Understanding Future Safety of Dams in a Changing Climate

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AGING DAMS AROUND THE WORLD. For centuries, humans have been building water management infrastructures, big and small, that alter the surface water availability for human needs. In the past century, numerous dams have been built for irrigation, hydropower generation, transportation, and municipal water use (Chen et al. 2016). Figure 1 shows the dams that had been built by 2010 around the world (Lehner et al. 2011). As can be seen here, some dams, especially those in the United States and Europe, were completed nearly 100 years ago. While the structural integrity of these large infrastructures varies across construction quality, use, and age, an often less-discussed question is whether these dams are safe under current and future climate.

Larger dams located upstream of population centers are often designed for downstream flood-control purposes. Therefore, they are also called critical or high-hazard dams. The overall safety of these critical dams over their life cycle is largely determined by how well extreme flood risks (which are often caused by extreme precipitation) can be assessed and safely handled (National Research Council 2012). Such dams were designed and built to handle the extreme storm/flood risks known at that time. However, observational records since the

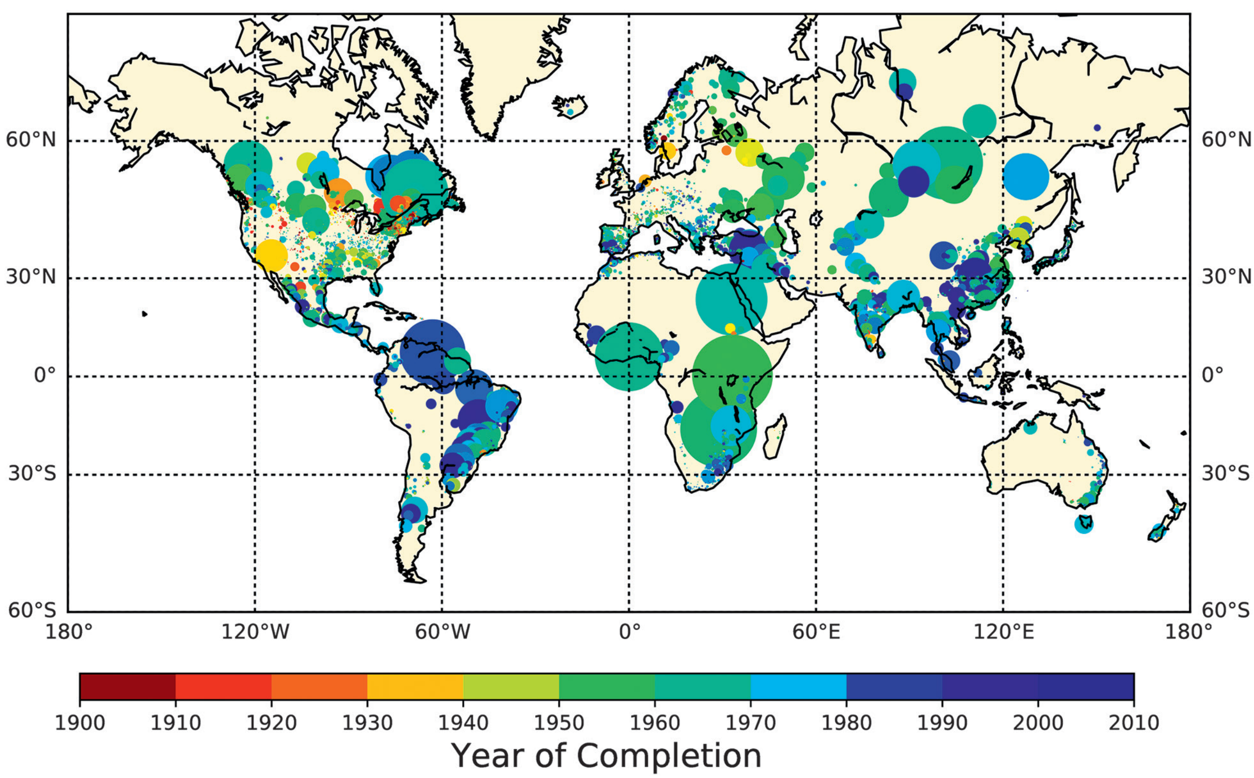

Fig. 1. Year of dam completion. Colors show the decade of dam completion, and the sizes of circles show the relative reservoir capacity. All the dams that have been built by 2010 are shown here. [Data source: GranD dataset (Lehner et al. 2011).]

construction of most high-hazard dams indicate that extreme storm magnitude has been increasing in the past decades (Kunkel et al. 2013a; Allan and Soden 2008; Trenberth et al. 2003; Kang et al. 2007). In the future, extreme storms—as well the floods they generate—are projected to be more frequent and intense in many regions around the world, exceeding known historical records when these dams were constructed (Kunkel et al. 2013b; Veijalainen and Vehviläinen 2008). Along with structural safety, the hydrologic safety is equally important, since overtopping or embankment failure can bring catastrophic human and societal loss to downstream population centers. For example, the structural damage to both the primary and emergency spillways of the Oroville Dam in California during a series of heavy rainstorms in February 2017 led to an evacuation of more than 188,000 downstream residents (Vahedifard et al. 2017). Therefore, it is timely to reevaluate the safety of these existing critical dams under the current and future climate (Chernet et al. 2014).

PROBABLE MAXIMUM PRECIPITATION AS THE SAFETY DESIGN STANDARD OF CRITICAL DAMS. These critical or high-hazard dams are designed to handle extreme storm/flood risks. As reviewed by Hossain et al. (2012), almost all such dams in the United States are designed using extreme storm scenarios. These critical dams are required to withstand not only the observed worst-case scenario but also all those events that can be reasonably expected in the future over a very long duration. It is for this reason that high-hazard dams need to be designed with something larger than the maximum observed precipitation. In engineering practice, probable maximum precipitation (PMP) was introduced as a safety design standard to capture such a low climatological risk. PMP indicates the upper bound of extreme precipitation and is defined as the "theoretical maximum precipitation for a given duration under modern meteorological conditions" (World Meteorological Organization 2009). PMP has been a number that engineers can estimate by utilizing precipitation and other meteorological variable observations, albeit with assumptions—many of which may be inappropriate or based on an outdated scientific foundation (Abbs 1999; Chen and Bradley 2006).

The World Meteorological Organization (WMO) suggests several methods for PMP estimation: statistical method, generalized method, transposition method, and moisture maximization method. The moisture maximization approach is the recommended method in the United States. To facilitate the PMP estimation using the moisture maximization approach, NOAA has published a series of instructions for various climatological regions across the United States, which are now known as hydrometeorological reports (HMRs). The moisture maximization method estimates PMP as PMP = $p \times$ PWM/PW, where p is the observed precipitation, PW is the observed precipitable water, and PWM is the climatologically maximum precipitable water (estimated from surface dewpoint temperature assuming hydrostatic conditions). Through this manipulation, the observed extreme precipitation p can be maximized to a higher level, which will, in theory, capture all the possibilities (including those having occurred and those that could have happened).

THE ISSUE WITH CONVENTIONAL PMP ESTIMATION. The purpose of this study is not to promote any specific method(s), but rather to explore ways to modernize PMP estimation in engineering practice by using the latest knowledge on atmospheric science and modeling. There have been several issues identified in conventional PMP estimations that have been used in engineering practice for dam design or estimation of overtopping risk. First, traditional PMP estimation makes no allowance for a long-term climatic trend that is expected to continue in the future (Milly et al. 2008; Cheng and AghaKouchak 2014). By applying the PMP derived from historical observation to planned dams in the future, a stationary climate is assumed. However, as reviewed by Mahoney et al. (2018), climate change will lead to nonnegligible change of extreme precipitation, thus

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PMP estimates for dam sites. Second, conventional PMP is a deterministic value, which does not provide any uncertainty information. This makes it less appealing for risk assessment scenarios given the recent trend of accounting for uncertainties in water management activities (Micovic et al. 2015; Baecher 2016). Third, the idea of moisture maximization is hard to justify from a scientific standpoint. Moisture maximization implicitly assumes a constant precipitation efficiency (p/PW). However, this is not the case in the extreme storms, and further, the relationship between PW and surface dewpoint temperature is not that simple (Abbs 1999; Chen and Bradley 2006). All of these analyses call for more physics-based PMP estimation approaches.

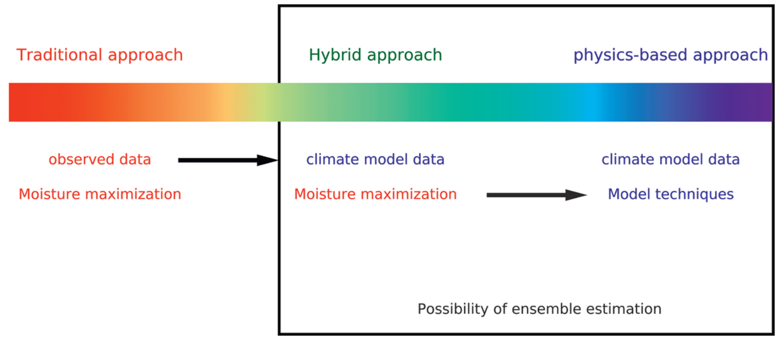

Fig. 2. Schematic of different PMP estimation approaches, from the "conventional approach" that has been adopted by the engineering community to the future-proof "physics-based approach."

Recent attempts to address the limitations of the conventional PMP estimation involve the derivation of uncertainty from ensemble estimates, as well as using modern numerical atmospheric models (Micovic et al. 2015; Tan 2010; Ishida et al. 2015; Rastogi et al. 2017). Numerical model-based efforts typically increase the relative humidity artificially in the modeling domain to create the most precipitation-conducive conditions (Rastogi et al. 2017; Tan 2010). Such modeling efforts invariably assume that precipitation is most sensitive to moisture availability, although other studies suggest that such sensitivity has high spatial heterogeneity (Loriaux et al. 2016; Lepore et al. 2015). At the same time, these studies show that precipitation can be sensitive to various meteorological factors other than moisture availability. This has led to large discrepancies between the modern scientific approaches and conventional engineering methods, leading to confusion among the engineering community on how to interpret the model-based PMP estimates (Chen and Hossain 2018).

The differences between the conventional PMP and physics-based PMP up to now are summarized in Fig. 2. It is clear that these two approaches involve distinct data sources (i.e., observation versus Earth system model data) and different "storm maximization methods" (i.e., simple moisture maximization versus modification of various model boundary conditions). These inconsistences lead to different interpretations between physics-based PMPs and conventional PMPs. Also, this makes it hard to assess the risk of conventional PMPs under climate change using physics-based results. It is likely that engineering communities care most about the "relative change of PMP" under climate change, but the usability of this delta change heavily relies on the similarities of historical PMP estimation. To illustrate this predicament, as an example let us consider a dam in the United States that has a 700-mm PMP estimation based on the conventional approach (HMR). This means that the dam is designed to withstand the flood caused by this 700-mm precipitation event. Now, let us think of three situations: 1) a new approach indicates that PMP is 600 mm for the historical period and 650 mm for the future period. Now it would be difficult to tell the safety of this existing dam—whether the future risk would increase by 50 mm (650–600 mm) or is still safe (as 650 mm is still lower than 700 mm). 2) A different approach indicates that the PMP is 800 mm for the historical period and 900 mm for the future period. Does this mean we just need to fix the dam to handle the extra 100-mm (900–800 mm) storm risk increase, or do we need to fix the dam to handle all the projected 900-mm total storm risk? 3) Another new approach indicates that historical PMP is 700 mm and future PMP is 750 mm. This time we know that we can convey this 50-mm PMP increase to the engineering community and they would correctly understand what this means. Through this example, it is clear that a consistent estimation of historical PMP is vital for the safety reassessment of those existing dams.

PMP ESTIMATION MODERNIZATION REQUIRES STEP-WISE EVOLUTION FOR ENGAGING CONVENTIONAL ENGINEERING PRACTICE. As a response to the emerging demands by engineers to reevaluate

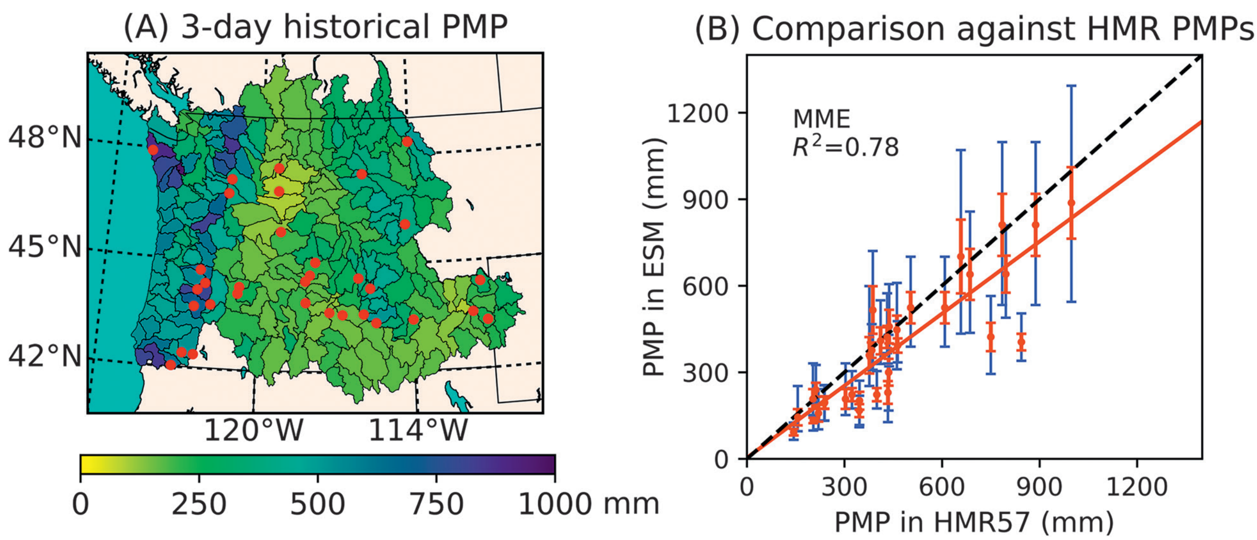

Fig. 3. Demonstration of hybrid PMP estimation approach in U.S. Pacific Northwest (PNW) watersheds. (a) The 8-digit hydrologic units in the PNW and the mean of multimodel ensemble (MME) hybrid PMP estimates (based on 1970–2016 ESM data) in each watershed. Red dots are the locations of the dams with PMP estimated available from the conventional approach (in hydrometeorological report 57). (b) Conventional estimates (*x* axis) compared with values from hybrid approach (*y* axis). Orange dots are the mean of ensemble estimates, orange bars are the standard deviation, and blue bars are the range of ensemble estimates.

the safety of existing infrastructures, we propose a practical approach—hereafter named the "hybrid" approach—that merges both conventional method and Earth system model (ESM) data. The basic idea of the hybrid approach is illustrated in Fig. 2. It uses the same technique used widely in engineering practice (i.e., moisture maximization), so the difference between hybrid and conventional approaches is the source of data. This would reveal how sensitive PMP estimation is to the input data. Meanwhile, by sharing as much of the same technique with the conventional approach as possible, the hybrid approach is likely to provide more consistent PMP estimation of the historical period, which will make the interpretation of future increase much easier. Also, the hybrid PMP is easier for engineers to understand, as it follows the techniques they are familiar with and does not yield the large quantitative discrepancies observed from the exclusive use of numerical models. Compared with physics-based approaches, they share the same data source. Thus, the hybrid approach can be treated as a benchmark of model-based techniques developed for physics-based approaches. For example, given the same input, how sensitive is PMP estimation to various maximization techniques? In other words, our proposed hybrid approach serves as a bridge, a step-wise evolution, between conventional and physics-based approaches that is necessary for building engagement with the engineering community.

With our proposed hybrid method, nonstationarity can be addressed by estimating PMP for different historical/future periods. The method is grounded in basic physics to allow the projection of PMP under the future climate using state-of-the-art hydrometeorological records in a computationally efficient manner. The availability of numerous ESM outputs can now allow multimodel ensemble (MME) PMP estimations to be made. Such an ensemble can provide indications on the uncertainty of the PMP estimates (Micovic et al. 2015; Chen et al. 2017). The consistency of these MME estimates with results based on conventional approach indicates that the climate models capture 1) correct precipitation climatology, and 2) reasonable physical mechanisms of precipitation in the study region. This is important to keep the estimates aligned with conventional approach, and streamline the criteria and verification of selecting good climate models.

DEMONSTRATION OF HYBRID PMP APPROACH IN THE U.S. PACIFIC NORTHWEST. Here we take the 3-day PMP in the U.S. Pacific Northwest (PNW) region (Fig. 3a) as a demonstration of our proposed hybrid approach. In practice, 3-day PMP is often used in critical dams whose failure would cause catastrophic loss of life. The PNW region features the Cascade Range barrier to air moisture (Fig. 3a), and extreme precipitation shows a distinct drop across the range. Conventional PMP in the PNW region is estimated through moisture maximization, which is outlined in the above section.

For the moisture maximization and other methods to work properly, high-resolution precipitation data that fully resolve the impact of surface topography and land conditions, together with related meteorological fields (e.g., precipitable water or surface dewpoint temperature), are required. These data are available through dynamic downscaling of ESM (i.e., regional climate model) output. Alternatively, they can be obtained via statistical downscaling techniques. In the PNW region, moisture availability is characterized by sea surface temperature (SST) rather than surface dewpoint temperature, as most of the extreme precipitation in the region is induced by deep ocean-originated atmospheric rivers. The relationship between the precipitation event and SST is determined by backtracking of the precipitating air mass in the wind fields. This process is now facilitated by the Hybrid Single-Particle Lagrangian Integrated Trajectory (HYSPLIT) model in this demonstration. This enables a more realistic 3D back-trajectory instead of the surface back-trajectory used in the hydrometeorological report for this region (HMR57). Given the large-scale spatial homogeneity of SST fields, it is possible to use them without further downscaling. More details on the PMP estimation procedures can be found in the Chen et al. (2017) study.

Output from 10 Earth system models (ESMs) were selected for ensemble estimation, and the information of these models is provided in the supplemental Table ES1. They were selected based on the quality of their precipitation fields as well as the reconstruction of atmospheric river climatology that is evaluated against reanalysis products (Gao et al. 2015; Rupp et al. 2013). Here we follow the instructions from HMR57, with necessary modifications to adapt to the ESM output. As a summary, for the extreme precipitation event, we use the back-trajectory technique to find out its moisture origin in the ocean. Taking the SST as "dew point temperature," we use this information to estimate the moisture input to the precipitation system, and maximize the precipitation amount. Regarding the back-trajectory procedure, since climate model data provide complete 3D fields, we conducted more realistic 3D back-trajectory as opposed to the surface back-trajectory in HMR57. [For more details, see Chen et al. (2017).] The historical PMP is estimated using ESM output for the years 1970–2016. These results were compared against established values that are already used in current infrastructure design (Fig. 3b). The conventional PMP estimates are well inside the envelope of ensemble hybrid estimation, suggesting that the MME approach provides reliable and consistent results (Chen et al. 2017). It is also important to note that this specific application of the hybrid approach is only applicable to the regions that are affected by atmospheric rivers (ARs). From the perspective of atmospheric dynamics, ARs simplify the PMP estimation in the AR-affected regions since they can be captured by the current climate models (Gao et al. 2015). However, from the perspective of current engineering practice, such back-trajectory is one of the more complex cases compared with the local moisture maximization (i.e., in equation PMP = $p \times$ PWM/PW, every variable is taken from local observation/simulation). For other regions, the PMP estimation procedures from conventional approach are likely to be less complicated, and it is only necessary to conduct moisture maximization based on local observation of precipitation and dewpoint temperature (Rouhani and Leconte 2016; Rouhani 2016; Rousseau et al. 2014).

The consistency between our hybrid approach and the conventional engineering approach provides a clear basis for engaging the traditional engineering community and helping understand the PMP's relative change under future climate scenarios. We should remember that the PMP based on the archaic engineering method is already embedded in the hydraulic design of the critical water infrastructures and hence represents the necessary baseline for comparing against future scenarios. *It is because of this fundamental reason that any modern and model-based approach must recognize this archaic approach in order to be useful for interpretation of risk and resilience into the future by the current engineering community.*

It is worth noting that our hybrid approach involves as much raw ESM data as possible, as compared to other similar studies that take full use of regional climate model data. The consistency between hybrid PMP and conventional PMP in the historical period indicates that raw ESM data are skillful in selected regions where extreme precipitation is triggered by large-scale weather systems (such as atmospheric rivers). This helps to save a significant amount of workload in downscaling raw ESM data and makes the approach more appealing to engineering communities. For other regions where precipitation is produced by local or mesoscale systems (such as mesoscale convective systems, hurricanes, and orographic precipitation), data at much finer resolution are required. Fortunately, at these regions conventional PMPs are often based on local moisture maximization. Thus the data needed for hybrid PMP are only precipitation and precipitable water. These two fields can be downscaled reasonably well through statistical methods (rather than running expensive regional climate simulations). Thus, the computational burden is not a major concern in the hybrid approach.

Since the hybrid approach takes all the required information from climate model data, it is possible to employ it to predict the future PMP under climate change. Using the ESM output under the representative concentration pathway 4.5 (RCP4.5, moderate emission) and RCP8.5 (high emission) scenarios for 2050–99, we can now estimate PMPs by the end of the twenty-first century, which indicate a consistent increase of extreme precipitation risk (Fig. 4). In general, the future extreme precipitation risk as quantified by MME mean PMP will likely experience an increase of 50% of current PMP level by 2099 under the RCP8.5 scenario, and such increase is statistically significant at $\alpha = 0.01$ level (Fig. 4a). Under the RCP4.5 scenario, however, the overall 20% increase of PMP is not significant (Fig. 4b). Furthermore, under the RCP8.5 scenario, in humid or rain-abundant watersheds (i.e., where historical PMP is high), the increase is more significant. Though most of the large infrastructure design standards require 3-day PMP estimation, this modeling framework can be applied to PMPs of other durations, with examples of 1-day and 2-day PMPs shown in the supplemental Fig. ES1. Overall, the increase of extreme storm risk as quantified by PMP is projected to increase by ~20% under the RCP4.5 scenario. Such consistency is likely because the days of extreme 1-day precipitation are often the highest precipitation days in the corresponding 3-day precipitation events. Therefore, the back-trajectory and the moisture maximization function are similar among 1-, 2-, and 3-day PMP estimates.

FUTURE WORK ON PHYSICS-BASED PMP ESTIMATION. With high-resolution cli-

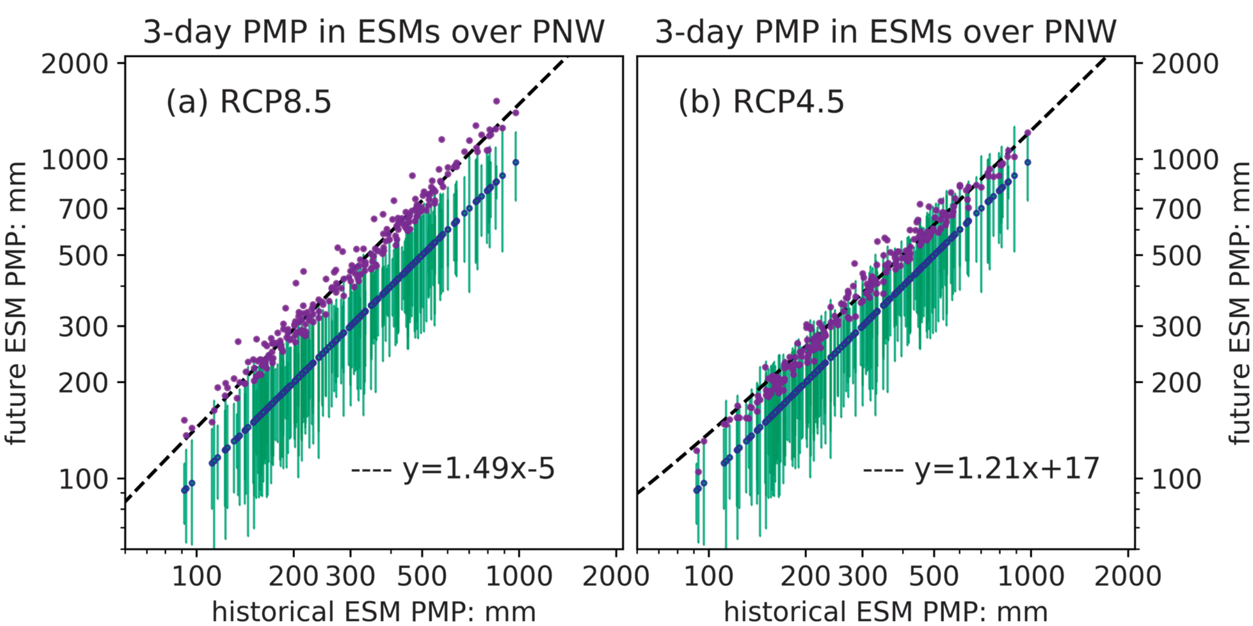

Fig. 4. Future change of PMP as indicated by ESM data for (a) RCP8.5 and (b) RCP4.5 scenarios. The *x* axis shows the historical MME mean PMP (1970–2016) across all the hydrological unit watersheds in the PNW (Fig. 3a). Their values are also illustrated on the *y* axis as the black dots, which form the 1:1 lines. The *y* axis shows the mean of future MME PMP during 2050–99 (purple dots) and the 99% confidence interval of historical MME PMP (green bars). The black dashed lines are the regression between future MME mean and historical MME mean. They indicate a consistent increase of 20% and 50% of historical PMP level by 2099 under RCP4.5 and RCP8.5 scenarios, respectively. At $\alpha = 0.01$ level, such an increase is not significant under RCP4.5 scenario, but is significant under RCP8.5 scenario.

mate data available (either from the next generation of Earth system modeling or downscaling of current ESM output), our proposed hybrid approach is suitable for the traditional engineering community for application at a global scale. Around the world where critical dams continue to be planned or built using the conventional engineering approach of PMP estimation, there is an urgent need to take advantage of more up-to-date hydrometeorological records and ESM outputs to understand future risks more physically, particularly in developing nations. Atmospheric model-based PMP estimation (i.e., physics-based approach) will continue to mature and improve over the archaic engineering PMP estimates. The hybrid approach provides an interim bridge and benchmark to these model-based estimations. It demonstrates to the engineering community that the departure from sparse and outdated ground observations to well-selected Earth system model data can provide a tangible way to derive relative changes of PMP (and risk) into the future. Regarding the model selection, some good examples can be found in Overland et al. (2011), Pierce et al. (2009), and Rupp et al. (2013).

As the name suggests (and also shown in Fig. 2), this hybrid approach is not intended to be the final method of PMP estimation for both engineering and science communities. Given the similarities of input data (i.e., climate model data) in hybrid and physics-based approaches and the efficiency in computing PMP, the hybrid approach can still serve as a baseline for any new technique developed in the future. Previous studies have proposed and experimented with various techniques—for example, relative humidity maximization, wind perturbation, and artificial boundary conditions (Ishida et al. 2015; Ohara et al. 2011; Tan 2010; Rastogi et al. 2017). However, up to now there have not been studies on PMP estimation based on storm physics analysis. The key of the conventional approach is the assumption that precipitation magnitude is most related to moisture availability. Therefore, any modern approaches to be developed need to correctly identify the key physi-

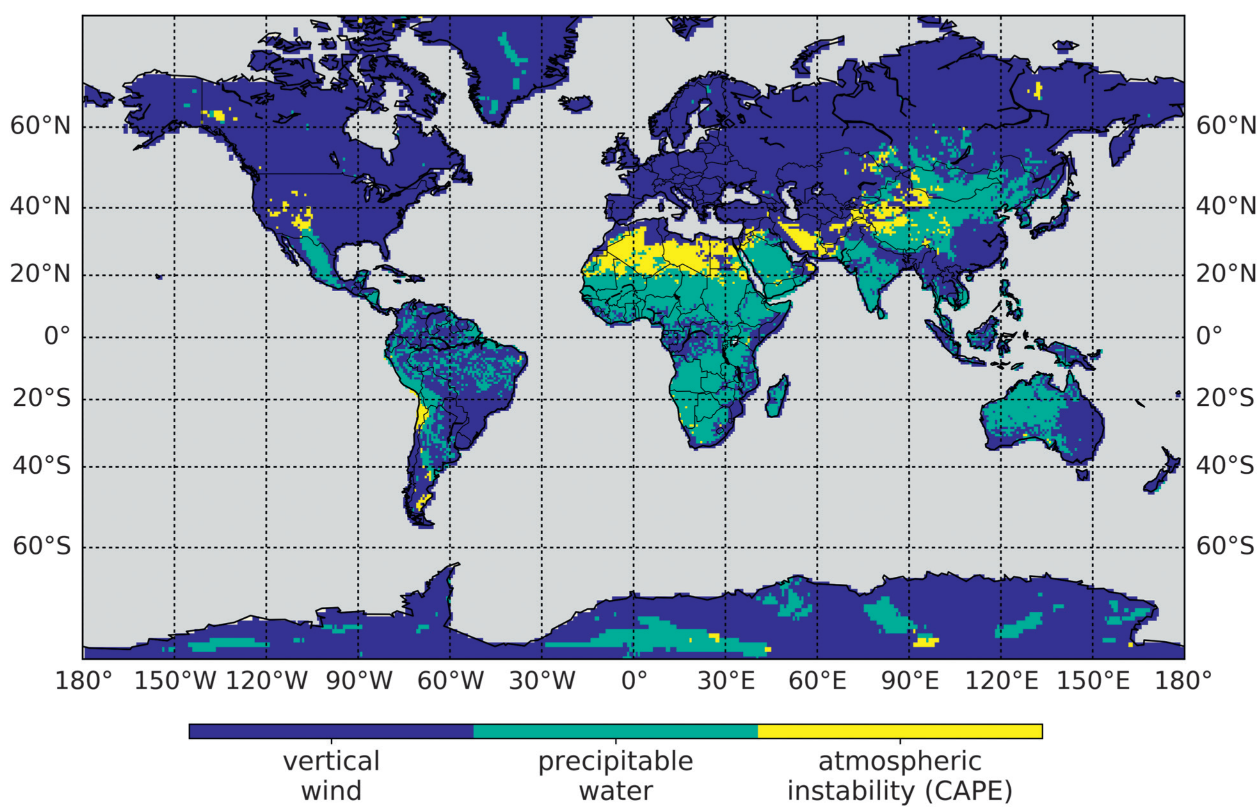

Fig. 5. Analysis of year-round co-occurrence of extreme 3-day precipitation and various meteorological factors (vertical wind speed, precipitable water, atmospheric instability) from ERA-Interim reanalysis during 1979–2015. At each location, one factor is identified among these 3, which gets extreme most often during the extreme 3-day precipitation events. Details on the analysis are available at Chen and Hossain (2018).

cal drivers to the precipitation event and take such knowledge to maximize the precipitation magnitude (as the new PMP). By involving the atmospheric reanalysis products, such knowledge can be obtained at the regional or global scale.

The study by Chen and Hossain (2018) has investigated the co-occurrence of storm magnitude and various extreme meteorological conditions [vertical wind speed, moisture availability, atmospheric instability as presented by convective available potential energy (CAPE)], and some global results are shown in Fig. 5. This study checks the statistical relationship between extreme precipitation and extreme meteorological conditions: *When extreme precipitation happens at a given location, which meteorological variables are also reaching their climatological maxima?* Note that here it evaluates the co-occurrence of extreme precipitation and extreme meteorological conditions, rather than the regression-based sensitivity of extreme precipitation magnitude to these conditions. For example, at a location that shows up as "CAPE" in Fig. 5, when there is an extreme 3-day precipitation event, CAPE also often reaches its local climatological maximum. This is a different analysis from the regression between precipitation magnitude and CAPE intensity. Based on statistical analysis of major atmospheric reanalysis products, regions where 3-day heavy precipitation is usually accompanied by the extreme condition of each meteorological factor (vertical wind, moisture, CAPE) can be delineated. From such analyses, more solid approaches can be developed for PMP estimation at different locations. For example, if we plan to build a new dam in Laos, from Fig. 5 we know that extreme precipitation in this region is usually accompanied by strong vertical wind fields. Therefore, at the safety design/PMP estimation stage, we will establish a collection of extreme storms in the dam life cycle and maximize the storm magnitude by adjusting wind speeds in the boundary condition of numerical simulations. In this way, we can obtain a physics-based PMP estimate at this dam site under the projected climate and it will provide better safety design of this planned dam. If we need to consider the seasonality of the above relationship, we can also make such maps for different seasons (see supplemental Fig. ES2–ES5).

It is notable that these results, as derived from current-generation reanalysis products, are still too coarse in certain regions where extreme precipitation is more controlled by weather systems at local scales, which is hard to be captured accurately in the coarse-resolution reanalyses. Analyzing the next-generation reanalysis products such as the ERA-5 reanalysis, as well as convective-permitting regional climate simulations such as the reconstructions by Chen et al. (2018), is likely to improve these maps. We can also use ESM results to produce these maps, which can reveal how such a relationship varies over time. In the meantime, by utilizing multiple ESMs we can estimate the uncertainty of these statistical relationships, which is lacking in the current reanalysis-based results. In short, knowledge about the physical drivers of extreme precipitation is necessary to establish physics-based PMP estimation. This not only ensures safe infrastructure design in the regions where limited historical observation is available, but also promotes better safety reevaluation of existing dams where climate may change significantly. With a better bridge between atmospheric science communities and engineering communities, the infrastructure communities will be better prepared for the projected climate change.

FOR FURTHER READING

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