Science Plan on WCRP Global Precipitation Experiment

GPEX Science Team
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Executive Summary

The future of the global water cycle in general, and specifically the prediction of freshwater availability for humans around the world remain among the frontiers of climate research and are relevant to several UN Sustainable Development Goals. Especially the prediction of precipitation, which is the product of a complex integrated system, remains problematic. Improving precipitation predictions requires improved observations and modeling of all critical processes in the coupled system including land (encompassing natural and anthropogenic vegetation), ocean, snow and ice, and atmosphere. The Global Precipitation EXperiment (GPEX) will take on the challenge of improving precipitation predictions around the world, including polar and high-mountain regions. It is a new cross-World Climate Research Programme (WCRP) initiative centralized around the WCRP Years of Precipitation (YoP) and associated activities before and after.

GPEX is motivated by the recognition that, despite some progress over the past few decades (e.g., through WCRP core projects, such as GEWEX, CLIVAR, SPARC), the required improvement of precipitation predictions has been hampered by major gaps in observing, understanding, and modeling precipitation. Extreme events like floods and debris flows are often caused by extreme precipitation and projected to be exacerbated by a warmer climate. Accelerated improvements in the provision of precipitation products are needed to help emergency managers, water resource managers, and infrastructure planners better respond to and prepare for precipitation changes and mitigate their impacts on communities and ecosystems.

GPEX provides a unique opportunity to foster progress in filling gaps in observing and understanding phenomena and processes critical to precipitation and to accelerate progress in improving precipitation prediction and its applications for resilient and sustainable development by leveraging existing WCRP programs and community capabilities in satellite and ground observations, modeling and research, and conducting new and focused activities.

The GPEX/YoP will include coordinated global field campaigns with an emphasis on different storm types (atmospheric rivers, mesoscale convective systems, monsoons, and tropical cyclones, among others) over different regions and for different seasons, gridded data evaluation and analysis (including identifying the need of enhancing existing global observing network), km-scale modeling, understanding of processes critical to precipitation (e.g., through field experiments and also new approaches such as feature tracking and instrument simulators), and prediction of precipitation events, including extremes as well as changes in precipitation seasonality. GPEX will focus on the following four science questions:

- What are the sources and magnitude of uncertainties in quantitative precipitation estimates over global land and ocean, particularly in regions of vulnerable populations and limited observing capabilities, and how can we address them?

- How is precipitation produced by complex moist processes and their interactions with atmospheric dynamics and other components of the Earth system?
- What are the sources of precipitation errors in weather and climate models and how can we reduce them to improve predictions and projections of precipitation at different temporal and spatial scales?
- How can we enhance regional and local capacity building for precipitation observations, process understanding, prediction services (e.g., early warning systems), projection, and applications?

The opportunities for scientific advancement generated by GPEX activities are anticipated to attract increased interest from national and international funding agencies from around the world, and hence attract more scientists to GPEX (and hence WCRP), but this also represents the top risk (i.e., lack of new national and international funding). GPEX activities will take 8-10 years to complete through three (Pre-YoP, YoP, and Post-YoP) phases. While specific activities are briefly discussed at the end of this Science Plan, they need to be further developed in the near future.

1. Motivation and History

Precipitation is one of the most important weather, climate, and hydrological variables with direct connection to society and the environment. The observation, modeling, and prediction of precipitation as a source of the available freshwater over land or ocean remains one of the fundamental frontiers in weather and climate research. The urgency to make progress in this field becomes increasingly obvious as the availability and access to freshwater is at risk in many parts of the world, and floods have become more frequent and more severe in other parts of the world, as highlighted during the UN Water Conference in March 2023 in New York. The difficulty in making progress in the prediction of water availability arises from the fact that precipitation features (e.g., intensity, frequency, amount, duration, type, hydrometeor size and distribution, seasonality, and extremes) exhibit large temporal and spatial variability and are the product of a complex integrated system.

Despite progress over the past few decades [e.g., through World Climate Research Programme (WCRP) projects], the improvement of precipitation prediction and projection skill remains a challenge due to major gaps and limitations in observing, understanding, and modeling precipitation. For instance, the recent US Priorities for Weather Research Report stated that “Unfortunately, precipitation forecast skill has not improved substantially over decades and remains one of the major technical challenges in atmospheric sciences.” Important shortcomings remain, such as:

- Large uncertainties in global satellite and ground-based (liquid and solid) precipitation estimates with high temporal and spatial resolutions over mountainous and high-latitude regions, over global oceans but also over the tropics;
- Poor understanding of precipitation processes and their interactions with the local, regional, and global circulation and with (land, ocean, snow/ice) surface processes;
- Limited improvements in the prediction of drought onset, duration, severity and recovery;

- Lack of progress in precipitation prediction and precipitation change projection with high fidelity, particularly for extreme precipitation events (e.g., local extreme precipitation events leading to hazards like floods and landslides), across different temporal and spatial scales;
- Limited understanding of the root causes or sources of errors in precipitation prediction in terms of model deficiencies vs. inadequate initial conditions (due to a lack of observational data and/or inadequate data assimilation); and
- Little understanding of the sources and limits of precipitation predictability and how they should be adequately captured by prediction models from weather to decadal timescales.

Global Precipitation EXperiment (GPEX) was first discussed in 2020 among agencies of the U.S. Global Change Research Program (USGCRP) to address the gaps in precipitation prediction. USGCRP met with WCRP and its two core projects (GEWEX and CLIVAR) in 2021 to explore the possibility of taking this as a WCRP (international) initiative. In May 2022, WCRP JSC approved the GPEX Tiger Team. After receiving the White Paper in September 2022, the JSC appointed a GPEX Science Team to develop the Science Plan that will explicitly address:

- What is new in science (and possibly technology, service)? - In other words, what has not been done by other WCRP projects? What GPEX activities are innovative and visionary? What can be done in five years?
- What is the justification for GPEX to be a Pan-WCRP project (and hence possibly Light-House Activity - LHA) rather than a more specialized project? – In other words, what activities of GPEX would exploit the synergies with current WCRP core projects and LHAs?

The Science Team membership was mostly finalized by December 2022 and represents almost all existing WCRP projects (see **Appendix**). The Science Plan (this document) has been developed through an iterative process, including the use of team members' 1-pagers and written discussions and extensive input from the broad WCRP and other communities (including WMO Hydrology and WWRP).

2. Details and Scope of GPEX Activities

2.1. Vision, Mission, and Key Goals

GPEX vision: Understanding and predicting precipitation in a changing climate to support resilience and sustainable development.

GPEX mission: To accelerate advances in precipitation knowledge and prediction at different temporal and spatial scales, to enhance open access to relevant datasets, and to benefit the society, all by coordinating national and international activities.

Key questions and actions needed to accelerate the improvement of precipitation understanding and prediction include:

Q1: What are the sources and magnitude of uncertainties in quantitative (liquid and solid) precipitation estimates over global land and ocean, particularly in regions of vulnerable populations and limited observing capabilities, and how can we address them?

Actions needed: enhanced precipitation measurements using shielded gauges (including improved temporal reporting), dual polarization Doppler radar, and satellite remote sensing; development of strategies for deployment of future installations; innovative use and integration of spaceborne and surface-based measurements; rigorous assessment of precipitation products (e.g., uncertainty quantification at different temporal and spatial scales); identification of optimal methods to quantify solid precipitation; and better data sharing and integration.

Q2: How is precipitation produced by complex moist processes (e.g., cloud microphysics, aerosols, and those associated with organized convection) and their interactions with atmospheric dynamics (e.g., dynamically forced or convective ascent, variations in horizontal transport of water vapor that feeds precipitation) and other components of the Earth system (e.g., ocean processes, topography, land use, and land processes)?

Actions needed: enhanced global observing networks and improved data assimilation for better prediction and reanalysis data for process understanding; innovative process studies (particularly of extreme precipitation events) through field campaigns and using a hierarchy of numerical models; use of tracer variables (such as stable water isotopes) to differentiate processes leading to precipitation, and identifying sources and limitations of predictability of precipitation (including extreme events) and of precipitation changes in a warming climate.

Q3: What are the sources of precipitation errors in weather 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; organizing model intercomparisons specifically designed for diagnosing model precipitation biases; identifying priority processes and phenomena that are key to enhancing precipitation prediction capability and improving precipitation predictions from weather to climate timescales; incorporating improved model physics (including the use of stable water isotopes) and considering processes important for hydrological processes but not yet represented in state of the art Earth System Models (ESMs); higher resolution and hierarchical modeling and coupled data assimilation; combining physics models and data-driven artificial intelligence (AI) models for precipitation prediction; and developing metrics for precipitation predictions/projections to meet the needs of users and decision support community.

Q4: How can we enhance regional and local capacity building for precipitation observations, process understanding, prediction services (e.g., early warning systems), projection, and applications?

Actions needed: investments in measurements, modeling and other tools (with an aim towards operational use); two-way collaborations with stakeholders and end users (by providing training and education and by seeking feedbacks); and link with activities organized by the WCRP Academy.

The overall strategy is to plan the first WCRP Years of Precipitation (YoP) and associated exciting activities before and after it: the YoP will help attract more funding and participants into WCRP activities, and it will bridge the communities and activities for better and greater scientific outcome than what can be achieved without GPEX.

2.2. Key Activities

a) WCRP Years of Precipitation (YoP)

The understanding and prediction of precipitation and its applications (e.g., in hydrology) are widely regarded as a grand challenge. Usually these issues have been addressed separately by different communities. The question is: what is the pathway for the improvement of precipitation measurements, understanding, prediction, and applications from end to end, including the sources of predictability influencing precipitation from large-scale variability and slowly varying processes in the Earth system?

An optimal approach is to plan and implement WCRP Years of Precipitation (YoP) as a flagship activity of GPEX by leveraging and coordinating with existing WCRP activities and other international projects. This should link to the UN "International Decade for Action on Water for Sustainable Development" (2018-2028) by organizing the YoP (or part of it) during this period. The YoP will help promote international collaborations, enhance community involvement, and increase the visibility of GPEX. Outreach before, during, and after the YoP will provide the lasting momentum to connect the scientific community with civil society and help build stronger trust between them to engage into actions towards more sustainable collaborations and better delivery of products for societal benefits.

The most critical step for the YoP planning is to engage and coordinate with national and international funding agencies. For instance, NOAA is planning the Tropical Pacific Observing System (TPOS) field experiment in 2026/2027 to improve the understanding of ocean-atmosphere interactions. The YoP planning would take 2-4 years and need to follow recommended practices from prior efforts. This would provide the necessary financial resources to support participating scientists in different countries for measurements, understanding, model evaluation and improvements, prediction, and applications. Equally important, GPEX needs to engage scientists from different regions in the YoP planning, with clear objectives and careful consideration of logistics (e.g., availability of aircraft, ships, instruments, uncrewed/autonomous observing systems, information technology platform, and personnel).

Satellite observations are crucial in planning for GPEX campaigns. Ahead of the campaigns, they can be used to identify potential basic locations, trajectories, and expected frequencies of events of interest. During the campaigns, satellite data can provide situational awareness of the environmental conditions (e.g., on distribution of aerosols transported over long distances that may in turn impact clouds and thus precipitation), and contribute to real-time planning through both qualitative consideration by mission forecasters and the use of such data in data assimilation used to initiate quantitative forecasts. The campaigns can in turn provide information that supports the satellite programs – e.g., coincident measurements with satellite overpasses that contribute to their calibration/validation activities.

For YoP activities, GPEX will identify crucial partners and necessary infrastructure to coordinate field campaigns globally for at least one month in each season with a focus on specific storm types in selected regions around the world where those storm types are key contributors to mean and extreme precipitation. For instance, GPEX can study atmospheric rivers and the precipitation after landfall, organized convection (e.g., mesoscale convective systems), monsoons, and tropical cyclones and their precipitation after landfall. These storm types may occur over different seasons and between seasons in different regions. As specific weather events may or may not occur at a given time, it is better to have fixed periods in field campaign planning. Also note that precipitation is sometimes influenced by a combination of phenomena, such as atmospheric rivers and extratropical cyclones, or frontal systems and mesoscale convective systems, occurring at the same time, and for some events it is difficult to differentiate the dominant storm types that cause both mean and extreme precipitation.

The underpinning science focus is (1) understanding and stratifying precipitation predictability by connecting precipitation to storms and the storm 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, both weather and climate communities are interested in diurnal variation and low-frequency mode such as the Madden-Julian Oscillation (from ocean-atmosphere interaction over the tropics) and the impact of land surface condition in spring over high mountains on global precipitation in summer. As a lesson learned from the YOPP (Year of Polar Prediction), modelling activities should be tightly integrated with observational campaigns from the outset.

For atmospheric river (AR) events, coordinated field campaigns are needed over global oceans (where atmospheric rivers first form) and land (for the AR’s effects on the natural system and human activities – including hydrological operations). New activities that use emerging technologies and instruments should be encouraged. These efforts should leverage existing AR reconnaissance (AR Recon) activities and associated data sets, teams and expertise. In particular, the AR Recon is conducted annually to meet the operational requirement of the US National Winter Season Operations Plan for weather reconnaissance. The leading driver of AR Recon is to improve forecasts of landfalling atmospheric rivers and their associated extreme precipitation on the US West Coast. 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. Besides weather forecasting, other modeling activities for process understanding and parameterization development should also be planned in conjunction with the field campaigns.

Mesoscale convective systems contribute 50-90% of the annual precipitation over the tropics. Coordinated field campaigns are required over global oceans and land to understand how these systems interact with their environment throughout the 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 should leverage existing and planned observational and modeling activities. For instance, the GEWEX community is working on storm tracking that would allow precipitation to be linked more explicitly to the storms and their dynamic and thermodynamic environments. Another example where GPEX could engage with an existing activity would be the AsiaPEX (Asia Precipitation Experiment) initiative that will be coordinating observational and modeling initiatives over the whole Asian region including the Asia Maritime Continent and Tibetan Plateau over 2025-2028. Coordination with modeling experiments including regional and global storm-resolving simulations should target more closely integrated activities to improve process understanding and address model uncertainties.

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 the events and their precipitation in general but also how they are connected in different regions. This should leverage existing tropical cyclone reconnaissance activities.

Similarly, monsoon precipitation has been 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 and AsiaPEX.

Precipitation measurements should obviously include specific characteristics, like phase and size distributions. For this purpose, GPEX should determine where measurement setups are lacking and propose strategies and funding opportunities to establish further networks with a focus on relevant and challenging sectors, including 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. For example, gauges over Antarctica are so limited that the Global Precipitation Climatology Center (GPCC), and consequently the Global Precipitation Climatology Project (GPCP), have no product over that vast region. Additional field campaigns similar to the WMO SPICE (Solid Precipitation Intercomparison Experiment) are also needed to quantify and improve gauge undercatch that could be as much as 10% of global land precipitation. For orographic precipitation, which is a major challenge for both the satellite and ground-based remote sensing and modeling community, precipitation transect measurements can help us better understand how precipitation changes with altitude as well as distance to the ocean. Measuring precipitation at high time-resolution will enable insight into intense precipitation events, leading for example to flash floods.

GPEX should also leverage the multi-decade stable water isotope measurements from the Global Network of Isotopes in Precipitation (GNIP) under the auspices of IAEA (International Atomic Energy Agency) and WMO. Observing and modeling the water isotope composition in precipitation and water vapor can better constrain the hydrological cycle in weather and climate models, as it is a process tracer that links different hydrological compartments and provides insight into evaporation conditions, alterations during transport within weather systems, and microphysical environments for precipitation.

Furthermore, these globally coordinated field campaigns should include comprehensive measurements in the atmosphere (e.g., via aircraft – including dropsondes; meteorological towers and rawinsondes over land or islands), in the upper ocean (e.g., ships, buoys, floats, drifts, gliders), and at and below land surface (e.g., soil moisture, temperature, groundwater, snowpack, and surface-based remote sensing instruments for the atmosphere). Innovative technologies, such as the use of uncrewed/autonomous observing systems, should be encouraged. These field campaigns should also include strong two-way collaborations with local, regional and national research activities: regional projects would share regional research contexts and promote their own implementation of observational platforms, while GPEX may propose global common observational methods which are simple and not so expensive. These measurements will provide the ground truth for satellite data calibration/validation (and hence possibly attract funding from space agencies). These measurements and global satellite measurements will provide comprehensive data for other activities of GPEX.

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 most benefits from these measurements, GPEX should carry out a variety of activities with user 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 operation and research communities;
- to coordinate global km-scale analysis and precipitation forecasts from different centers for the whole YoP period;
- to coordinate hierarchical modeling and model intercomparison from the cloud resolving (usually with a grid size of tens to hundreds of meters) to the regional and global cloud permitting (or storm resolving, usually with a grid size of kilometers) and cloud parameterizing scales in ESMs (usually with a grid size of tens of kilometers);
- to apply these products and measurements in process studies of precipitation, its interactions with the environment, its predictability sources and limits, improved representations of precipitation processes in coupled models, and hydrological extremes;
- to coordinate evaluations of precipitation products and precipitation forecasts (e.g., associated with the storms and storm environments);

- to coordinate with GEWEX and the hydrological community to understand the knowledge gaps and requirements for improved hydrological prediction (e.g., the need for high-resolution hydrological modeling, including anthropogenic impact and cryosphere); and
- to facilitate collaborations between the science and applications communities and directly contribute to societal needs.

b) Precipitation-Relevant Databases

Numerous global and regional precipitation datasets already exist. The question is: what are the uncertainties of these precipitation datasets (e.g., for light, moderate, and dense precipitation rates), particularly over regions without or with limited in situ measurements (e.g., oceans, mountains, high latitudes)? GPEX should support the establishment and/or expansion of global and regional precipitation databases from satellite, surface radar, and gauge measurements, with proper metadata and documentation, for prediction initialization, evaluation, data assimilation, data mining technologies and AI modeling, and process understanding. It is also important to assess where and under what conditions reanalysis precipitation is most useful (e.g., over sea ice). GPEX should focus on activities that will add values to existing efforts (e.g., improving gauge undercatch correction for specific types of gauges). In particular, the collaboration with the GEWEX Data and Analysis Panel (GDAP) will be mutually beneficial, as GDAP has years of experience in the assessment of global precipitation datasets by working closely with data developers and providers.

For instance, GPEX should work with other projects (e.g., GEWEX) to set up a baseline surface precipitation network (BSPN) over land– similar to the long-term baseline surface radiation and atmospheric aerosol networks. For each BSPN site, comprehensive high temporal resolution (10 min or less) precipitation hydrometeor size distribution and phase measurements will be made (e.g., with windshield), along with metadata, quality control, and equitable access. In particular, support needs to be found for both installing and maintaining these sites over the Global South (e.g., through the continuous backup by WMO). For instance, these data can be used to assess and improve satellite and ground based remote sensing for precipitation intensity, hydrometeor phase and size distributions. Further, tools and techniques need to be developed to complement a few accurate data by many less accurate data (e.g., via machine learning), 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 standards, particularly across regions like Africa, the Amazon, and high mountains that have a low density of rain/snow gauge or radar network. For this, commitment of national meteorological and hydrological agencies under WMO is critical. It is key to solicit recommendations from the community (including precipitation products developers) to determine high impact regions, where addition of in situ data is critically needed. In particular, due to strong spatial gradients of precipitation over mountains, it is important to increase the number of sites for precipitation measurements (using both rain and snow gauges). For existing sites, it is important to work with different countries to relax their rules for sharing in situ data. It is also important to improve and validate interpolation methods (e.g., reanalysis, high-resolution modeling, data assimilation, and innovative interpolation methods without using data assimilation) by facilitating collaborations among the relevant groups and intercomparison of various methods (including the use of hydrological budget as a constraint for river basins). Such efforts (including the determination of gaps and opportunities) should also be coordinated with the hydrological as well as cryospheric community (e.g., for snowfall accumulation measurements).

Over global oceans, buoy rain gauges become available, but they are not widely used, as they are perceived by atmospheric scientists as not reliable. GPEX should work with other projects (e.g., CLIVAR, GEWEX, SPARC) to organize a dialogue between oceanographers and atmospheric scientists to design gauges for buoys, under the constraint of costs and quantified uncertainties (e.g., due to ocean spray). Precipitation radars can be placed over small oceanic islands (e.g., via member state support for WMO infrastructure). Furthermore, passive aquatic listeners may be mounted on buoys or profilers in the ocean as underwater acoustical rain gauges. Identifying location priorities is an important task that can be obtained through community targeted discussions.

Recognizing that instruments installed during field campaigns are frequently abandoned afterwards (due to a lack of maintenance funds) or vandalized in certain locations, GPEX should emphasize the development of low-cost, easy-to-maintain instruments for enhancing the global precipitation measurement network. With local community and institutional buy-in for sustained observations, such instruments with local data visibility may also be used by volunteers, with the innovative use of data from citizen science - particularly important in urban areas. GPEX should also advocate for greater adoption of hydrometeor size distribution and phase measurements (via micro-rain radar and/or disdrometers). Both the initial installation and long-term maintenance costs need to be addressed. GPEX also needs to work with WMO and others to ensure that all precipitation and related measurements are openly available and accessible.

GPEX should work with other projects (e.g., GEWEX, WMO Integrated Processing and Prediction System (WIPPS)) on the further assessment and quantification of uncertainties of gridded precipitation products (including those from reanalysis) at different spatiotemporal scales. Sometimes the differences between precipitation products can be as large as those between models. One way to constrain precipitation data uncertainty and improve process understanding is to link with other components of the water cycle (total water storage, evaporation, water vapor, soil moisture, runoff, groundwater, glaciers, etc), as emphasized by GEWEX. For instance, snowfall measurement uncertainties can be constrained by snow water equivalent measurements. Together with IAEA, the global network for stable isotopes in precipitation (GNIP) measurements should be rejuvenated and densified at strategic locations.

While gridded precipitation data availability, accessibility, and preservation are straightforward, data from research-based observational campaigns tend to be less organized, less well documented, and less well preserved (or scattered across different data repositories). GPEX should play an active role in preserving them, making them accessible, and properly integrating them with other sources for climatological analysis.

GPEX should also coordinate between precipitation measurement and modeling (see below) communities regarding what observational datasets and at what quality are required by modelers and what modeling output would be helpful to plan observations. To the degree feasible, measurement and modelling activities should be coordinated and synchronized as early as possible.

As prediction models are improved, prediction error sources in initial conditions would emerge to play a bigger role in prediction skills. GPEX should pay special attention to identifying such error sources (due to a lack of observational data and/or inadequate data assimilation) and work with other organizations, programs, and projects to address this issue and to fill observation gaps to minimize the prediction error sources in initial conditions.

c) Precipitation Modeling, Prediction, and Process Understanding

Several components are required to model precipitation across scales, such as cloud microphysics that determines the intensity and phase of precipitation, land and ocean surface evaporation, moisture transport and convergence, interaction between atmospheric 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). At the largest scales we need global coupled models, and at the smallest scales cloud resolving models, with km-scale cloud permitting or storm resolving models (SRMs) in between. These SRMs, whether regional (mesoscale or regional climate models) or global, are the workhorses of many predictions from weather to climate.

To improve simulation of precipitation at small scales, it is desirable to have the explicit representation of some convective processes, related processes and fine scale interactions between the circulation and the land-surface, atmospheric boundary layer and local topographic features. However, significant biases persist even in SRMs. Despite their improved realism, biases in SRMs in some cases can even be larger than in their coarse resolution, parameterized counterparts or cloud resolving models. Clearly, we still lack key process understanding and the implementation of this understanding in our modeling systems. Furthermore, the in-situ observational networks (needed to initialize, monitor, verify, and validate such high-resolution simulations and their representation of the water cycle) do not exist over much of the world. New observational means (e.g., sub-regional process-oriented observational platforms at scales of tens to hundreds of kilometers) and new model evaluation metrics also need to be devised to explore the added value of higher resolution.

To address this challenge, GPEX needs to leverage multi-model SRM ensembles developed globally (e.g., from WCRP Digital Earth) or over specific regions (e.g., from the CORDEX Flagship Pilot Studies or the GEWEX GHP studies) and a hierarchy of models (from process-scale models, idealized modeling, large-eddy simulations, and SRMs) for

- process understanding of precipitation and its whole life cycle;
- identification of model deficiencies and gaps in observational networks that, if filled, could help better quantify the sources for model deficiencies;
- identification of sources of precipitation predictability and predictability limit to set realistic improvement targets and to help design metrics to measure the success, and

- testing the transferability of model improvement from one region to another (e.g., from Alps to Lake Victoria and Tibetan Plateau; from U.S. to South America) and from one area to another within a large region to explore commonalities and key differences (e.g., some errors will be systematic while others may depend crucially on local features).

GPEX should also coordinate precipitation analysis and forecasts from different centers (particularly national meteorological and hydrological centers), at different scales, from a kilometer on up, for a common period prior to YoP and for the YoP period, and support the establishment of multi-model databases, along with common evaluation metrics for deterministic, probabilistic, and extremes forecasts of precipitation. Such high-resolution and multi-scale modeling should better resolve convective processes (including hydrometeor phase) and heterogeneous surfaces, such as urban, mountainous, and coastal regions while efficiently understanding large scale interactions from the mesoscale to global scale. At the same time, emerging technology of satellite remote sensing will provide valuable observations that were unavailable before for testing and refining model physics. For instance, the EarthCARE and INCUS missions, each to be launched during the GPEX period, will measure convection, microphysics, and turbulence. Model output analyses should focus on:

- identifying and addressing errors and their sources in precipitation prediction systems, and understanding the key physical processes that have the strongest imprint on the model biases and precipitation prediction.
- exploiting and maximizing the prediction skill of multi-model ensembles already available.
- improving model physics and atmospheric coupling with land, ocean, and snow/ice through their transition zones so that models can better simulate precipitation at local, regional, and global scales. In addition to the atmospheric processes as mentioned above, the atmosphere-surface coupling should receive more attention. Such coupling includes the ocean-atmosphere coupling; coupling of land surface and subsurface processes to the atmospheric boundary layer, convection, and the free troposphere; and improved timing of precipitation diurnal cycle.
- developing novel approaches (e.g., applications of artificial intelligence and machine learning (AI/ML), innovative numerical configurations, high time-resolution model output, stable water isotopes in precipitation) to understand and represent processes critical to precipitation in regional and in global coupled models. For instance, recent successes in using AI/ML in weather forecasting raise the question of what the AI/ML algorithms learn about precipitation drivers and processes from their massive training datasets.
- developing data assimilation capability for atmosphere-ocean-land-ice coupled models and improving the assimilation of precipitation products and surface-based and spaceborne precipitation radar data.

Finally, GPEX should support the research on precipitation predictability, prediction techniques and applications at various time scales. While the importance of precipitation prediction at weather, subseasonal, and seasonal time scales is widely recognized, there is also a growing need for precipitation projections at multi-year to multi-decadal timescales to be used in agriculture and resources management decision making in coming decades, such as drought, flood, water supply, wildland fire, and hydropower; e.g., in collaboration with the WMO Hydrological Status and Outlook System (HydroSOS). GPEX should leverage the outcomes of existing model intercomparison frameworks for subseasonal-to-seasonal prediction and for climate projection (via CMIP6 and future CMIP7). In particular, GPEX should focus on models with simulations at various resolutions (e.g., km-scale, 0.25°, and 1°) and address questions: How do specific processes (e.g., in terms of land-atmosphere interaction, influence of ocean variability and changes) 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"?

d) National/Regional Activities and Capacity Development

GPEX should support existing national/regional activities and/or the establishment of new activities, partly through capacity building (e.g., AsiaPEX, the Precipitation Prediction Grand Challenge in the U.S., African precipitation initiative). User engagement is crucial for better understanding of the user requirements and for providing products tailored to user needs. New tools (e.g., using the technologies of video games) need to be developed for data visualization and delivery, particularly for the Global South. These would also help motivate national funding agencies to support regional components of GPEX, addressing precipitation grand challenges.

GPEX should support the capacity development by entraining scientists and graduate students into YoP, particularly from the Global South whose populations are most vulnerable to climate variability and change. *In situ* researchers understand regional and local processes and can contribute to model evaluation, development, and inclusive experiment design for these regions. For instance, to enhance and maintain observational networks in the Global South in a sustainable way, it is important to train local operational and academic personnel and evaluate approaches that safeguard from potential vandalization or misuse (e.g., through citizen science, local ownership, innovative technologies). For this purpose, it would be useful to support studying abroad and to host training courses on precipitation science, prediction, modeling and applications in these countries. For such training, START would be a good collaborator, and funding should be sought from relevant national funding agencies (e.g., USGCRP, China, Japan) and international organizations (e.g., European Union, Asia Pacific Network). GPEX should work with the WCRP Academy to coordinate these opportunities.

While storm resolving models (SRMs) are possible for scientists in the Global North, a specific GPEX goal in capacity development is to make this available for resource-challenged scientists in the Global South where SRMs could bring much added value. One way is to give these scientists access to the km-scale simulation tools and to share advances in enabling remote analysis. 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. CORDEX already engages in this manner, so GPEX could explore the CORDEX approach.

For all these activities, funding mechanisms and opportunities (from individual countries, international organizations such as the World Bank, and nonprofit foundations) need to be explored and coordinated.

3. WCRP Relevance and Partnerships

As precipitation is an essential climate variable, GPEX will directly contribute to all four objectives of the WCRP Strategic Plan 2019-2028: fundamental understanding of the climate system, prediction of the near-term evolution of the climate system, long-term response of the climate system, and bridging climate science and society. Precipitation is also central to the WMO's mission on water, weather, and climate.

Precipitation is emphasized within numerous activities of WCRP core projects and LHAs and other international projects (e.g., WWRP). For instance, precipitation has been one of the central foci of GEWEX over the past three decades (e.g., on observational data assessment, process studies, and high-resolution modeling). Precipitation is the core manifestation of global and regional monsoons, as the main source of water for millions of people living in those regions (explored via the CLIVAR/GEWEX monsoons panel). Precipitation over land is affected by remote ocean processes through teleconnections (explored via CLIVAR). Deep convection provides a mechanism for the troposphere-stratosphere interaction (emphasized via SPARC), and snowfall is the source for snow/ice over ice sheet and sea ice (studied via CliC). Precipitation affects human and natural systems (emphasized via RiFS), and model intercomparisons have been coordinated via ESMO. GPEX also strongly aligns with several new WWRP activities planned for 2023-2027 (e.g., the Hydrology and Precipitation Working Group).

Furthermore, the science and applications of precipitation have been addressed by other international programs. For instance, precipitation (particularly extremes) has been a focus of WWRP. The applications of precipitation have been emphasized by START. Precipitation as part of hydrology has received substantially increased attention in the WMO Vision and Strategy for Hydrology and its related Plan of Action, reflected also in the WMO Research Strategy for Hydrology. Precipitation and runoff isotope composition data have been collected for decades within IAEA's isotope hydrology section.

Satellite precipitation measurements have been the focus of space agencies for a long time (e.g., NASA, NOAA, JAXA, ESA, Copernicus). Satellite precipitation measurements are not only made possible by the continuation of existing satellite capabilities but benefit from new technologies (the TRMM and GPM precipitation radars as notable examples in the last decades) advancing the ability of accurately measuring precipitation. GPEX and space agencies share mutual interests in that the GPEX outcomes will help the space agencies shape their future satellite missions, such as the NASA Atmosphere Observing System (AOS) and beyond, in light of the science and society needs specified in the GPEX goals.

Nevertheless, major gaps in observing, understanding, and modeling precipitation remain (as discussed in Section 1). Therefore, GPEX should build on international initiatives already under way within WCRP programs, including planned observational campaigns, modeling activities, process studies, capacity development activities, and activities on the usage of precipitation information by stakeholders. For instance, km-scale modeling carried out by several WCRP projects (Digital Earth, GEWEX/GHP, ESMO/CORDEX) could be valuable for precipitation process understanding and model improvement. GPEX should also partner with global and regional organizations and agencies that focus on building and maintaining sustained observing networks and identifying observation gaps that must be filled for improved precipitation prediction (via improved process understanding and initial conditions).

With these analyses, the strategy of GPEX is to focus on the YoP and associated coordinated global field campaigns, gridded data evaluation and analysis, km-scale modeling, process understanding, and prediction of extreme events. This has not been done by other WCRP projects (e.g., GEWEX, CLIVAR); it has to be done via GPEX by drawing on the expertise across all the WCRP projects and many other programs (e.g., WWRP, WMO Hydrological Coordination Panel and Standing Committee on Hydrological Services). This is new and exciting, and if successful, this will be a major legacy of the whole WCRP (rather than GPEX alone).

Because of the cross-WCRP nature, the GPEX effort is referred to as a Lighthouse Activity (LHA), rather than a more specialized WCRP project. Furthermore, compared with other WCRP LHAs, GPEX is the only one with substantial globally coordinated field campaigns.

Furthermore, the excitement of GPEX activities may attract new support from national and international funding agencies, and hence attract more scientists to GPEX (and hence WCRP). In other words, GPEX intends to “grow the pie” (i.e., entrain more resources and participants) for WCRP activities, rather than compete against existing WCRP projects in a zero-sum game. This includes training and capacity development opportunities that would require engagement across all WCRP Core Projects and LHAs (particularly the WCRP Academy).

4. Deliverables, Outcomes, and Risks

The primary outcomes of GPEX are expected to use precipitation as the unifying force for cross-WCRP activities, to attract more national and international funding and hence attract more scientists (including those from the Global South) to WCRP activities, and to provide scientific deliverables:

- Plan and organize globally coordinated field experiments;
- Evaluate, improve, and develop gridded datasets of precipitation;
- Evaluate, improve, and develop precipitation modeling and prediction; and
- Increase capacity for precipitation related efforts via provision of open access precipitation datasets and model predictions.

The top risk is the lack of new or dedicated funding from national and international agencies for field campaigns, precipitation measurements, understanding, and model improvements. Without new funding, a new activity (like GPEX) would likely add more tasks to existing scientists who are already over-committed to WCRP projects in a zero-sum game. A related risk would be the lack of buy-in from the community (and a loss of enthusiasm by the community). We need to closely engage with funding agencies throughout the whole process of GPEX science plan development and its implementation. Equally important, we need to engage with the research community. The active participation of scientists from different countries is also necessary to seek and obtain the support from funding agencies.

Another related risk is the lack of sustained funding for long-term capacity development of scientists from the Global South. Global km-scale modeling (rather than regional by and for wealthy countries) would benefit the Global South by giving access to the km-scale simulation tools and sharing advances in enabling remote analysis. The support of research communities in the Global South to run km-scale simulations over regions most vulnerable to climate variability and change, and to analyze these results, also requires long-term, sustained funding.

5. Requirements and Budget, Communication and Capacity Exchange, Implementation and Timeline

Requirements and Budget. To facilitate interactions with existing WCRP projects and eventual transition to core WCRP projects, GPEX activities can be coordinated by supporting the hire of 1-2 additional staff, collocated with a core WCRP project office. This can be set up quickly, with the support from funding agencies. Some meeting support will be required from WCRP, for precipitation-related workshops and science steering committee meetings.

Communication and Capacity Exchange. It is preferable to have GPEX meetings collocated with the open science meetings of WCRP and its existing projects. For instance, GPEX was launched during the WCRP Open Science Conference in October 2023. Besides the celebration of the GPEX launch during a plenary session, a townhall for further iterations with the broader community was held. GEWEX will have its open science meeting in July 2024 in Japan, and GPEX could have dedicated sessions and steering committee meetings there. Publication of the GPEX Science Plan in the Bulletin of the American Meteorological Society will also help engage with the community.

Implementation and Timeline. GPEX activities should be guided by its Scientific Steering Committee appointed by the WCRP JSC, with the same criteria as those for the current science team membership. These activities should be carried out over an 8-10 year period, with subsequent work through regular core project activities. It is also important to have regional/national committees that will organize their own GPEX related/focused activities and interact with existing WCRP projects.

For the implementation of GPEX, activities can be divided into three phases:

- Pre-YoP Phase (e.g., Years 1-3): The priority is to seek and encourage large (selected or new) GPEX-endorsed projects as anchors for the global field campaigns and then entrain additional projects from various countries. GPEX will use the same vetting mechanism from the YOPP (Year of Polar Prediction) for the endorsement of these projects. This endorsement will act as an incentive to get involved, as it will provide some automatic support from an international organization for proposals. It will also enhance connectivity and inclusivity. At the same time, GPEX should pursue activities outlined in Sections 2b,c,d.

- YoP Phase (e.g., Years 4-6): GPEX should focus on all activities in Section 2.
- Post-YoP Phase (e.g., Years 7-9): GPEX should pursue activities outlined in Sections 2b,c,d with a focus on the use of new measurements.

The timeline for the above activities needs to be flexible, as financial, logistical/political, and technical issues often delay planned field campaigns. We envisage the GPEX activity to be completed and fully integrated into WCRP Core Projects in 2-3 years after the field campaigns are completed. This would happen in 8-10 years.

Appendix: GPEX Science Team membership

Name	Organisation	Country	Core Project /LHA
Xubin Zeng	University of Arizona	USA	GEWEX & Chair of the GPEX Science Team
Annalisa Cherchi	Institute for Atmospheric and Climate Sciences (CNR-ISAC)	Italy	CLIVAR/GEWEX Monsoons Panel
Sara Pryor	Cornell University	USA	RIfS co-chair
Lincoln Alves	National Institute for Space Research (INPE)	Brazil	RIfS
Stefan Sobolowski	NORCE Norwegian Research Centre & Bjerknes Center for Climate Research	Norway	RIfS
Jin Huang	NOAA	USA	USGCRP
Takeshi Horinouchi	Hokkaido University	Japan	SPARC
Andrew Gettelman	Pacific Northwest National Laboratory (PNNL)	USA	Digital Earth - LHA
Michael Wehner	Lawrence Berkeley National Laboratory	USA	EPESC - LHA
Marion Saint-Lu	Laboratoire de Météorologie Dynamique (LMD)	France	SLC - LHA
Jakob Steiner	Himalayan University Consortium and University of Graz	Pakistan, Austria	MCR - LHA
Stefan Uhlenbrook	World Meteorological Organization	UN Specialized Agency	WMO-Hydrology Division
Yali Luo	Nanjing University of Information Science and Technology	China	WWRP- Southern China Monsoon Rainfall Experi.
Chris Lennard	University of Cape Town	South Africa	WCRP Academy and CORDEX Africa
Bjorn Stevens	Max Planck Institute	Germany	WCRP Expert
Edward Hanna	University of Lincoln	UK	CliC co-chair
Marie-Amélie Boucher	Université de Sherbrooke	Canada	WMO Hydrology Expert
A.P. Dimri	Indian Institute of Geomagnetism	India	CliC
Ruby Leung	Pacific Northwest National Laboratory	USA	WCRP Expert
Charlotte DeMott	Colorado State University	USA	CLIVAR