Global Precipitation Experiment - A New World Climate Research Programme Lighthouse Activity

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ABSTRACT

The future state of the global water cycle and prediction of freshwater availability for humans around the world remain among the challenges of climate research and are relevant to several United Nations Sustainable Development Goals. The Global Precipitation EXperiment (GPEX) takes on the challenge of improving the prediction of precipitation quantity, phase, timing and intensity, characteristics that are products of a complex integrated system. It will achieve this by leveraging existing World Climate Research Programme (WCRP) activities and community capabilities in satellite, surface-based, and airborne observations, modeling and experimental research, and by conducting new and focused activities. It was launched in October 2023 as a WCRP Lighthouse Activity. Here we present an overview of the GPEX Science Plan that articulates the primary science questions related to precipitation measurements, process understanding, model performance and improvements, and plans for capacity development. The central phase of GPEX is the WCRP Years of Precipitation for 2-3 years with coordinated global field campaigns focusing on different storm types (atmospheric rivers, mesoscale convective systems, monsoons, and tropical cyclones, among others) over different regions and seasons. Activities are planned over the three phases (before, during, and after the Years of Precipitation) spanning a decade. These include gridded data evaluation and development, advanced modeling, enhanced understanding of processes critical to precipitation, multi-scale prediction of precipitation events across scales, and capacity development. These activities will be further developed as part of the GPEX Implementation Plan.

CAPSULE

GPEX – The Global Precipitation Experiment is a new World Climate Research Programme Lighthouse Activity designed to take on the challenge of reducing knowledge gaps in measurement and modeling of precipitation across scales and improving precipitation predictions around the world.

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Precipitation is a critical component of the water cycle, and it has a direct connection to society, the environment and natural hazards. The robust observation, modeling, and prediction of precipitation over land and oceans remain one of the fundamental challenges in weather and climate research (Douville et al. 2022). The urgency to make progress in this field is evident as the availability and access to freshwater is at risk in many parts of the world, and floods and droughts become more frequent and more severe (NOAA SAB 2021). Many of these high-impact weather events are strongly linked to precipitating storm systems (WMO 2021). The difficulty in making progress in the prediction of water availability arises from the fact that precipitation features (intensity, frequency, amount, duration, type, hydrometeor size and distribution, seasonality, and extremes) arise from complex interactions across a range of spatial and temporal scales.

Precipitation has already received much attention. For instance, satellite precipitation measurements have been the focus of space agencies for a long time, precipitation has been emphasized by numerous national and international projects (e.g., Stephens et al. 2023), and precipitation as part of hydrology has received substantially increased attention in the World Meteorological Organization (WMO) Research Strategy for Hydrology. Nevertheless, there remain major challenges in accurate measurement and modeling of precipitation across scales. These include:

- Large uncertainties in satellite and ground-based precipitation estimates over many regions of the globe, particularly in the tropics and oceans where surface measurements are sparse, and in regions of complex terrain where sampling challenges are particularly pronounced and spatial coverage of ground-based radar measurements is limited due to terrain blockage;
- Insufficient understanding of some microphysical and precipitation processes, their interactions with local, regional, and global circulation and their interactions with surface/sub-surface water;
- Limited progress in precipitation prediction and precipitation change projection with high fidelity, particularly for extreme precipitation events, across different temporal and spatial scales;
- Limitations with respect to the scale-dependence and fidelity of modeling approaches and their ability to represent dominant scales of precipitating systems;

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- Incomplete understanding of the sources and limits on precipitation predictability across time scales of minutes to decades, and across many orders of magnitude in spatial scales;
- Large gaps in data access or availability, especially in already vulnerable regions, hampering improvement of predictions in these regions.

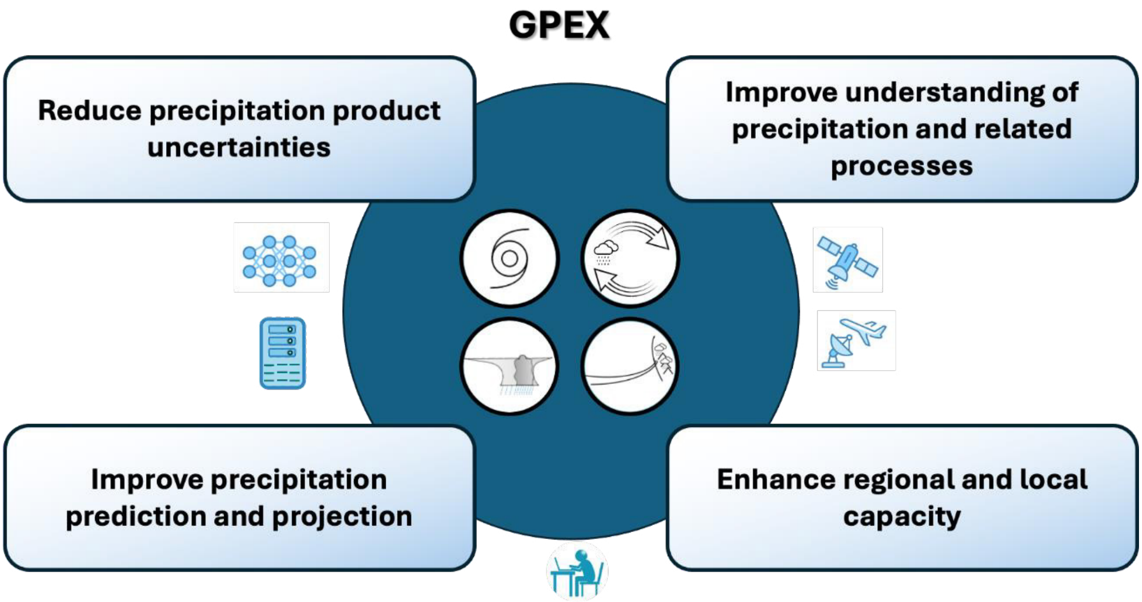

Figure 1. Schematic depiction of key elements of the GPEX Science Plan.

The Global Precipitation EXperiment (GPEX) was first discussed in 2020 among agencies of the U.S. Global Change Research Program to address the slow progress in improving precipitation prediction. These agencies met with the World Climate Research Programme (WCRP)[1] and its two core projects [GEWEX (Global Energy and Water Exchanges) and CLIVAR (Climate and Ocean: Variability, Predictability and Change)], and representatives of various research communities in 2021 to explore the possibility of elevating this to a WCRP (international) initiative. In May 2022, the WCRP Joint Scientific Committee approved the GPEX Tiger Team assigned to draft a white paper on the strategy of how WCRP can address major science gaps in the field of precipitation. After receiving the White Paper in September 2022, this WCRP committee appointed a GPEX Science Team, with membership sampling the

[1] WCRP includes six core projects with enduring research efforts, six lighthouse activities with transdisciplinary efforts on specific issues for 5-10 years, and an academy as the research training advisory and coordination arm.

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breadth of the community expertise related to this complex topic. The Science Plan was subsequently developed through an iterative process, including extensive input from the broad research and operational communities.

GPEX was launched as a new WCRP Lighthouse Activity in October 2023 at the WCRP Open Science Conference in Kigali, Rwanda. **Figure 1** summarizes the key elements of the GPEX Science Plan: The four key points are related to the four science questions of GPEX; and the four key activities of GPEX will cover various storm types (as indicated by the icons in the center) using various approaches (as represented by the five icons outside the circle), including field measurements, satellites, modeling/computing, artificial intelligence, and capacity development. These points are further discussed below, with more details available from the WCRP website (https://www.wcrp-climate.org/lighthouse-activities/gpex/GPEX-SciencePlan-Nov2023.pdf).

Key science questions

GPEX's vision is to enhance understanding and predictability of precipitation in a changing climate and thereby to support resilience and sustainable development. Its mission is to accelerate advances in precipitation knowledge and prediction at different temporal and spatial scales, to enhance access to relevant datasets, and to benefit society, through the coordination of national and international activities. The key science questions and actions needed to achieve the vision and mission include:

Q1: What are the sources and magnitude of uncertainties in quantitative liquid and solid precipitation estimates over land and ocean, particularly in regions of vulnerable populations and limited observational capabilities, and how can we reduce these uncertainties?

Actions needed: Enhanced precipitation measurements using shielded weighing and/or tipping bucket rain gauges, dual polarization Doppler radar, satellite remote sensing, and other emerging low-cost and high-fidelity technologies. Development of strategies for optimal deployment of future installations to maximize information gain. Innovative use and integration of spaceborne and surface-based measurements. Rigorous assessment of gridded precipitation products across scales and in terms of precipitation phase, intensity and probability of occurrence. Identification and rigorous documentation of optimal methods to quantify liquid/solid and mixed phase precipitation. Improved data sharing and integration (e.g., by providing strong incentives).

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Q2: How is precipitation produced by complex moist processes and their interactions with atmospheric dynamics and other components of the Earth system?

Actions needed: Enhanced global observing networks and improved data assimilation for better prediction and generation of reanalysis output for process understanding. Innovative process studies through field campaigns and use and evaluation of a hierarchy of numerical models. Use of tracer variables to differentiate processes leading to precipitation. Identifying sources and limitations of precipitation predictability across scales and of changing hydroclimate conditions in a warming climate.

Q3: What are the sources of errors in model precipitation intensity, phase, and duration in meteorological and climate models and how can we reduce them to improve predictions and projections of precipitation at different temporal and spatial scales?

Actions needed: Use of an integrated observational and Earth system modeling strategy. Organization of model intercomparison experiments specifically designed for diagnosing model precipitation biases. Improving model physics parameterizations, including processes important for hydrological processes but not yet represented in Earth system models. Combining physics models and data-driven artificial intelligence models for precipitation prediction. Developing metrics for precipitation predictions/projections across scales and model resolution to meet the needs of practitioners and decision support community. Identifying the appropriate modeling frameworks (e.g., the appropriate spatial resolutions) for forecasting precipitation on a variety of timescales and projecting its changes into the future.

Q4: How can we enhance regional and local capacity for precipitation observations, process understanding, prediction and projection services including those designed to aid drought and flood early warning systems and applications to climate change adaptation?

Actions needed: Investments in measurement technologies and instrument networks, modeling and other tools with an aim towards operational use. Two-way collaborations with stakeholders and practitioners by providing training and education and by comprehensively assessing available capacities and integrating available knowledge into planned activities. Linking with activities organized by the WCRP Academy.

The overall strategy is to plan the WCRP Years of Precipitation (YoP) for 2-3 years[2] as the GPEX flagship activity and associated activities before and after it. The YoP will bridge the

[2] One year would be too short to coordinate field campaigns on different storm types.

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communities and activities for better and greater scientific outcome than what can be achieved without GPEX. The four key activities are discussed below.

WCRP Years of Precipitation

A critical step in planning and implementing the YoP is to leverage and coordinate with existing WCRP activities and other national/international projects, and engage with funding agencies. Further, the YoP will partly overlap with the United Nations (UN) "International Decade for Action on Water for Sustainable Development" (2018-2028; https://www.un.org/en/events/waterdecade). It is anticipated that YoP planning will take 2-3 years and needs to engage scientists from different regions to articulate refined and regionally relevant objectives and plan logistics for field campaign activities.

The underpinning science focus of the YoP is (1) understanding and stratifying precipitation predictability in the context of the large-scale forcing by connecting precipitation to storms and their environments, which can be further linked with large-scale atmospheric processes, land-atmosphere interactions, and atmosphere-ocean interactions; and (2) bringing the weather and climate communities together on a common challenge that has been addressed from different perspectives. For instance, GPEX needs expertise and input on data assimilation, process understanding, teleconnections, and modeling of mesoscale processes such as storms, capabilities that traditionally reside more dominantly in either the weather or climate community, or both. Consistent with lessons learned from the Year of Polar Prediction (YOPP 2016), modelling activities will be tightly integrated with observational campaigns from the outset.

Satellite and surface-based observations are crucial in planning for GPEX field campaigns. Ahead of the campaigns, particularly satellite-derived data can be used to identify potential locations, air-mass trajectories, and expected frequencies for events of interest. During the campaigns, satellite data (and numerical weather forecasting) can provide situational awareness of the environmental conditions for real-time planning. The campaigns can in turn provide information (e.g., coincident measurements with satellite overpasses) that supports satellite programs (e.g., calibration/validation activities). These field campaigns and global satellite measurements will also provide comprehensive data for model evaluation activities within GPEX.

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For YoP activities, GPEX will identify crucial partners and necessary infrastructure to coordinate field campaigns in high priority regions that have a duration of at least one month and, where relevant, sample across different seasons. The duration and season will be dictated by conditions (i.e. storm types) that are key contributors to mean and extreme precipitation. Several key phenomena responsible for extreme precipitation events and their interactions across scales (e.g., Prein et al. 2023) will be the foci of the YoP. Atmospheric Rivers (AR) are long, narrow, and transient corridors of strong horizontal water vapor transport that fuel extreme precipitation often associated with mid- and high-latitude cyclones and can be enhanced by orographic effects. Mesoscale Convective Systems (MCSs) in the tropics and mid-latitudes are a fundamental feature for organizing convection and associated precipitation. Tropical cyclones are an additional major driver of extreme precipitation events in the tropics and can extend into the subtropics and mid-latitudes. Finally, monsoon circulations are vitally important in regulating seasonal precipitation patterns and connecting monsoon precipitation to different storm types (e.g., frontal mid-latitude cyclones and MCSs) in highly populated regions. These four storm types are further discussed in the **Sidebar**.

A key theme within GPEX is promoting new techniques for quantitative estimates of precipitation intensity, phase, and hydrometeor diameter from new remote sensing technologies/inversion methods plus supporting expansion of measurements (including in situ networks) to better sample the Global South, high elevations, high latitudes, and global oceans. GPEX should also develop recommendations about the instrument suite needed to optimally characterize precipitation for a future global baseline precipitation network. Key knowledge gaps related to gauge undercatch for solid precipitation and discrepancies between precipitation intensity/phase and hydrometeor size distributions from different measurement technologies will also be addressed in GPEX. Precipitation transect measurements will be planned to improve understanding of orographic precipitation gradients and forcing from satellite and ground-based remote sensing and modeling. GPEX will also leverage the multi-decade stable water isotope measurements from the Global Network of Isotopes in Precipitation (https://www.iaea.org/services/networks/gnip), as they can better constrain the hydrological cycle in weather and climate models.

These globally coordinated field campaigns will also be designed to include comprehensive measurements in the atmosphere, in the upper ocean, at and below land surface, and within the planetary boundary layers where these Earth system components interact. Innovative

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technologies, such as the use of uncrewed/autonomous observing systems, including the partnership with the private sector, will be encouraged. These field campaigns should also include strong two-way collaborations with local, regional, and national research activities.

Activities can also be designed to use data from previous field campaigns related to the storm types being studied to augment new campaign data. An important outcome of these activities is to develop a synthesis of field campaign data on specific storm types collected around the world, with improved data quality control, data curation, and data management to promote broader use.

To support and gain the most benefits from these measurements, GPEX will carry out a variety of activities with practitioner engagement throughout the entire process as an input to guide future research needs and requirements for improvements:

- to establish commonly acceptable data sharing policy and mechanisms for non-routine observations (e.g., from field campaigns) to be timely available for operational and research communities;
- to synthesize data from different sources with different spatio-temporal coverage and accuracy to support analysis, numerical modeling, and machine learning applications;
- to develop common metrics for coordinated evaluation of km-scale analysis and precipitation forecasts from different centers for the whole YoP period;
- to apply these products and measurements in precipitation-related process studies;
- to facilitate collaborations between the science and applications communities and directly contribute to societal needs.

Precipitation-Relevant Databases

It is important to acknowledge that a wide range of global and regional precipitation datasets already exist (Roca et al. 2021). GPEX will contribute to the systematic evaluation of such data sets as well as aid the establishment and/or expansion of global and regional precipitation databases from satellite, surface radar, and gauge measurements. Proper metadata and documentation of these datasets will be emphasized for prediction initialization, evaluation, data assimilation, data mining technologies and AI modeling, and process understanding. For instance, GPEX could develop methodologies to deal with the consistency of extremes in gridded precipitation datasets (Timmermans et al. 2019).

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It is also relevant to acknowledge that GPEX is designed to be complementary to other coordinated efforts within WCRP and beyond. GPEX will work with other projects (e.g., WCRP GEWEX and CliC - Climate and Cryosphere for the cryosphere regions) to set up a baseline surface precipitation network over land similar to the long-term baseline surface radiation and atmospheric aerosol networks. For each site, comprehensive high temporal resolution (e.g., 10 min) precipitation hydrometeor size distribution and phase measurements should be made, along with metadata, quality control, and equitable access. In particular, GPEX should target national and international development agencies to influence their existing commitments to the Global South for both installing and maintaining these sites. Further, tools and techniques need to be developed to complement a few accurate data by many less accurate data, leading to expansion or improvement of observational data at minimal cost.

Similarly, existing ground-based observational networks need to be enhanced along with common operational procedures and WMO standards (https://community.wmo.int/en/standards-and-requirements-climate-observations), particularly across regions that have a low density of rain/snow gauge or radar network. For existing sites, it is important to work with different countries to relax their rules for sharing in situ data, both historical and current. The rescue of historical data is particularly key for extremes that require long records for robust estimates of statistics. All these efforts should also be coordinated with the hydrological as well as, in coordination with CliC, the cryosphere community.

Over global oceans, GPEX will work with other projects (e.g., CLIVAR, GEWEX) to organize a dialogue between oceanographers and atmospheric scientists to design gauges for buoys, under the constraint of costs and quantified uncertainties. Precipitation radars can be placed over small oceanic islands (e.g., via member state support for WMO infrastructure).

Recognizing that instruments installed during field campaigns are frequently deliberately or accidentally decommissioned afterwards, GPEX will seek to stimulate development and deployment of low-cost, easy-to-maintain instruments for enhancing the global precipitation measurement network. Given the importance of hydrometeor size and phase to some applications (e.g. soil erosion and renewable energy projects, Pryor et al. 2022), GPEX will advocate for greater adoption of hydrometeor size distribution and phase measurements (via micro-rain radar and/or disdrometers). GPEX also needs to work with WMO (e.g., Global

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Basic Observing Network) and others to ensure that all precipitation and related measurements are openly available and accessible.

GPEX will work with other projects and interact with data users on the further assessment and quantification of uncertainties of gridded precipitation products (including reanalysis) at different spatiotemporal scales. One way to constrain precipitation data uncertainty and improve process understanding is to link with other components of the water cycle, as emphasized by GEWEX. Together with the International Atomic Energy Agency, the global network for stable isotopes in precipitation measurements should be rejuvenated and densified at strategic locations. To the degree feasible in the GPEX planning, measurement activities discussed here should be coordinated and synchronized with modeling activities (see below) as early as possible.

Precipitation Modeling, Prediction, and Process Understanding

Several components are required to model precipitation across scales, such as cloud microphysics (particularly ice and mixed phase), surface evaporation, moisture transport and convergence, interaction between planetary boundary layer and convective and microphysical processes, the dynamical organization of moisture from the mesoscale to the general circulation, and data assimilation (for weather prediction). In particular, km-scale models are the workhorses for regional prediction (Rasmussen et al. 2023) and are also used in some global studies. They are able to (at least partially) explicitly represent deep convective-scale and mesoscale dynamical processes and thus avoid the use of the parameterization of moist convection, which remains probably the largest uncertainty in weather and climate models with coarser resolutions. To gain the most benefit from km-scale modeling, new observational products and model evaluation metrics will need to be developed. To address this challenge, GPEX will need to work with the km-scale global and regional modelling communities.

GPEX will seek to coordinate precipitation analyses and forecasts from different centers (particularly national meteorological and hydrological centers) for the GPEX period, and support the establishment of multi-model databases, along with common evaluation metrics for deterministic, probabilistic, and extreme forecasts of precipitation. Model output analyses should focus on:

- quantifying and attributing precipitation prediction errors;
- exploiting and maximizing the prediction skill of multi-model ensembles;

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- improving atmospheric model physics and atmosphere-surface coupling;
- developing novel approaches to understand and represent processes critical to precipitation modeling (e.g., learning about precipitation drivers and processes from the massive training datasets used to train artificial intelligence in weather forecasting);
- developing data assimilation capability for coupled models and improving the assimilation of precipitation products.

Finally, GPEX intends to support research on precipitation predictability, prediction techniques and applications at various time scales. It will leverage the outcomes of existing model intercomparison frameworks for subseasonal-to-seasonal prediction and for climate projections and further quantify and exploit the roles of land and ocean in precipitation predictability. In particular, it will focus on models with simulations at various resolutions (e.g., km-scale, 0.25^o, and 1^o) and address questions: How do specific processes affect model performance at various resolutions? How can process understanding from higher-resolution modeling help improve coarser resolution modeling? What are the limits (in space and time) to the predictability of precipitation, in particular at subseasonal to decadal time scales, beyond which we must just learn to "embrace the uncertainty"?

National/Regional Activities and Capacity Development

GPEX should support existing national/regional activities and/or the establishment of new activities, partly through capacity building. Full engagement with all interested parties needs to be implemented to ensure usability of GPEX products. New tools need to be developed for data visualization and delivery (e.g., using the technologies of video games). For these and other activities, funding mechanisms and opportunities (from individual countries, international organizations such as the World Bank, and nonprofit foundations) need to be explored, coordinated and realized.

GPEX will seek to support capacity development by entraining early career scientists, students, and institutions into the YoP, particularly from the Global South whose populations are particularly vulnerable to climate variability and change. Local researchers understand regional and local processes and will contribute to model evaluation, development, and inclusive experiment design for these regions. GPEX will seek innovative ways to support studying abroad and to host training courses on precipitation science, prediction, modeling, and applications in such countries in partnership with the WCRP Academy.

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GPEX should help make km-scale modeling available for resource-challenged scientists in the Global South. One way is to give these scientists access to km-scale simulation tools and to share advances in enabling remote analysis. Another is to apply emulators for their regions of interest that can build on comprehensive km-scale models. These scientists and countries can also contribute to GPEX by providing regional observations (with open data access encouraged), their regionally downscaling results, and model and product evaluations using their observations. GPEX could explore the approaches used by the WCRP Coordinated Regional Downscaling Experiment (https://cordex.org/).

Implementation, Timeline, and Path Forward

While the detailed implementation plan of GPEX remains to be developed, we can divide GPEX activities into three phases:

Pre-YoP Phase (e.g., Years 1-3): Data synthesis and development, modeling, and capacity development. The priority is to seek and encourage large GPEX-endorsed projects as anchors for global field campaigns and then entrain additional projects from various countries. GPEX will use the same vetting mechanism as the Year of Polar Prediction (YOPP 2016) for the endorsement of these projects. This endorsement of proposals from an international organization will incentivize involvement.

YoP Phase (e.g., Years 4-6): Field campaigns, data development, modeling, and capacity development.

Post-YoP Phase (e.g., Years 7-9): Analyses of data collected during the field experiments and linking those to long-term records, modeling advances, and capacity development.

The timeline for the above activities is flexible, as financial, logistical/political, and technical issues often delay planned field campaigns. It is also important to recognize the need for regional/national committees that will organize their own GPEX related/focused activities and interact with existing WCRP projects. We envisage the GPEX activity to be completed and fully integrated into one or more of WCRP Core Projects in 2-3 years after the field campaigns are completed. This would happen within a decade. The primary outcomes of GPEX are expected to use precipitation as the unifying force for transdisciplinary activities, to make major progress in addressing the four science questions of GPEX, and to provide the most comprehensive global observational data and associated analysis/reanalysis, forecasting, and modeling products on various storm types.

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GPEX should emphasize its unique role as the only international project with substantial globally coordinated field campaigns and draw on the expertise across all the WCRP projects and many other programs (including the World Weather Research Programme). It should focus on a small set of activities outlined above, with remaining tasks led by other programs.

Through this article, we invite the broader community to contribute to GPEX as we seek to engage in an unprecedented global effort to advance understanding of the hydroclimate, and the modeling and measurement of precipitation. Moving forward, the priority is to set up the GPEX Scientific Steering Committee and working groups in 2024. We are also seeking leaders to coordinate field campaigns on each storm type, development of precipitation related datasets, and modeling and prediction experiments. Furthermore, we are seeking anchor projects for global field campaigns.

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Data Availability Statement.

This study does not generate any new data.

Sidebar: Four Storm Types

The GPEX YoP will focus on different storm types (four storm types described here, among others) over different regions and seasons.

Atmospheric river (AR) events contribute up to 50% of annual precipitation in key regions of the world, including west coasts of continents (Dettinger et al. 2011) and polar regions (Maclennan et al. 2022). For these events, coordinated field campaigns are needed over global oceans (where atmospheric rivers first form) and land (for AR's effects on the natural system and human activities). These efforts will leverage existing AR reconnaissance (AR Recon) activities and associated data sets, teams, and expertise (Ralph et al. 2020). For example, the AR Recon is conducted annually to meet the operational requirement of the US National

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Winter Season Operations Plan for weather reconnaissance. With the demonstrated improvement in weather forecasting, AR Recon is also expanding to include the Gulf of Mexico/East Coast of US cases, and possibly in the northeast Atlantic and northwest Pacific.

MCSs contribute 50-90% of the annual precipitation over the tropics (Schumacher and Rasmussen 2020) and are associated with damaging extreme weather at mid-latitudes including hail. Coordinated field campaigns are required over global oceans and land to understand how these systems interact with their environment throughout their life cycle, including the upscale growth from individual deep convective cells to larger, organized convective systems, and how these interactions vary from land to ocean and from one region to another. This will leverage existing and planned observational and modeling activities such as work on MCS storm tracking that would allow precipitation to be linked more explicitly to the storms and their dynamic and thermodynamic environments.

While field studies have been carried out in the past on tropical cyclones in specific regions, GPEX will focus on them through globally coordinated field campaigns. This will help us better understand tropical cyclones, their large-scale and mesoscale environments, their transition to extra-tropical cyclones, their genesis and lifecycle including rapid intensification which is a major challenge for forecasting, and their regional variability. Notably, there are major gaps in observing and understanding how land surface states (e.g., soil moisture) and land use (e.g., urbanization) may influence tropical cyclones before and after making landfall. This component of GPEX will naturally leverage existing tropical cyclone reconnaissance activities (Knaff and Slocum 2023).

Similarly, monsoon precipitation has been extensively studied regionally, but GPEX's focus on globally coordinated field campaigns will help us better understand global and regional monsoons in general, how they are connected, and the contributions of different storm types (embedded in the monsoon systems) and their large-scale and mesoscale environment to monsoon precipitation. These activities should be coordinated closely with the CLIVAR/GEWEX Monsoon Panel.

In some regions and during certain seasons, some of the above storm types may overlap (e.g., MCSs and monsoons) and the precipitation they produce is often enhanced by the complex orography, highlighting the importance for global coordination of the YoP field campaigns to leverage overlapping goals, geographic regions, and seasons. While the field campaigns are mainly designed to address gaps in process understanding and modeling, they

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should also be informed by gaps in understanding and uncertainties in projecting how the different storm types may change in a warming climate.

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