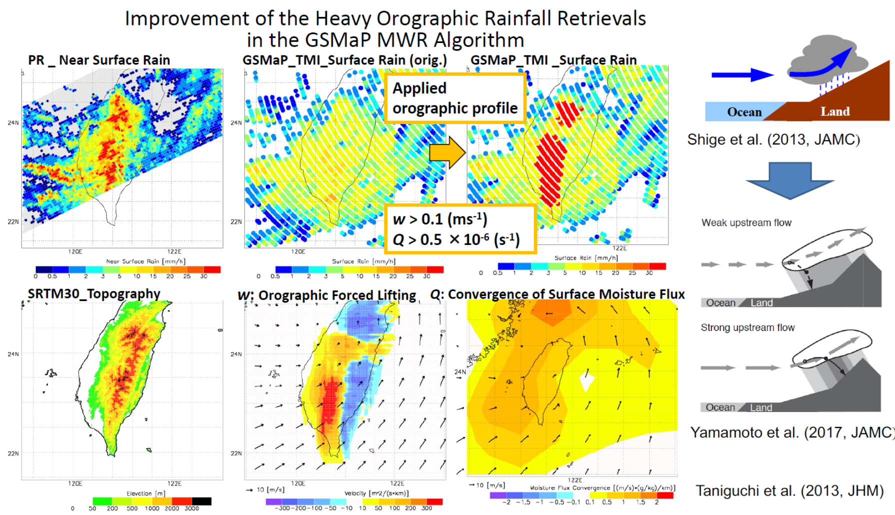

Figure 5. Example of how IPWG can transfer knowledge of algorithm improvements associated with physical/transboundary processes (Shige, 2022)

Observing System Simulation Experiments

An Observing System Simulation Experiments (OSSE) uses computer models to test different designs of the new satellite systems before their instruments are built or deployed, and to compare the performance of the new satellites against current observing platforms. The results can help to guide the design of new instruments and to determine if a new satellite platform will be cost-effective (GMAO, 2022).

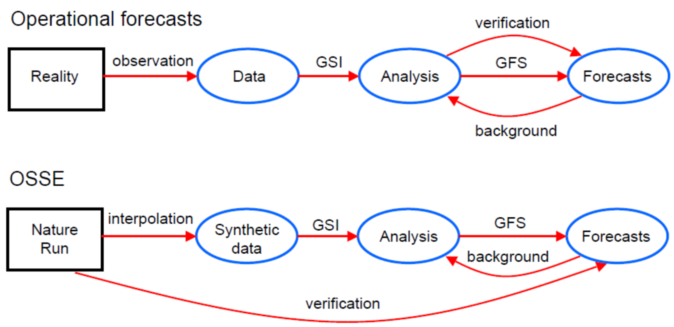

Figure 6. Overview of how Observing System Simulation Experiments work (Prive, 2011), comparing steps in operational forecasts (upper) vs OSSEs (lower).

JMA is conducting OSSEs of a hyperspectral infrared sounder for the Himawari follow-on satellite, and has confirmed that the use of a hyperspectral infrared sounder has improved heavy rain forecasts in NWP (Okamoto, 2020; Owada, 2022; see also Figure 7).

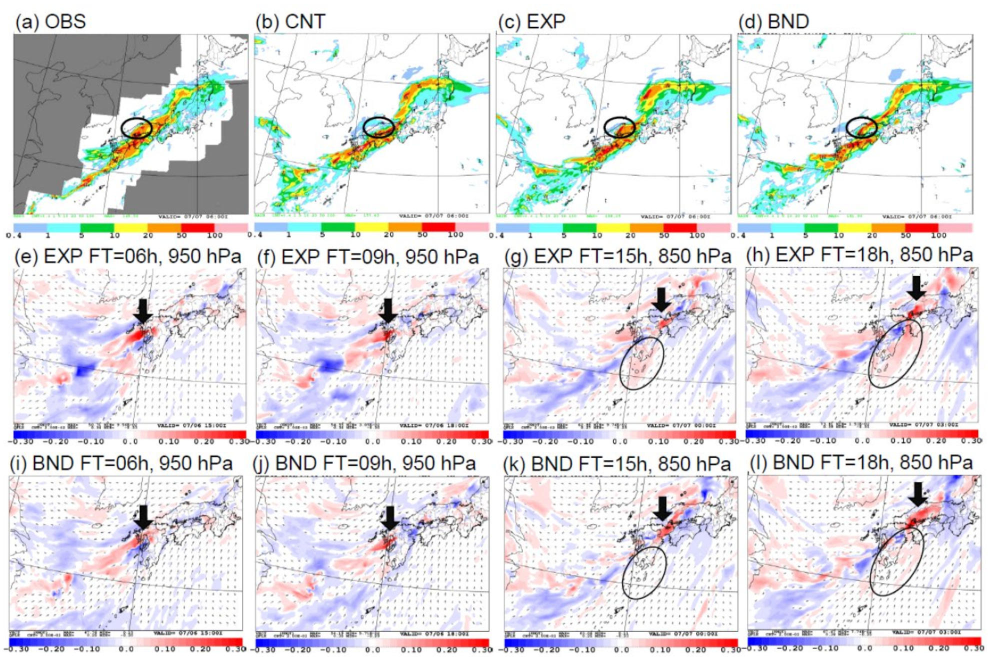

Figure 7. Results of an OSSE demonstrate the impacts of a geostationary hyperspectral infrared sounder on forecasts of precipitation (Okamoto, 2020). OBS=Radar; CNT=operational configuration; EXP=Global CNT+GeoHSS; BND=Regional CNT+GeoHSS. Refer Okamoto (2020) for details.

Observations and Field Campaigns

Field campaigns are important to ground-truth space-based observations, to collect observations that characterise the environment in which space-based observations are made, and to collect observations that are not (currently) possible to collect from space-based sensors.

The mission of the Global Hydrometeorology Resource Centre (GHRC) is to provide a comprehensive active archive of both data and knowledge augmentation services with a focus on hazardous weather, its governing dynamical and physical processes, and associated applications. Within this broad mandate, GHRC focuses on lightning, tropical cyclones and storm-induced hazards through integrated collections of satellite, airborne, and in-situ data sets (GHRC, 2023).

Models and Analyses
It is beyond the scope of this session to describe details of individual models. However, the observations, products, and activities above are supported by numerical models. These models are increasing in complexity (spatial and temporal resolution, data assimilation improvements, convection resolving) and capability in line with the observing system, user demand and computational performance increases.

Advances to both models and observing systems are fundamental to the provision of improved guidance around transboundary processes.

Key Users

World Meteorological Organization
The World Meteorological Organization (WMO) has several regional offices that produce regional climate outlooks. WMO initiated Regional Climate Outlook Forums (Figure 8) bring together national, regional and international climate experts, on an operational basis, to produce regional climate outlooks based on input (e.g. climate predictions) from all participants. The implementation of each forum has been tailored to meet the local conditions but typically includes meetings of experts, formulation or response strategies, training Workshops and outreach sessions to develop effective communications strategies.

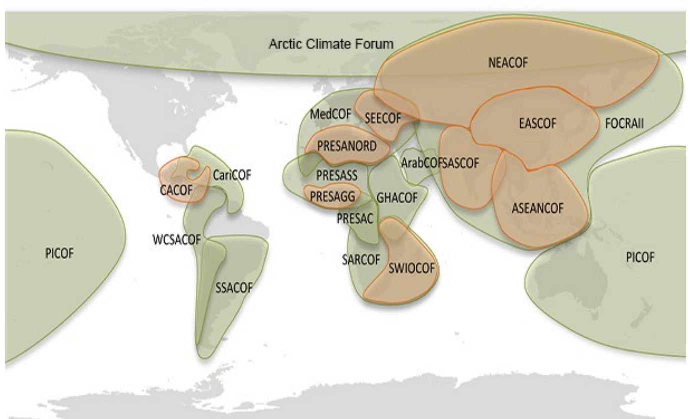

Figure 8.Map indicating the region of coverage of each WMO Regional Climate Outlook Forum. Source WMO

Forums active in the Indo-Pacific include FOCRAII, EASCOF, SASCOF, ASEANCOF (ASMC), and PICOF. Forums meet and distribute outlooks at different frequencies (e.g. AMSC meets twice per year and produces quarterly reports). As noted above, each form focuses on regional transboundary phenomena (but each of the Indo-Pacific forums include discussion of the influence of El Niño/La Niña).

The East Asian winter monsoon can have a significant impact on the weather and climate of the EASCOF region. It can bring clear skies and low humidity to the coast, but also can cause cold and dry conditions that can lead to droughts and crop damage. It also plays a role in the formation of the East Asian fog and haze, which is caused by the combination of dry air, desert dust and pollutants from human activity.

SASCOF and ASEANCOF/ASMC provide climate outlooks heavily influenced by El Niño/La Niña, Indian Ocean Dipole, and monsoon conditions (e.g. Figure 9 and Figure 10). ASMC provide regional fire and haze analyses (Figure 12) and outlooks, which are affected by rainfall. Regular bulletins feature significant weather events and can include information around the performance of forecasts and warnings.

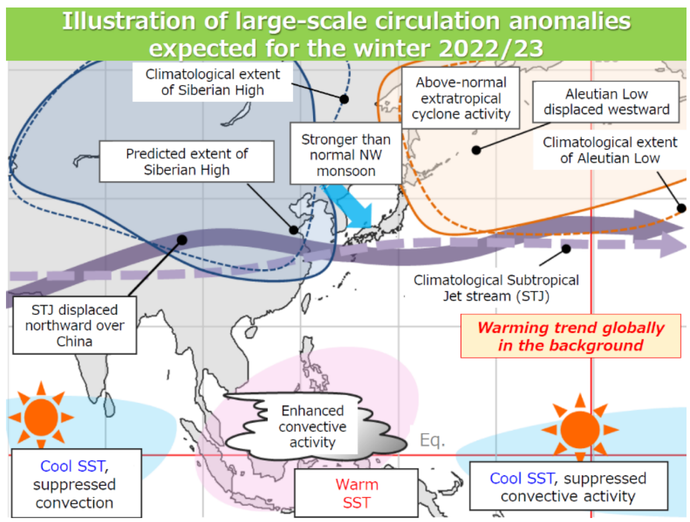

Figure 9. Example of factors affecting seasonal prediction, including factors affecting extreme precipitation, for winter 2022/23 the EASCOF region (Oikawa, 2022).

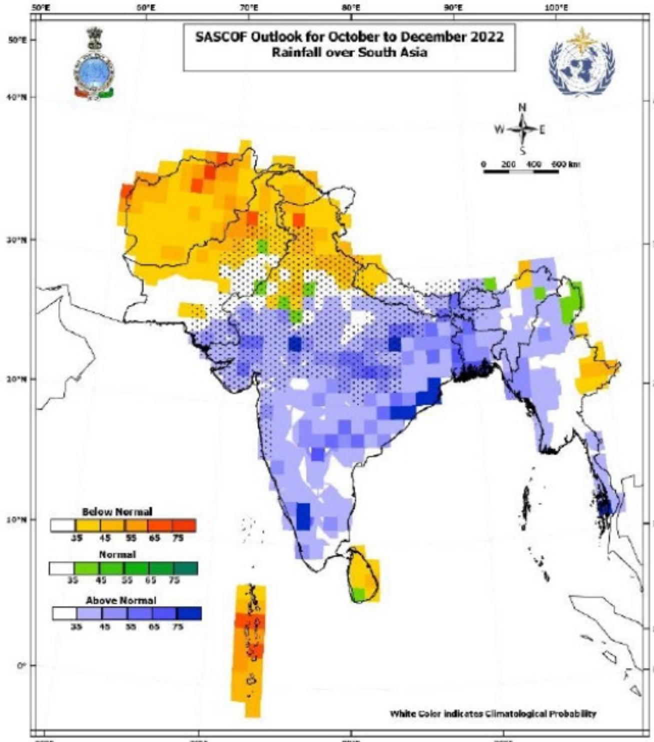

Figure 10. Example SASCOF seasonal outlook map for OND 2022 rainfall over South Asia (SASCOF, 2022)

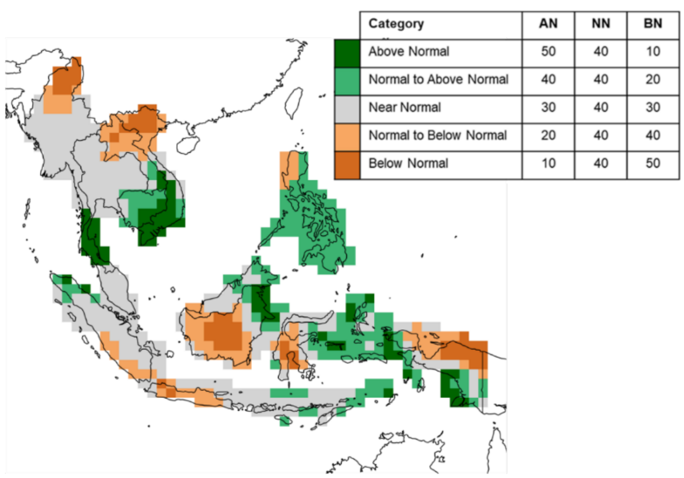

Figure 11. ASEANCOF consensus map of probabilistic rainfall outlook for DJF 2022/203 season (ASEANCOF, 2022)

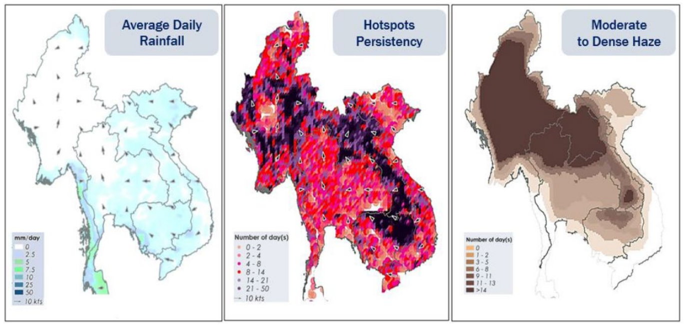

Figure 12. ASMC figures showing average daily rainfall (left), hotspot persistence (middle) and density of haze (right) for January-May 2022 (ASMC, 2022)

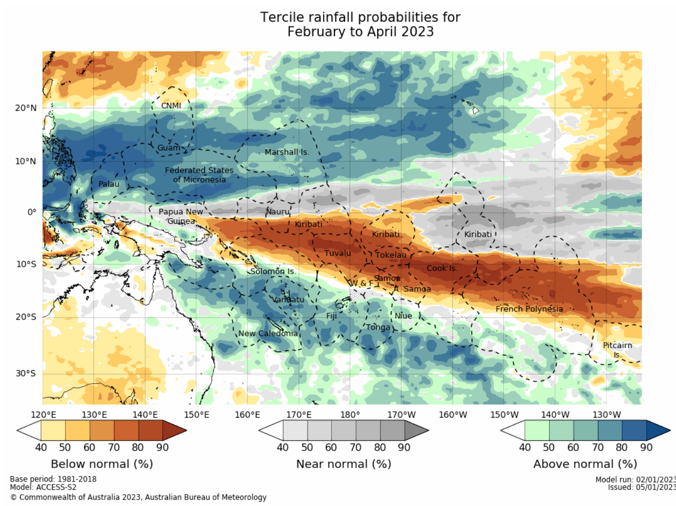

Figure 13. Example of rainfall probabilities over for Pacific island countries (PICOF, 2023)

National Meteorological and Hydrological Services and Emergency Managers

National Meteorological and Hydrological Services (NMHS) are responsible for providing forecasts and warnings of extreme precipitation to their government, public, industry and emergency services. These forecasts and warnings can be used to mitigate risk to varying degrees.

NMHS can produce seasonal outlooks (which may be influenced by WMO Regional Climate Outlook Forums) that can be used by emergency managers to communicate risk to communities, and to influence resource distributions (e.g. pre-deployment of resources to locations at higher risk).

Discussion Topics for Panel of Experts

Challenges

Complexity of processes being studied

Observations in the right place at the right time

Compute requirements for realistic simulation a

Model development

Assessing social impacts: Impact of rainfall on malaria outbreaks
Relevant experience and applicability in the Indo-Pacific Region
Impact of events
Services
Research

Quad Members' capabilities

How we can tie into existing mandates and activities

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