Model-Based Probable Maximum Precipitation Estimation: How to Estimate the Worst-Case Scenario Induced by Atmospheric Rivers?

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ABSTRACT

The concept of probable maximum precipitation (PMP) is widely used for the design and risk assessment of water resource infrastructure. Despite its importance, past attempts to estimate PMP have not investigated the realism of design maximum storms from a meteorological perspective. This study investigates estimating PMP with realistically maximized storms in a Pacific Northwest region dominated by atmospheric rivers (ARs) using numerical weather models (NWMs). The moisture maximization and storm transposition methods used in NWM-based PMP estimates are examined. We use integrated water vapor transport as a criterion to modify water vapor only at the modeling boundary crossing the path of ARs, whereas existing methods maximize relative humidity at all initial/boundary conditions. It is found that saturation of the entire modeling boundaries can produce unrealistic atmospheric conditions and does not necessarily maximize precipitation over a watershed due to storm structure, stability, and topography. The proposed method creates more realistic atmospheric fields and more severe precipitation. The simultaneous optimization of moisture content and location of storms is also considered to rigorously estimate the most extreme precipitation. Among the 20 most severe storms during 1980–2016, the AR event during 5–9 February 1996 produces the largest 72-h basin-average precipitation when maximized with our method (defined as PMP of this study), in which precipitation is intensified by 1.9 times with a 0.7° shift south and a 30% increase in AR moisture. The 24-, 48-, and 72-h PMP estimates are found to be at least 70 mm lower than the Hydrometeorological Reports estimates regardless of duration.

1. Introduction

Probable maximum precipitation (PMP) is theoretically defined as the greatest depth of precipitation for a given duration meteorologically possible for a given area (WMO 2009). The PMP concept has been adopted in many parts of the world, and several approaches to estimate PMP have been developed such as the

statistical method (Hershfield 1965) and the storm maximization method (WMO 2009). For areas in the western United States, the National Weather Service provides estimated design storms, with the PMP estimation guidance, using the storm maximization approach, published in the Hydrometeorological Reports (HMRs 52 and 57) (Hansen et al. 1982, 1994).

The storm maximization approach (also referred to as the storm separation method in HMRs), which consists of moisture maximization and storm transposition, is the most commonly adopted and extensively studied approach (Casas et al. 2011; Rouhani and Leconte 2016; Hansen et al. 1994). This approach maximizes observed large storms through several steps (see supplemental material S2 in the online supplemental material) under the assumption that at least one storm has the potential to reach the PMP (Hansen et al. 1994). The moisture

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maximization process assumes that maximizing the moisture in storms [i.e., precipitable water (PW)] maximizes precipitation produced by the storms. However, due to the lack of direct observations of PW, PW is estimated by the pseudoadiabatic profile assumption using surface dewpoint temperature or sea surface temperature (SST) of the moisture source area. Therefore, the traditional HMR method essentially maximizes storm precipitation with respect to surface dewpoint temperature or SST alone.

The two main assumptions in the moisture maximization method are 1) the linear relationship of precipitation to PW and 2) the pseudoadiabatic profile to estimate PW from surface dewpoint temperature or SST. However, according to numerical weather simulation results by Zhao et al. (1997) and Abbs (1999), nonlinearity between precipitation and PW was found for the studied mesoscale convective storms. Further, the second assumption of the pseudoadiabatic profile was found to overestimate PW based on extensive observations (Chen and Bradley 2006). Satellite observations also revealed that the rate of PW changes by the increase of surface air temperature would change its behavior for extreme temperature (Fujita and Sato 2017). Recently, some studies have used data produced by climate models to circumvent the lack of observations; however, these studies still use either both of the above two assumptions (Chen et al. 2017) or the first assumption only (Rouhani and Leconte 2016).

Other researchers have developed approaches to numerically simulate maximized storms by numerical weather models (NWMs), which do not depend on the traditional assumptions mentioned above. The initial uses of NWMs in PMP studies were done by Zhao et al. (1997), Abbs (1999), and Cotton et al. (2003). Recent developments on NWM-based PMP estimations were made by Ohara et al. (2011) and Ishida et al. (2015a,b), where they modulated both initial and boundary conditions to simulate design extreme storms. In their moisture maximization process (Ohara et al. 2011; Ishida et al. 2015b), the relative humidity at initial and boundary conditions is maximized to 100%. Furthermore, Ohara et al. (2011) proposed the shifting of atmospheric boundary conditions to transpose storms to the target area without the need to empirically separate orographic and nonorographic precipitation, which is required in the transposition method outlined in the traditional HMR method (Hansen et al. 1994). The above numerical NWM-based estimation approaches are advantageous as they search for the largest storm that can be simulated in a physically based model.

However, little attention has been paid to the realism of the simulated atmospheric fields (e.g., precipitation and atmospheric water vapor) compared to the final

FIG. 1. (a) Schematic diagram of the storm transposition and moisture maximization methods by the previous numerical weather model-based PMP studies (Ohara et al. 2011; Ishida et al. 2015a,b). (b) Schematic diagram of the proposed PMP estimation framework.

PMP values. The moisture maximization method of Ohara et al. (2011), which systematically saturates all the boundaries, potentially introduces disturbances to the fields beyond what is realistic (Fig. 1a). The definition of realism is one of the central issues in this study. It is challenging to define the realism of extreme storms outside of the observed record. This has been demonstrated through numerous unexpected extreme events all over the world (e.g., Hurricane Harvey; van Oldenborgh et al. 2017). Yet PMP estimated by extreme modeling conditions, such as saturating the entire model domain, cannot be scientifically supported. Therefore, we define realistic storms in the current study as the storms that do not significantly deviate from historical storms with respect to the spatial patterns of atmospheric moisture and precipitation. This definition reconciles with the HMR assumption that at least one historical storm has the potential to reach the PMP depths and intensity. Furthermore, recent evidence shows that increasing atmospheric moisture may not result in an increase in precipitation due to storm structure, atmospheric stability, and complex topography (Ohara et al. 2017; Yang and Smith 2018). Hence, atmospheric moisture content may need to be incrementally increased rather than

maximized to simulate the most extreme precipitation intensity, while also retaining the original storm structure. Last, the relationship between moisture perturbation and transposition methods needs to be investigated. While [Ishida et al. \(2015b\)](#) applied the moisture maximization method after finding the optimal shifting location, they did not consider the change of precipitation pattern due to the moisture maximization. Since the modulation of atmospheric moisture would change the evolution of atmospheric thermodynamics, the effects of moisture perturbation and transposition must be simultaneously analyzed.

The main objective of the current study is to propose a new framework as shown in [Fig. 1b](#) for estimating realistic PMP over the west coast of North America, where atmospheric rivers (ARs) are dominant. The fundamental questions are whether the simulated atmospheric fields are realistic, and whether the maximized ARs still preserve the realistic geometry of these fields as compared to historical conditions. Therefore, we aim to increase the physical plausibility of the estimated PMP by introducing a more refined physical treatment of the spatial structure of ARs into the moisture maximization method of [Ohara et al. \(2011\)](#). Second, we re-examine the term “moisture maximization” used in PMP studies. We propose a method termed “moisture perturbation,” which we define as incrementally increasing the atmospheric water vapor to maximize precipitation over a target watershed. This further extends the meteorological plausibility of the design storm since the spatial structure of ARs would not change as significantly as saturating all initial/boundary conditions. We also investigate the relationship between the moisture perturbation and transposition methods simultaneously. The proposed framework simultaneously optimizes the atmospheric water vapor and position of a storm to maximize precipitation produced by the storm. We use the term “optimization” in this study to describe the combination of atmospheric water vapor and storm position that results in maximum precipitation over a watershed based on a number of storms ([Fig. 1b](#)). In this study, we define PMP as the maximum precipitation simulated by NWM from the optimization process. Finally, the simulated atmospheric fields of the PMP scenario are analyzed, and the final PMP estimates are compared to the estimates by the conventional HMR methods.

2. Methods

a. Study area, model, and data

This study focuses on the 18 800 km² Willamette River watershed upstream of Salem, Oregon, as a test case to

FIG. 2. Nested 36-, 12-, and 4-km resolution model domains over the Willamette watershed (18 800 km²) upstream of Salem, Oregon (blue line).

estimate the PMP over a watershed in the Pacific Northwest ([Fig. 2](#)). Over the eastern Pacific Ocean, ARs transport massive amounts of water vapor from the tropics and contribute to the majority of wintertime extreme storms ([Dettinger et al. 2011](#)). ARs frequently make landfall in the Willamette watershed and result in precipitation that causes extreme floods within this orographic watershed. The recent PMP estimates over the watershed ([USACE 2017](#)) are available along with the HMR57 estimates ([Hansen et al. 1994](#)) for comparisons. The 72-h duration is chosen for the main focus of this study because it is one of the widely used durations in PMP studies ([WMO 2009](#)). Furthermore, 72-h precipitation has been shown to produce the highest correlations with unregulated river discharge for the U.S. West Coast basins ([Warner et al. 2012](#)).

The Weather Research and Forecasting (WRF) Model version 3.7.1 ([Skamarock et al. 2008](#)) is employed to conduct numerical experiments on the PMP estimation. Three one-way nested modeling domains with resolutions of 36, 12, and 4 km are used to dynamically downscale atmospheric fields to the Oregon coast, including the Willamette watershed, as shown in [Fig. 2](#). The model parameterization schemes include the Goddard microphysics scheme ([Tao et al. 1989](#)), the New Goddard longwave radiation scheme ([Chou and Suarez 1999](#)), the Fu–Liou–Gu shortwave radiation scheme ([Gu et al. 2011](#)), the Bougeault–Lacarrere planetary boundary layer scheme ([Bougeault and Lacarrere 1989](#)), the old Simplified Arakawa–Schubert cumulus scheme ([Pan and Wu 1995](#)), and the Rapid Update Cycle (RUC) land surface model ([Benjamin et al. 2004](#)). The cumulus

convection scheme is turned off in the innermost domain. This configuration is selected following the calibration and validation results of Toride et al. (2019), who compared daily and 3-day precipitation simulated with various WRF physics options over the Willamette watershed to the gridded Parameter-Elevation Regressions on Independent Slopes Model (PRISM; Daly et al. 2008) dataset during 10 AR events. Additionally, they reconstructed long-term precipitation using the above WRF configuration, and found the Nash–Sutcliffe efficiency coefficient to be 0.69 for daily basin-average precipitation during water years 1982–2010.

The initial and boundary conditions used for WRF simulations are obtained from the Climate Forecast System Reanalysis (CFSR; Saha et al. 2010). CFSR is a global reanalysis dataset generated by a coupled ocean–atmosphere general circulation model by assimilating various observations such as radiosonde data, aircraft observations, surface observations, and satellite radiance observations. The CFSR 6-hourly product with 0.5° horizontal resolution is utilized to reconstruct 4-km historical atmospheric fields over the Willamette basin during the period of water years 1980–2016. The root-mean-square error of annual 3-day precipitation maxima between the reconstructed data using CFSR and the PRISM data is 18 mm over the Willamette watershed during the water years from 1982 to 2016. Additional analyses, including validation of the historical simulation and severe storms, are provided in supplemental material S3.

Severe storm events are then selected based on the 20 largest 72-h basin-average precipitation using the reconstructed hourly precipitation data during 1980–2016 over the Willamette basin. This is based upon the hypothesis used in PMP studies that at least one of the selected severe storm events would reach PMP with storm maximization processes. To confirm the existence of ARs, an AR is identified based on the integrated water vapor transport (IVT) threshold of $250 \text{ kg m}^{-1} \text{ s}^{-1}$ over the northeastern Pacific for each selected storm (Rutz et al. 2014). Supplemental material S4 shows the 72-h averaged PW fields of the selected storm events. The start and end times of a storm are defined by the threshold of 10 mm in 72-h basin-average precipitation (i.e., the storm event starts when 72-h running sum of basin-average precipitation exceeds 10 mm and ends when it is below 10 mm). For maximization purposes, each storm is simulated starting 7 days before the storm starts until 7 days after the storm ends to ensure enough time for initialization. The selected storms are listed in Table S1 in the online supplemental material.

In the storm maximization processes discussed in the following sections, atmospheric initial and boundary

conditions that are given by the reanalysis dataset are modified. Relative humidity at each atmospheric layer is adjusted in the moisture perturbation process. The coordinates of 3D atmospheric variables (temperature, relative humidity, horizontal wind speeds, and geopotential height) are modified through the storm transposition method.

b. Moisture maximization along the pathway of atmospheric rivers

Ohara et al. (2011) developed a moisture maximization method, called relative humidity maximization (RHM), for estimating PMP with NWMs where the relative humidity is increased to 100% at all initial and boundary conditions (Fig. 1a). In this study, we aim to improve this approach by maximizing only the moisture flow in the ARs in order to reduce unnecessary disturbances to associated fields and to reduce the dependency on the selection of the modeling domain. For this purpose, we introduce an IVT criterion to the RHM method as IVT is considered to be the most appropriate variable to characterize ARs (e.g., Ralph et al. 2004, 2005; Neiman et al. 2008a; Warner et al. 2015). The idea of this approach is to maximize the relative humidity only at the boundaries where high IVT values are observed. We use the $250 \text{ kg m}^{-1} \text{ s}^{-1}$ threshold at the outer domain boundary because it is often used to detect ARs (e.g., Rutz et al. 2014, 2015) and is validated to be useful by another approach of Guan and Waliser (2015) in the Pacific Northwest region. IVT values in this study are calculated by the following equation:

$$\text{IVT} = \frac{1}{g} \int_{1000}^{300} q \bar{U} dp, \quad (1)$$

where g is the gravitational acceleration (m s^{-2}), q is the specific humidity (kg kg^{-1}), $\bar{U}$ is the horizontal wind speed (m s^{-1}), and p is the pressure (hPa).

Experiments with the IVT criterion are conducted first by using the historically significant AR event of 5–9 February 1996 (Halpert and Bell 1997). The February 1996 event exhibited clear AR structure (Colle and Mass 2000) and produced the third-largest 72-h precipitation depth in the Willamette basin during the period of 1980–2016 (Table S1). Figure 3a displays IVT and geopotential height during the 5–9 February 1996 storm event. Figure 3b shows the relative humidity field at the 850-hPa level with $250 \text{ kg m}^{-1} \text{ s}^{-1}$ of IVT, indicating the location along the boundary where the relative humidity is maximized in the experiment. When the AR starts to enter the modeling domain at 1800 UTC 5 February, relative humidity along most of the western boundary is maximized. When the AR

FIG. 3. (a) Integrated water vapor transport (IVT; $\text{kg m}^{-1} \text{s}^{-1}$) at 1800 UTC 5 Feb 1996, 0600 UTC 7 Feb 1996, and 1800 UTC 8 Feb 1996. Light gray contours show the geopotential height (m) at 850 hPa, and the red box shows the outer domain of the WRF model. (b) Relative humidity (%) at the same times. The white contours denote $250 \text{ kg m}^{-1} \text{s}^{-1}$ of IVT. The visualized fields are based on the CFSR dataset.

impacts the Pacific Northwest at 0600 UTC 7 February, the maximizing location is shifted toward the south. At the final stage of the AR at 1800 UTC 8 February, the maximizing location becomes limited only to the southern boundary. Rather than maximizing at the entire outer boundary, this approach only maximizes those sections that experience high values of IVT. For instance, the dry atmosphere at high geopotential height around the south of the modeling domain remains at the original conditions. Once the AR passes through, the boundary conditions are no longer modified. This new RHM approach that is based on IVT (hereafter RHM-IVT), as well as the original RHM approach of Ohara et al. (2011) (hereafter RHM), are applied to this 5–9 February 1996 event, and then compared with the control simulation that uses the original initial and boundary conditions.

c. Moisture perturbation and transposition of atmospheric rivers

It is understood that maximizing relative humidity may not result in maximizing precipitation. To increase water vapor in the atmosphere while maintaining the structure of an AR, vertical profiles of relative humidity can be adjusted by several methods. One way is through increasing the relative humidity where it is originally dry as done by Yang and Smith (2018). They made perturbations to relative humidity by the following equation to estimate PMP in Arizona:

$$\text{RH} = (100 - \text{RH}_0)\alpha + \text{RH}_0, \quad (2)$$

where RH_0 and RH are the original and modified relative humidity (%), respectively, and α is a multiplication parameter, ranging from 0 to 1. Another way, as discussed in this study, is through intensifying the original structure by proportionally increasing the relative humidity. In the current study, the relative humidity along the path of an AR is modified for both initial and boundary conditions as follows:

$$\text{RH} = \begin{cases} \min(\beta \text{RH}_0, 97), & \text{if } \text{RH}_0 < 97\% \\ \text{RH}_0, & \text{if } \text{RH}_0 \geq 97\% \end{cases}, \quad (3)$$

where β is a multiplication parameter greater than 1. The cap of 97% is chosen to avoid the saturation immediately after moisture is injected into the modeling domain. The threshold of 97% was also used in an earlier study by Zhao et al. (1997).

The comparison of the two moisture perturbation methods [Eqs. (2) and (3)] is shown in Fig. 4. Following the previous discussion, the atmospheric moisture content is increased only when ARs intersect with the modeling boundary (Fig. 4a). One of the characteristics of ARs is the existence of strong low-level moisture transports as shown in Fig. 4b. If the relative humidity profile is modified by Eq. (2), the increase is dominant in the upper atmosphere (Fig. 4c) where the relative humidity is typically low. On the other hand, the perturbation method by Eq. (3) only increases the relative humidity at the low- to the middle-level atmosphere, and does not modify the upper atmosphere (Fig. 4d).

FIG. 4. Examples of moisture perturbations along the path of an atmospheric river. (a) Integrated water vapor transport (IVT; $\text{kg m}^{-1} \text{s}^{-1}$) at 0600 UTC 6 Feb 1996. The black box shows the outer model domain. (b) Relative humidity (shading; %) vertical cross section along the western modeling domain [line A–B in (a)]. The contours denote water vapor flux ($\text{g kg}^{-1} \text{m s}^{-1}$). Changes in the vertical profile of relative humidity at point C in (a) and (b) with the moisture perturbation methods used in (c) Yang and Smith (2018) [Eq. (2)] and (d) this study [Eq. (3)]. The visualized fields are based on the CFSR dataset.

We choose the perturbation method by Eq. (3) because the purpose of this study is to intensify only the precipitation triggering system and maintain surrounding environments as realistic as possible. This method increases the relative humidity proportionally along the path of ARs. Hence, this method is referred to as RHP-IVT as a whole, and RHP110-IVT when β is 1.1, RHP120-IVT when β is 1.2, and so on.

Additionally, the atmospheric boundary condition shifting method (Ohara et al. 2011; Ishida et al. 2015a) is applied to transpose storms over the target watershed. Please note that geospatial transposition is referred to as “shifting” in this manuscript. Since AR is a synoptic-scale phenomenon (the defined length scale of ARs is

more than 2000 km; Neiman et al. 2008b), the effects of shifting an order of magnitude in the hundreds of kilometers must be evaluated to consider the worst-case scenario. In the present study, atmospheric boundary conditions are shifted with respect to latitude only (hereafter meridional shifting). The latitudinal shifting is limited to 5° north or south so that the change of the Coriolis force component of the absolute vorticity stays less than 10% (Hansen et al. 1994). Shifting with respect to longitude is not employed in the present study because it might render unrealistic atmospheric conditions due to the land–sea contrast in the surface layer and the north–south orientation of the U.S. Pacific Coast. Model experiments indicated that longitudinal shifting did not

contribute to an increase in the most extreme precipitation value over this region (as discussed in more details in supplemental material S5). One of the improvements proposed in this study over the [Ishida et al. \(2015a,b\)](#) approach is the order of shifting and moisture perturbation. While [Ishida et al. \(2015a,b\)](#) maximized the relative humidity at the model domain boundary after they transposed the storms to the optimal locations, we simultaneously optimize the moisture content and position of a storm to account for changes in thermodynamic conditions due to altering relative humidity.

d. Proposed PMP estimation framework

We propose a PMP estimation framework in AR dominant regions as presented in [Fig. 1b](#), which consists of the identification of high potential storms and new storm maximization approach.

- 1) Identification of high potential storms. In this study, a 37-yr reconstructed historical precipitation dataset is used to select AR events that produced strong precipitation over a target watershed. Then, high potential storms can be identified by applying the storm transposition method to the selected AR events.
- 2) Storm maximization. In this step, basin-average precipitation is maximized for a specific duration using the identified high potential storms. The position and atmospheric water vapor are simultaneously optimized to formally estimate the upper bound of precipitation over a study area for a given storm.

The first step in the PMP estimation framework assumes that meridional shifting is a dominant factor for increasing precipitation over a target watershed because of the narrow spatial structure of ARs. To test this hypothesis, we apply meridional shifting without modifying relative humidity and meridional shifting with RHP110-IVT to the selected 20 historical storm events to examine the difference of the impacts.

The maximum precipitation obtained from the above procedure is the PMP estimate of this study. The storm which produces the PMP by a specific amount of transposition and moisture perturbation is called the design storm, and the simulation configuration is called the PMP scenario in this study. The PMP scenario obtained by this method is analyzed and compared to the control simulation. Furthermore, after analyzing the proposed PMP estimation framework using 72-h duration, the method is extended to 24- and 48-h durations. For this purpose, two sets of top 20 severe storm events based on 24- and 48-h basin-average precipitation each are selected using the reconstructed data during 1980–2016 (Table S2). Then, an additional 7 storm events are identified by removing the overlapping events (Table S3) as the strong AR events.

3. Results

a. Moisture maximization along the pathway of atmospheric rivers

[Figure 5a](#) shows the evolution in the control simulation of PW and 500-hPa wind field of the AR during 6–9 February 1996. The narrow band of intense PW intersects the Oregon coast and stretches west to the western domain boundary at the beginning of the storm. Over the next 48–72 h, the streamlines of the AR shift toward the southeast, and move away from the south modeling domain. Vapor transport is significantly strong when the AR hits the Oregon coast, but it diminishes by the end of the event as atmospheric water vapor and the southwesterly flow weaken. Anomalies of PW from the control run are presented in [Fig. 5b](#) (RHM experiment) and [Fig. 5c](#) (RHM-IVT experiment). The RHM method, which maximizes the relative humidity at all initial and boundary conditions, generates unrealistic atmospheric fields. The RHM method forces the atmosphere to have an excessive amount of water vapor throughout the simulation period and significantly modifies the structure of the AR ([Fig. 5b](#)). Worse, under this moisture setting, the PW decreases in some parts of the modeling domain. Overloaded moisture stays in atmospheric columns even after the storm exits the domain. On the other hand, [Fig. 5c](#) shows that the RHM-IVT method only injects moisture when and where the AR exists. The distinct jetlike moisture path coming from the Pacific, the so-called pineapple express ([Dettinger 2004](#)), is present in this method. In addition, the geometry of the AR is preserved as the ratio of the length/width of the AR (PW greater than 20 kg m^{-2}) is greater than 2, following the definition of [Rutz et al. \(2014\)](#) and [Guan and Waliser \(2015\)](#) as shown in supplemental material S4. The southern sector of the AR is most influenced by the RHM-IVT method, where it originally was relatively windy and dry. The intensification of atmospheric water vapor is reduced as the storm passes through and returns to conditions similar to the control simulation on 9 February.

[Figure 6](#) shows the spatial distribution of 72-h precipitation when the basin-average precipitation reached its peak over the Willamette basin obtained by the control, the RHM, and the RHM-IVT simulations. The corresponding time series of basin-average precipitation are shown in [Fig. S6](#). The results show that limiting the maximization location of relative humidity results in higher maximum 72-h precipitation (174 mm for the control, 224 mm for RHM, and 245 mm for RHM-IVT). Thus, increasing water vapor at all boundaries does not necessarily increase precipitation over a target watershed and may significantly modify the spatial structure of the original storms. Hourly precipitation shows that RHM also can

FIG. 5. Analyses of precipitable water for 6–9 Feb 1996: (a) precipitable water (shading; kg m^{-2}) for the control simulation and 500-hPa winds (m s^{-1}); (b) precipitable water anomalies (kg m^{-2}) from the RHM experiment; and (c) precipitable water anomalies (kg m^{-2}) from the RHM-IVT experiment. Anomalies are departures from the control simulation. The thick black line shows the Willamette basin upstream of Salem.

generate precipitation when no rain is observed in the control simulation due to the unrealistic amount of added water vapor in the atmosphere (Fig. S6). On the contrary, RHM-IVT is more adept at amplifying the existing amount of precipitation because this method

only intensifies ARs. The secondary effect of the unrealistically loaded water vapor by RHM appears as heavy precipitation produced after the AR passes through the domain. This phenomenon of spatially overproduced precipitation in the original RHM method is generally

FIG. 6. The spatial distribution of 72-h accumulated precipitation depth (mm) when the basin-average depth reached the maximum for the storm event in February 1996. (a) The control (CTL); (b) maximizing the relative humidity at all boundaries (RHM); and (c) maximizing the relative humidity along the atmospheric river (RHM-IVT250). Each maximum basin-average precipitation depth is shown in the box at the lower right of each panel.

consistent with other modeled storm events as seen in Fig. S7.

The selection of the IVT threshold may affect PMP results. To investigate the sensitivity of the IVT threshold, additional experiments using 15 different ARs are conducted. Figure S7 shows the results of the sensitivity experiments with $\pm 50 \text{ kg m}^{-1} \text{ s}^{-1}$ change in the IVT threshold to maximize the relative humidity. In general, 72-h maximum precipitation increases as the threshold decreases since a larger portion of the boundary is maximized. However, most of the percentage changes with the $\pm 50 \text{ kg m}^{-1} \text{ s}^{-1}$ are less than 5% and the average change among the 15 events is within $\pm 3\%$. This indicates the difference in estimated PMPs by the RHM-IVT method with different IVT thresholds would be small.

We have shown improvements in the atmospheric moisture and precipitation fields by adding a maximization criterion based on an IVT threshold to the moisture maximization method (also see supplemental material S4 for the other events). However, although unrealistic precipitation produced near the modeling boundary by the RHM method (Fig. 6b) is reduced by the RHM-IVT method (Fig. 6c), it is still present where the AR enters. Therefore, the issue of the modeling domain dependency is not fully addressed. Furthermore, the spatial distributions of precipitation resulting from both RHM and RHM-IVT simulations are dramatically modified with respect to the control simulation (Fig. 6a). These results lead to questioning whether the traditional term “moisture maximization” is appropriate in physical NWM-based PMP estimations. Also, since modifying the atmospheric water vapor at the boundary changes the spatial structure of precipitation, PMP needs to be estimated by simultaneously optimizing the transposition location and the moisture conditions of target storms.

b. Moisture perturbation and transposition of atmospheric rivers

To evaluate the effectiveness of the RHP-IVT method (recall that RHP-IVT differs from RHM-IVT in the treatment of the vertical profile in which the relative humidity is modified proportionately from the original structure), the spatial distributions of 72-h accumulated precipitation are analyzed with simulations adjusting the relative humidity and shifting atmospheric boundary conditions simultaneously. Figure 7 shows the simulation results for the AR event in February 1996. As the atmospheric moisture content along the path of the AR is increased (Figs. 7a–d), the areal extent of precipitation enlarges and the basin-average precipitation depth increases. Compared to the RHM-IVT simulation (Fig. 6c), the structure of the precipitation distribution is much better preserved and the unrealistic amount of

precipitation near the boundary disappears. Therefore, the dependency on the selection of the modeling domain becomes small with this approach. Supplemental material S4 also shows that the RHP-IVT method preserves the AR geometry in all events compared to RHM and RHM-IVT. Furthermore, the basin-average precipitation depth of RHP130-IVT (250 mm) is larger than that of RHM-IVT (245 mm), which clearly reveals the need to optimize the atmospheric moisture in order to maximize storms over a target watershed. Higher precipitation can be obtained with more realistic atmospheric conditions. It should be also noted that the precipitation distribution moves toward the south as moisture is increased (Figs. 7a–d). This result confirms that the moisture content and position should be optimized simultaneously.

As atmospheric boundary conditions are shifted toward the south (Figs. 7a,e,i), the precipitation distribution is also shifted toward the south. Basin-average precipitation shows a sharp peak when shifted 1° south. Again, this 1° shift can be justified by the fact that ARs have a horizontal scale of 2000 km. Combining the moisture perturbation and shifting methods, the basin-average precipitation depth reaches its maximum with RHP120-IVT and 1° south shifting (Fig. 7g). The maximum basin-average 72-h precipitation is obtained as 319 mm, which represents more than 80% increase from the control (174 mm) and 56% larger than the historical maximum (205 mm). The precipitation depth decreases when an additional 10% of the moisture is added to this case (Fig. 7h).

Having the proposed PMP estimation approach shown to maintain realistic structures of ARs and precipitation fields, we apply the method to the top 20 severe storms in the Willamette watershed (Table S1). To identify the storms that have high potentials, meridional shifting without modifying relative humidity and meridional shifting with RHP110-IVT are performed on these historical storms. Here meridional shifting is applied with 1° increments. For comparison, simulations applying meridional shifting with RHM-IVT are also conducted. Figure 8 shows the maximum precipitation results when shifted to the optimal location for each moisture condition. As can be seen from the figure, high potential storms, which significantly increase their precipitation by shifting or moisture perturbations, can be identified. The average increases of 72-h precipitation are 23.3 mm (16%) for meridional shifting, 28.4 mm (19%) for meridional shifting with RHP110-IVT, and 37.2 mm (25%) for meridional shifting with RHM-IVT over the watershed. The incremental increase of precipitation is largest by meridional shifting because of the narrow bands of ARs which signify the importance of transposing storms to the optimal locations. With respect to the moisture

FIG. 7. The spatial distribution of 72-h accumulated precipitation depth (mm) when the basin-average depth reached the maximum for the storm event in February 1996. (a) The control (CTL); (b) increasing the relative humidity by 10% along the atmospheric river (RHP110-IVT); (c) increasing the relative humidity by 20% along the atmospheric river (RHP120-IVT); and (d) increasing the relative humidity by 30% along the atmospheric river (RHP130-IVT). (e)–(h) As in (a)–(d), but with shifting atmospheric boundary conditions 1° south. (i)–(l) As in (a)–(d), but with shifting atmospheric boundary conditions 2° south. Each maximum basin-average precipitation depth is shown in the box at the lower right of each panel.

perturbations, precipitation generally increases with more water vapor in the atmosphere. Nevertheless, highest precipitation depths are obtained by RHP110-IVT for the top two events in February 1996 and November 2006. These results imply that maximizing the relative humidity can generally increase precipitation but cannot create critical conditions that produce the most severe precipitation. Figure 8 also shows that some control events represent optimized conditions without transposition or increases in relative humidity (or have maximum storm efficiencies historically) such as the historical maximum event in January 2012, which shows small increases with moisture perturbations and transpositions.

According to the results in Fig. 8, three high potential storm events, which surpass 240 mm of 72-h basin-average precipitation in at least one simulation, are identified: the AR events in February 1996, November 2006, and January 1997. Then, these storm events are maximized by optimizing the shifting location with 0.1° resolution and the relative humidity with 0.1 step in the

multiplicative parameter β . The detailed sampling methodology is provided in supplemental material S6; however, some additional shifting experiments are conducted for the visualization of Fig. 9. The changes in 72-h precipitation depths and the optimal shifting location for each moisture perturbation are summarized in Fig. 9 and Table 1. Without changing the relative humidity, the shifting of the AR event in February 1996 shows a clear and sharp hyperbolic shape in 72-h precipitation as the AR moves toward the south (Fig. 9a). The maximum can be obtained as 296 mm with 1.2° south shifting when atmospheric moisture is not modified. As moisture increases, the shape of the curves does not change dramatically (unless it is maximized) but the optimal transposition location shifts toward the north. The 72-h precipitation reaches the maximum value of 328 mm, which corresponds to the PMP, with 0.7° south shifting and RHP130-IVT. If the effects of transposing the storm to the optimal location and of optimizing the relative humidity are assumed to be simply separated by

FIG. 8. Maximum 72-h basin-average precipitation (mm) for the 20 severe storm events. The comparison of the control (CTL), the maximum case obtained by meridional shifting (Shift), the maximum case obtained by increasing the relative humidity by 10% along the atmospheric river with meridional shifting (Shift + RHP110-IVT), and the maximum case obtained by maximizing the relative humidity along the atmospheric river with meridional shifting (Shift + RHM-IVT). The meridional shifting was applied from 5° south to 5° north with 1° increments.

neglecting nonlinear interactions, the transposition and moisture perturbation contribute to the precipitation increase by 122 and 32 mm, respectively, for the PMP scenario. Decreases in precipitation depth can be seen when the relative humidity is increased by more than 30%. With the RHM-IVT simulations, the precipitation depth becomes lower than the shifting only case, and does not exceed 250 mm.

The AR event in November 2006 yields the second largest 72-h precipitation (Fig. 9b). The maximum depth

of 286 mm is obtained by 0.4° south shift with increasing the relative humidity by 60%. The November 2006 event has a peak around 2° south shift when relative humidity is not modified or slightly modified, but another peak appears around 0.5° south shift as relative humidity increases. The maximum depths for the event in January 1997 are obtained by 2.0° south shift and RHP170-IVT (Fig. 9c). The 72-h precipitation for the January 1997 event almost stops increasing when relative humidity is modified by 50% and decreases when relative humidity

FIG. 9. Maximum 72-h basin-average precipitation (mm) with applying meridional shifting and moisture perturbations along atmospheric rivers for the high potential storm events in (a) February 1996, (b) November 2006, and (c) January 1997.

TABLE 1. Maximum 72-h precipitation depths (mm) obtained by increasing relative humidity together with optimized locations ($^{\circ}$ S indicates southward shift in degrees) for the storm events in February 1996, November 2006, and January 1997. The optimal shifting location indicates the location where 72-h precipitation depth becomes the maximum for each moisture perturbation.

	February 1996		November 2006		January 1997	
CTL	173.9	—	136.2	—	146.3	—
Shift	296.1	1.2 $^{\circ}$ S	254.3	2.2 $^{\circ}$ S	216.7	2.7 $^{\circ}$ S
Shift + RHP110-IVT	313.7	1.0 $^{\circ}$ S	263.8	1.8 $^{\circ}$ S	234.6	2.7 $^{\circ}$ S
Shift + RHP120-IVT	327.3	0.8 $^{\circ}$ S	261.5	0.7 $^{\circ}$ S	240.9	2.5 $^{\circ}$ S
Shift + RHP130-IVT	328.0	0.7 $^{\circ}$ S	268.8	0.6 $^{\circ}$ S	245.0	2.4 $^{\circ}$ S
Shift + RHP140-IVT	325.5	0.6 $^{\circ}$ S	275.6	0.6 $^{\circ}$ S	247.8	2.1 $^{\circ}$ S
Shift + RHP150-IVT	316.5	0.5 $^{\circ}$ S	282.7	0.4 $^{\circ}$ S	249.8	2.1 $^{\circ}$ S
Shift + RHP160-IVT	—	—	285.6	0.4 $^{\circ}$ S	250.6	2.0 $^{\circ}$ S
Shift + RHP170-IVT	—	—	283.2	0.3 $^{\circ}$ S	250.9	2.0 $^{\circ}$ S
Shift + RHM-IVT	247.0	0.2 $^{\circ}$ S	257.0	0.5 $^{\circ}$ S	242.6	2.4 $^{\circ}$ S

is maximized. From the results of the top three events, it can be concluded that atmospheric moisture content and position need to be simultaneously optimized to maximize precipitation for each storm event. In these top three events, the RHM-IVT simulations produce smaller 72-h precipitation depths than those of the RHP-IVT simulations. The maximum precipitation depth by the RHM-IVT simulation is less than 260 mm, which is much smaller than the 72-h PMP value estimated using RHP-IVT.

c. Analyses of the PMP scenario

We examine the atmospheric conditions of the PMP scenario by comparing with the control, the maximum simulation obtained by meridional shifting (1.2 $^{\circ}$ south), and the maximum simulation obtained by meridional shifting and RHM-IVT (0.2 $^{\circ}$ south and RHM-IVT). Figure 10 shows basin-average precipitation, IVT, PW, and their differences from the control simulation. The strong AR hits the watershed from 0000 UTC 5 February to 1200 UTC 9 February, where historical basin-average IVT is about $600 \text{ kg m}^{-1} \text{ s}^{-1}$ (Fig. 10c). During that period, there are two peaks in precipitation of about 4 mm h^{-1} each in the control simulation (Fig. 10a). As atmospheric boundary conditions are shifted toward 1.2 $^{\circ}$ south, the original two peaks are intensified, and stronger peaks appear during 1200 UTC 7 February–0000 UTC 8 February and 0000–1200 UTC 8 February where precipitation amounts are originally below 2 mm h^{-1} . The PMP scenario shows a similar increase with the 1.2 $^{\circ}$ south simulation with a stronger peak during 0000–1200 UTC 8 February of 7.7 mm h^{-1} . The changes in basin-average IVT are not strongly correlated with the changes in precipitation (Figs. 10b,d). IVT decreases at the first precipitation peak during 1200 UTC 7

February–0000 UTC 8 February and increases at the second precipitation peak during 0000–1200 UTC 8 February. The IVT and PW of the PMP simulation are generally higher than those of the 1.2 $^{\circ}$ south shifting simulation as shown in Figs. 10d and 10f but still considerably lower than the historical maxima. The historical maximum basin-average IVT and PW are $1089 \text{ kg m}^{-1} \text{ s}^{-1}$ on 3 December 2007 and 36.7 kg m^{-2} on 16 October 2012, respectively, according to the reconstructed data during 1980–2016. The RHM-IVT simulation produces a larger amount of water vapor over the watershed but IVT and precipitation are lower than those of the PMP simulation.

The distributions of time-averaged IVT when the AR hits the watershed are shown in Fig. 11. The strongest IVT region hits the northern part of the watershed in the control simulation (Fig. 11a), where it is adjusted to the south in the 1.2 $^{\circ}$ south shifting simulation (Fig. 11b). With the RHP130-IVT simulation, IVT becomes stronger and the strongest area is located in the southwest of the watershed (Fig. 11c). Figure 11d shows that the RHM-IVT simulation intensifies IVT near the boundary, though IVT becomes weaker before approaching the coast. This result confirms that the PMP estimate is produced by the AR structure that is similar to the control simulation. Similarly, realistic conditions of time-averaged PW can be found in the PMP simulation as shown in Fig. S8.

Figure 12 displays the time series of differences in basin-average humidity and wind speeds between the control and PMP simulations. Figure 12a shows that there is an increase in specific humidity in the lower atmosphere when precipitation is increased. The difference in zonal wind speed is not consistent but it tends to increase at the surface when extreme precipitation occurs (Fig. 12b). Interestingly, the meridional wind speed at 800–1000 hPa is weakened throughout the storm period as shown in Fig. 12c, although it is still flowing toward the north in the PMP simulation (not shown). This implies that although the change in the magnitude of IVT is not significant (Figs. 9c,d), the direction of vapor flux is changed. The direction of the AR becomes more westerly, which contributed to the enhanced orographic precipitation in the PMP simulation.

4. Discussion

a. Comparisons with previous studies

USACE (2017) estimated the basin-average PMP over the Willamette watershed upstream of Salem using the same general procedures as in HMR57 with some improvements as described in supplemental material S2. We estimated 24- and 48-h PMPs following the proposed framework (Fig. 1b) by using the original

FIG. 10. Analyses on basin-average variables during the storm event in February 1996 with the control (CTL), the maximum case obtained by meridional shifting (1.2° south), the PMP scenario (0.7° south + RHP130-IVT), and the maximum case obtained by maximizing the relative humidity along the atmospheric river with meridional shifting (0.2° south + RHM-IVT): (a) hourly precipitation (mm); (b) precipitation difference from CTL (mm); (c) integrated water vapor transport (IVT; $\text{kg m}^{-1} \text{s}^{-1}$); (d) IVT difference from CTL ($\text{kg m}^{-1} \text{s}^{-1}$); (e) precipitable water (PW; kg m^{-2}); and (f) PW difference from CTL (kg m^{-2}).

20 storms and the additional 7 storms. These PMP estimates are compared to the estimates by the traditional approaches (Table 2). The current study 24- and 48-h PMP estimates were both based on the AR event in November 2006. The 24-h PMP (150 mm) was estimated by 1.8° south shift with RHP110-IVT, while the 48-h PMP (242 mm) was estimated by 0.4° south shift with RHP160-IVT. Note that the experiments with the additional seven storm events did not exceed the 72-h PMP value based on the February 1996 event, indicating the storm selection criteria is robust.

The average PMP estimates of USACE (2017) are smaller than those of HMR57, and our NWM estimation approach produced even smaller PMP estimates than those. There are many possible reasons for the decreasing

PMP depth estimates. First, the traditional methods employ many empirical assumptions (supplemental material S2). One of the main reasons could be the invalidity of the empirical functions for the most extreme cases, such as the linear assumption between precipitation and PW. The increases from the historical maximum based on the reconstructed data during 1982–2016 are 29 mm (24%) for 24 h, 74 mm (44%) for 48 h, and 123 mm (60%) for 72 h with the current approach, and 97 mm (81%) for 24 h, 150 mm (89%) for 48 h, and 186 mm (91%) for 72 h for the USACE (2017) estimates. Hence, our approach results in amplification of the precipitation depth increase for the longer duration, while the USACE (2017) estimates are about 80%–90% larger than historical maximums regardless

FIG. 11. Analyses on time-averaged integrated water vapor transport (IVT; $\text{kg m}^{-1} \text{s}^{-1}$) from 1200 UTC 6 Feb to 1200 UTC 9 Feb 1996: (a) the control (CTL); (b) the maximum case obtained by meridional shifting (1.2° south); (c) the PMP case (0.7° south + RHP130-IVT); and (d) the maximum case obtained by maximizing the relative humidity along the atmospheric river with meridional shifting (0.2° south + RHM-IVT).

of duration. It is likely that shorter duration precipitation has recorded near the estimated PMP value historically, and the proposed approach is consistent with this explanation. It would be unsafe to close the discussion on which PMP values to use, but it should be realized that the physically based NWM approach with a realistic storm maximization method estimated lower PMP values than the traditional storm maximization methods over the Willamette watershed.

b. Future directions

Many avenues exist to further advance the NWM-based PMP estimation approach. We have shown that incorporating the morphology of a synoptic-scale phenomenon (i.e., AR) and optimizing atmospheric moisture improve the realism of atmospheric fields of the design storm and intensify consequent precipitation. Future work should further expand these concepts to other atmospheric phenomena such as tropical cyclones and mesoscale convective systems to rigorously estimate the upper bound of precipitation that physically based

atmospheric models can produce. [Chen et al. \(2017\)](#) used an empirical relationship between SST and PW, and the linear relationship between PW and precipitation to estimate PMP. Following that study, future work could focus on evaluating another moisture perturbation approach by increasing SST in numerical models. It is also necessary to revisit traditional PMP customary practices with numerical models. For instance, the present study assumed that changes in atmospheric moisture and storm location can produce PMP but did not consider other factors such as temperature ([Ishida et al. 2018b](#)), wind field, and flow direction ([Picard and Mass 2017](#)). Again, because changes in one factor may alter the atmospheric thermodynamic structure, these factors need to be simultaneously evaluated. Another area to explore is a critical reevaluation of within-storm temporal distributions and traditional design assumptions that rearrange the temporal sequence within a storm to maximize rainfall rates. Results shown in [Fig. 10](#) suggest that for the ARs analyzed here, within-storm temporal rearrangement (e.g., [Fig. 10a](#)) would not

FIG. 12. Time series of differences between the PMP scenario (0.7° south + RHP130-IVT) and control simulations in basin-average values during the storm event in February 1996 over the Willamette watershed (departures from the control simulation): (a) specific humidity (g kg^{-1}); (b) zonal wind speed (positive indicates wind flowing east); and (c) meridional wind speed (positive indicates wind flowing north).

preserve the IVT and storm morphology. Finally, PMP in a changing climate is one of the most difficult but essential questions that many studies have worked on (Kunkel et al. 2013; Rousseau et al. 2014; Ishida et al. 2018a; Chen et al. 2017). One of the advantages of the developed approach in the current study is that it only maximizes ARs based on the IVT threshold and does not modify the surrounding environments. This means that we estimated a robust PMP without accounting for climate change, rather than treating both effects at once. Thus, future applications of this framework could

TABLE 2. Comparisons of average PMP estimates (mm) by HMR57 (Hansen et al. 1994), U.S. Army Corps of Engineers (USACE 2017), and this study over the Willamette watershed upstream of Salem. The 24-, 48-, and 72-h PMP are obtained by the November 2006 storm maximized by 1.8° shift to the south with 10% increase in relative humidity along the atmospheric river, the November 2006 storm maximized by 0.4° shift to the south with 60% increase in relative humidity along the atmospheric river, and the February 1996 storm maximized by 0.7° shift to the south with 30% increase in relative humidity along the atmospheric river, respectively. Historical maxima are calculated based on the PRISM dataset during water years 1982–2016.

	24 h	48 h	72 h
HMR57	229	345	427
USACE (2017)	218	318	391
Current study	150	242	328
Historical maximum	121	168	205

evaluate how the PMP would change under climate change conditions by increasing the background temperature.

5. Conclusions

NWM-based PMP estimation is a growing research area that uses numerical atmospheric models to estimate the upper bound of precipitation based on physical principles with detailed temporal and spatial information that was not available when the traditional PMP estimation method was originally developed. However, the NWM-based approach has not yet been well established; more attention has been paid to the final PMP values rather than the simulated atmospheric fields that produce the PMP estimate. The purpose of this study was to advance the NWM-based approach with a focus on meteorological realism. In this study, a new NWM-based PMP estimation framework was developed by focusing on the characteristics of ARs. We demonstrated that the developed approach produces realistic atmospheric fields with stronger precipitation over the Willamette watershed when compared to the previous NWM-based studies. The main findings of this study are summarized below.

- 1) Limitations were identified in the moisture maximization method suggested by Ohara et al. (2011), which sets relative humidity at 100% at all initial and boundary conditions. The method was modified by adding a maximization criterion based on an IVT threshold of $250 \text{ kg m}^{-1} \text{ s}^{-1}$ to only maximize the moisture flow in ARs (RHM-IVT). The results showed improvements in the geometry and characteristics of resultant PW, IVT, and precipitation fields. In addition, larger precipitation depths with realistic atmospheric

fields were simulated by the proposed approach when compared to the previous NWM-based method by Ohara et al. (2011).

- 2) To further improve the realism of precipitation fields, the increase in moisture was limited by proportionally increasing the relative humidity along the paths of ARs (RHP-IVT). The results showed that maximizing the relative humidity at the modeling boundary does not necessarily maximize precipitation over a target watershed especially for most extreme cases. In addition, unrealistic amounts of precipitation near the modeling boundary, which were present in moisture maximized simulations, were eliminated, and the simulated precipitation distribution became more analogous to the original structure. We propose that “moisture perturbation” should replace the phrase “moisture maximization” in NWM-based PMP studies.
- 3) Perturbations in atmospheric moisture were found to change atmospheric thermodynamics and hence change the spatial distribution of precipitation. To rigorously estimate the upper bound of precipitation over a target watershed for a specific storm, “moisture perturbation” and “storm transposition” must be applied simultaneously.
- 4) The 72-h basin-average PMP for the Willamette basin was estimated by simulating the AR event of February 1996 with 0.7° shift toward south and 30% increase in atmospheric moisture (RHP130-IVT). No significant changes were found in the overall storm structure. Basin-average IVT and PW were below the historical maximums, but precipitation was 1.89 times larger than that of the original storm and 1.60 times larger than the historical maximum. The PMP was produced by a combination of the optimal atmospheric moisture, location, and direction of the AR.
- 5) NWM-based methods produced lower PMP estimates than the estimates by traditional methods. The PMP estimates from this study were 150 mm for 24-h, 242 mm for 48-h, and 328 mm for 72-h over the Willamette watershed. Larger differences with the traditional methods were found for shorter duration PMPs.

PMPs have been estimated since the mid-1930s due to engineering requirements for risk evaluation and risk-based design of water resource infrastructures (WMO 1986). Many assumptions and procedures that were employed by the conventional PMP estimation approaches led to debates on the concept itself. Although it is also crucial to evaluate other climate conditions such as the existence of stronger winds or warmer air masses,

we focused on improving the moisture maximization and storm transposition. The developed NWM-based PMP estimation method of this study, by providing a physical basis to the simulation of extreme precipitation in severe ARs, could provide a physically realistic alternative to conventional PMP estimation methods over the Western Pacific coastal region of North America as well as other AR dominant regions.

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