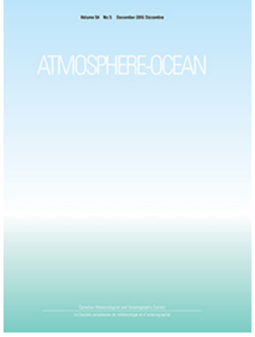

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Evaluation of Total Precipitable Water from CRCM4 using the NVAP-MEaSUREs Dataset and ERA-Interim Reanalysis Data

D. Paquin[1,*], A. Frigon[1], and K. E. Kunkel[2]

[1]*Ouranos Consortium on Regional Climatology and Adaptation to Climate Change, Montréal, Quebec, Canada*
[2]*Cooperative Institute for Climate and Satellites, North Carolina State University and NOAA National Centers for Environmental Information, Asheville, North Carolina, United States*

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ABSTRACT *The fourth-generation Canadian Regional Climate Model's (CRCM4) precipitable water is evaluated and compared with observational data and ERA-Interim reanalysis data over five Canadian basins with simulations driven by ERA-Interim (two) and global climate models (two). Considering the 22 years of data available in the observations, we analyze precipitable water's behaviour through its annual cycle, its daily distribution, and its annual daily maxima. For the simulations driven by reanalyses, differences in annual daily maximum values and their correlations with observations are examined. In general, the values for precipitable water simulated by CRCM4 are similar to those observed, and the model reproduces both the interannual and inter-basin variabilities. The simulation at 15 km resolution produces higher extreme values than simulations performed at 45 km resolution and higher than the observations taken at coarser resolution (1°), without much influence on the mean behaviour. Some underestimation is found with the simulation driven by the Canadian Centre for Climate Modelling and Analysis Model, version 3, a sign of a cold and dry bias, whereas the run driven by the European Centre Hamburg Model, version 5, is much closer to the observations, pointing to the importance of closely considering the regional–global model combination. Overall, CRCM4's ability to reproduce the major characteristics of observed precipitable water makes it a possible tool for providing precipitable water data that could serve as a basis for probable maximum precipitation and probable maximum flood studies at the basin scale.*

RÉSUMÉ *[Traduit par la rédaction] Nous évaluons les données d'eau précipitable du Modèle régional canadien du climat de 4^e^ génération (MRCC4) et nous les comparons aux données observées et aux données de réanalyses (ERA-Interim) pour cinq bassins versants canadiens. Les simulations sont pilotées par ERA-Interim (deux) et par des modèles mondiaux de climat (deux). En tenant compte des 22 années de données observées existantes, nous avons analysé le comportement de l'eau précipitable selon son cycle annuel, sa distribution journalière et ses maximums quotidiens annuels. Pour les simulations pilotées par les réanalyses, nous examinons les différences entre les valeurs maximales quotidiennes annuelles, ainsi que leur corrélation avec les observations. En général, les valeurs d'eau précipitable que simule le MRCC4 sont semblables aux observations. Le modèle reproduit aussi les variabilités interannuelles, et d'un bassin versant à l'autre. La simulation à 15 km de résolution génère des valeurs extrêmes supérieures aux simulations à 45 km de résolution et supérieures aux observations prises à résolution grossière (1°), mais sans montrer d'influence réelle sur le comportement moyen. Une certaine sous-estimation ressort de la simulation que pilote la version 3 du modèle du Centre canadien de la modélisation et de l'analyse climatique, un signe de biais froid et sec. La passe pilotée par la version 5 du modèle Hamburg du Centre européen reste beaucoup plus près des observations, et met au jour l'importance de considérer attentivement la combinaison des modèles régionaux et mondiaux. Somme toute, la capacité du MRCC4 à reproduire les caractéristiques observées majeures de l'eau précipitable en fait un outil capable de fournir des données d'eau précipitable qui pourraient servir de point de départ aux études sur les précipitations maximales probables et sur les crues maximales probables à l'échelle du bassin versant.*

KEYWORDS regional climate modelling; evaluation; precipitable water; observations

1 Introduction

In the context of climate change and projected increases in heavy precipitation in many regions of the globe (IPCC, 2012) and notably over North America (Mailhot, Beauregard, Talbot, Caya, & Biner, 2012; Paquin, de Elía, & Frigon, 2014), possible changes in probable maximum precipitation

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[*] Corresponding author's email: paquin.dominique@ouranos.ca

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(PMP) and probable maximum flood (PMF) in a non-stationary climate is a growing issue for dam safety (Kunkel et al., 2013). An essential component entering into the empirical estimation of PMP is the maximum atmospheric total column water vapour (precipitable water, hereafter PW). In the last few years, outputs from regional climate models (RCMs) have started to be used for computing PMPs and PW (Beauchamp, Leconte, Trudel, & Brissette, 2013; Rousseau et al., 2014) and some climate change studies were performed (Ouranos, 2015). Evaluation of PW using global climate models (GCMs) has been carried out (Gleckler, Taylor, & Doutriaux, 2008), but no evaluations have been carried out for RCMs, which are produced at a resolution best suited to basin representation and of more direct interest to users. The goal of this paper is to assess whether the PW produced by the Canadian RCM compares well with a new observational dataset and would thus be reliable for PMP studies.

2 Data and Methods

a *Observations – NVAP-MEaSUREs Dataset and ERA-Interim Reanalysis*

The first total reprocessing of the National Aeronautics and Space Administration (NASA) Water Vapor Project (NVAP) global water vapour dataset was carried out under the Making Earth Science Data Records for Use in Research Environments (MEaSUREs) program and is called NVAP-M (Vonder Haar, Bytheway, & Forsythe, 2012). This dataset features combined observations of both column-integrated and layered global water vapour from a variety of surface and spaceborne sensors from 1988 to 2009, and three separate data streams are available. We based our analyses on the NVAP-M climate stream because it uses consistent input data and algorithms through time, supporting a more reliable climate analysis. This stream is available at a daily time step with a spatial resolution of one degree. The data-integration approach is adapted to the different instruments potentially available, in which single radiosonde and global positioning system data are assumed to represent the grid box it occupies; if multiple data points are available within a grid box, they are averaged. Also, an error-weighted averaging technique combines all available non-zero total PW observations for a given day, and each sensor is weighted according to a variance based on comparison with observations (Vonder Haar et al., 2012). One must keep in mind that NVAP-M's daily values can come from any time of the day or from a combination of various times.

For a second dataset that incorporates observations, we used the European Centre for Medium-range Weather Forecasts (ECMWF) ERA-Interim data (Dee et al., 2011). Our analysis is based on the total column water (TCW) and total column water vapour (TCWV) available every six hours, derived from High-resolution Infrared Radiation Sounder (HIRS) satellite and radiosonde observations using a one- plus four-dimensional variational data assimilation (1D + 4DVar) method. The TCW is the vertical integral from the ground to the model's nominal top of the atmosphere expressing the total amount of water (vapour plus cloud water plus cloud ice), while TCWV contains only the vertically integrated water vapour.

Earlier versions of the ECMWF reanalysis (ERA-40) and NVAP column-integrated atmospheric water vapour were evaluated and compared with satellite observations by Trenberth, Fasullo, and Smith (2005). Both datasets showed major problems, particularly over oceans, and the authors recommended great care in their use. Fortunately, both products have been substantially improved (Dee et al., 2011; Vonder Haar et al., 2012) and are now considered to be more reliable datasets for evaluating simulated climate model cloud water.

b *Model – CRCM Description*

The four simulations used in this study were performed by the Climate Simulation and Analysis team at the Ouranos Consortium using version 4.2.4 of the Canadian Regional Climate Model (CRCM) (de Elía & Côté, 2010; Music & Caya, 2007) and are described in Table 1. This analysis is based on the data bank of simulations available in-house at Ouranos, which has been now static since the CRCM4 finished its last run in the spring of 2015. The first two simulations are driven by ERA-Interim reanalysis data at a resolution of 0.75°. The NA45_ERA run is performed over a large domain covering North America at 45 km resolution (true at 60°N), and the QC15_ERA run is focussed on a smaller domain (centred over Quebec) with a finer 15 km resolution.

Spectral nudging is applied in the NA45_ERA simulation, which covers the largest domain. The spectral nudging (Riette & Caya, 2002) is applied throughout the domain to drive the large-scale horizontal winds (with wavelengths larger than 1400 km) toward those of the driving data. The intensity of large-scale nudging varies in the vertical, starting from zero just above 500 hPa and increasing to a maximum strength corresponding to a relaxation time of 10 hours at the model top (~10 hPa). This nudging configuration is quite weak considering that at the top of the model a maximum of 5% of the CRCM's large-scale winds are replaced by those from the driving data. This technique is useful to weakly force the regional model's large-scale circulation toward that of the driving data in order to avoid decoupling between the two, a problem particularly prevalent in large domains.

For the smaller Quebec domain, the constraint from the driving data is sufficiently strong that spectral nudging is not needed. The 45 km NA45_CGCM and NA45_ECHAM simulations, performed over the large North American domain, are driven, respectively, by the Canadian Centre for Climate Modelling and Analysis Model, version 3 (CGCM3; member 4) (Flato et al., 2000; Scinocca, McFarlane, Lazare, Li, & Plummer, 2008) and the European Centre Hamburg Model, version 5 (ECHAM5; member 3) (Jungclaus et al., 2006); spectral nudging is used for these 45 km simulations, with a configuration identical to the NA45_ERA run.

TABLE 1. Configuration of the CRCM4 simulations.

Simulation	Driving Data and Period	Resolution	Grid Points	Spectral Nudging	Domain	Output Frequency
NA45_ERA	ERA-Interim 1979–2012	45 km	201×193	Yes	North America	6-hourly
QC15_ERA	ERA-Interim 1979–2012	15 km	226×226	No	Quebec	3-hourly
NA45_CGCM	CGCM3#4 1958–2100	45 km	201×193	Yes	North America	3-hourly
NA45_ECHAM	ECHAM5#3 1958–2100	45 km	201×193	Yes	North America	3-hourly

The runs driven by ERA-Interim can be examined in terms of their temporal correlation of PW with the observations, even though we cannot expect a very high correlation considering the large domain size. In the case of the two GCM-driven simulations, no temporal correlation can be expected, but the CRCM should reproduce the observed climatology, such as the annual cycle and the distribution of PW. In the CRCM4, PW is defined as the sum of the atmospheric TCWV and of the convective cloud ice and water because there is no cloud water or ice contribution from the large-scale scheme in this version; it is an instantaneous value.

c *Basins of Interest*

Five basins were selected over which to conduct the evaluation (Table 2). The choice corresponds to the interest these basins have for the hydroelectric producers who are members of the Ouranos Consortium, such that those same basins were selected for a PMF study under future climate (Ouranos, 2015). The five basins vary significantly in size with the lower Nelson being the largest basin, covering 91,000 km^2, which is more than 25 times larger than the smallest basin, Kenogami. Other intermediate-sized basins have areas ranging from 29,200 to 73,800 km^2. Despite their diversity in size, all basins have common features, notably their location in a northern continental climate.

d *Data Processing*

The original time series outputs of PW from the CRCM and ERA-Interim were integrated over each basin by taking the mean of all grid points contained within the basin contour (see Table 2 for the number of grids points used from each dataset). From these 6- or 3-hourly basin series, we produced daily PW values by computing both the daily mean (DMean) and by extracting the daily maximum (DMax), which is the maximum value of either four (6-hourly time series) or eight instantaneous values (3-hourly times series). We analyzed both types of daily PW values and favoured DMean for the analysis of the mean characteristics (e.g. mean annual cycle, distribution), whereas DMax was used to look at the extremes. In the case of the NVAP-M dataset, because the original data are provided at a daily time step, only one daily series is produced for each basin. The decision to compare DMax with daily NVAP-M for extremes was made with the aim of evaluating dam vulnerabilities with the highest possible values, an evaluation that can be useful with regards to the PMP that represents a dam security criterion.

3 Results

a *Observations Comparison*

Figure 1 depicts the annual cycle of monthly mean PW from the different sources. Concentrating first on observations and reanalysis, we can see that the values in the annual cycle of NVAP-M (black lines) are smaller than those of both ERA-Interim TCW (green) and TCWV (cyan), which are nearly identical (barely distinguishable) throughout the year for all basins. Comparable differences between NVAP-M and ERA-Interim and similarities between ERA-Interim TCW and TCWV can also be seen in the distributions of daily PW (Fig. 2 for DMean and DMax). ERA-Interim TCW and TCWV are very close, but TCW maxima and medians are systematically larger for all basins because of the additional cloud components, the difference being in the order of 1%. NVAP-M is available only at a daily time step, but ERA-Interim (like the CRCM simulations) shows larger values extracted from DMax than from DMean (Fig. 2). NVAP-M's 25th, 50th (median) and 75th quantiles (defined by the box), as well as the whisker (99.3% coverage defined by the whisker bars) are smaller than the corresponding ERA-Interim values. However, the outliers differ most, with ERA-Interim's outliers being smaller than NVAP-M's when taken from DMean and increasing to become comparable (and slightly larger for some basins) to NVAP-M's outliers when taken from DMax (the same will apply to the CRCM simulations discussed in Section 3.b). If we look at the mean of the top 10 larger events, the ERA-Interim DMean values are always smaller those of NVAP-M (mean of five basins is 8.2% lower), while the ERA-Interim DMax values are almost always higher than those of NVAP-M (mean of five basins is 5.5% higher).

In order to evaluate the model's ability to adequately reproduce the observed annual maximum for each basin and look at the interannual variability, we first computed the simulated maximum of the 365 (366) daily values: the annual maximum (Amax), calculated from DMean and DMax. ERA-Interim results, as well as ERA-driven simulations, NA45_ERA and QC15_ERA will be calculated as well because they are expected to reproduce the real climate interannual variability as opposed to GCM-driven simulations. We calculated the annual differences (in millimetres) of Amax precipitable water with respect to the NVAP-M dataset over the 1988–2009 period for each of the five basins, to see the over- and underestimates more easily, and displayed those differences in Fig. 3. Amax calculated from DMax is shown in Fig. 3a and from DMean in Fig. 3b. ERA-Interim TCW is shown, but TCWV is excluded for clarity because its

TABLE 2. Basin location, size and number of grid points for each dataset.

Name	Location (Canadian Province)	Size (km^2)	NVAP-M (# grid points)	ERA-Interim (# grid points)	NA45_ERA-NA45_CGCM-NA45_ECHAM (# grid points)	QC15_ERA (# grid points)
Kenogami	Quebec	3,390	0 (the nearest grid point was used)	1	3	17
Manic-5	Quebec	29,200	4	7	16	140
Mattagami	Ontario	36,800	5	9	24	218
Nelson	Manitoba	91,000	12	26	46	0 (outside model free domain)
Saguenay	Quebec	73,800	9	19	41	363

values are very similar to those of TCW. The figure shows that for most years, ERA-Interim Amax from DMax (green) overestimates the maximum annual daily values with regards to NVAP-M, notably for the Manic-5, Mattagami, and Saguenay basins. Results for the small Kenogami basin and, to a lesser extent, for the large Nelson basin have more variability, with a negative difference occurring in some years for both the model and reanalysis. This highlighted the differences between the two sets of observational data considered here (NVAP-M and the quasi-observational ERA-Interim) and the fact that the climate model is able to reproduce the interannual variability of the driving data and to simulate spatial variability of PW for each basin, as well. We found no direct or systematic link between the behaviour in annual differences from one basin to another (Fig. 3) and their mean annual daily maximum values, shown in Fig. 4. However, the negative differences for Kenogami and Nelson basins are clearly related to high values of NVAP-M Amax PW (not shown) that do not appear in either the reanalysis or the model. In fact, the reanalysis and CRCM4's underestimation (relative to NVAP-M) for 1999 over Nelson and 1998 over Kenogami correspond to the years when maximum daily values are found in NVAP-M from the 22-year period for both basins, which represent very high precipitable water content events (an Amax value of 47.53 mm compared with a mean of 40.82 mm over Nelson and an Amax value of 54.53 mm compared with a mean of 45.54 mm for Kenogami; see means on Fig. 4, Amax not shown). The annual maximum reanalysis values obtained from DMean (Fig. 3b) give differences from NVAP-M that are closer to zero or more often negative, depending on the basin. This behaviour is a direct consequence of the extreme values of ERA-Interim (and CRCM simulations) being larger with DMax than with DMean (see Fig. 2).

Mean values of annual daily maximum precipitable water (millimetres) for 1988–2009 over each basin (Fig. 4) show

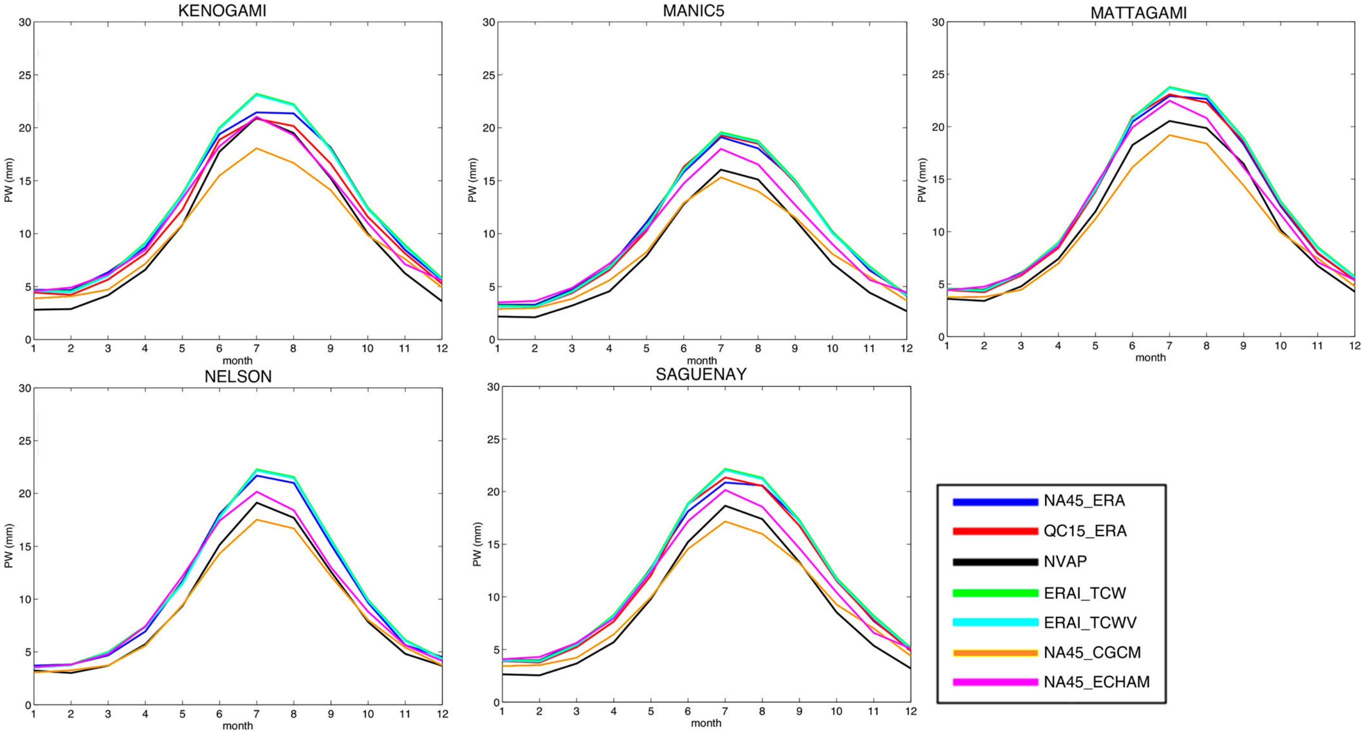

Fig. 1 Annual cycle of monthly precipitable water (mm) calculated over 22 years (1988–2009) for each of the five study basins. Model and reanalysis values are calculated from the daily mean (DMean).

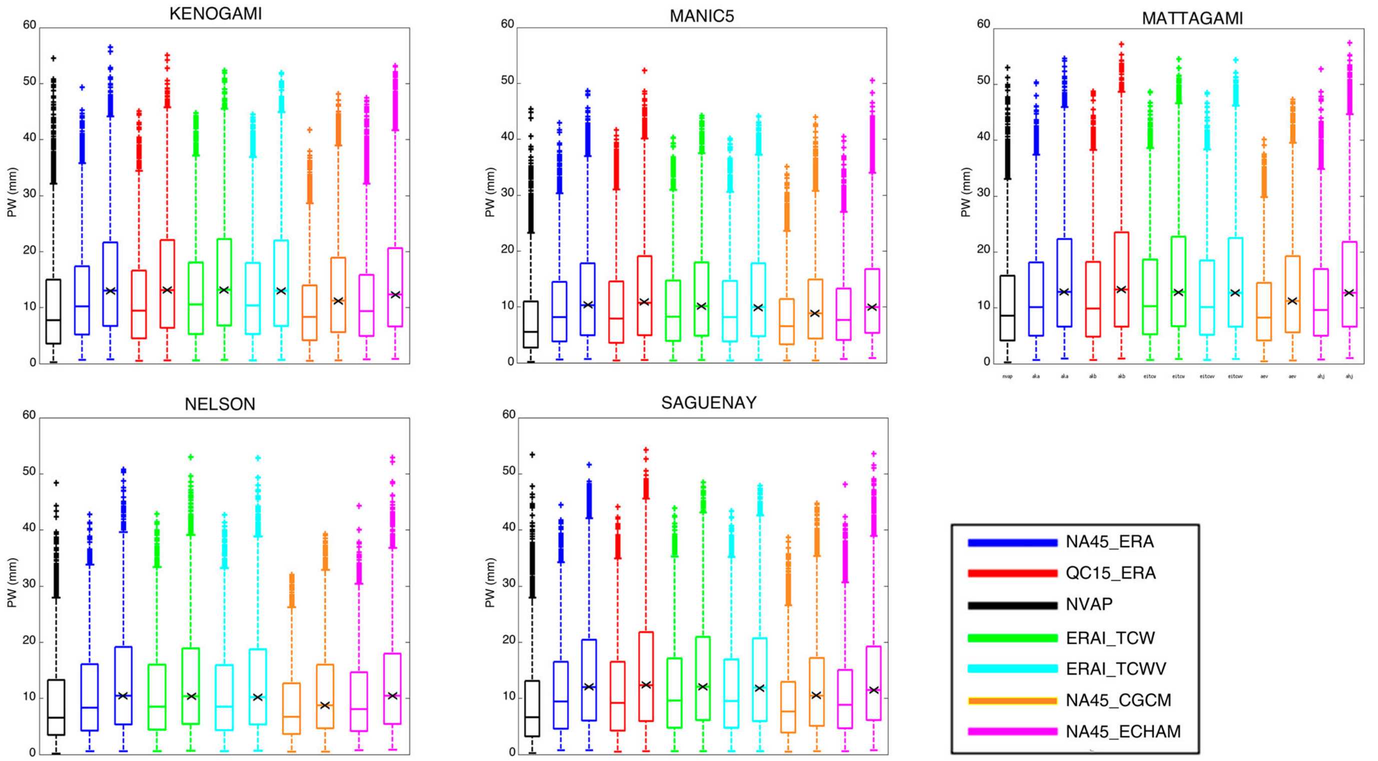

Fig. 2 Distribution of daily precipitable water (mm) for 1988–2009 for each of the five study basins. The 25th, 50th (median), and 75th quantiles are represented by the box. Whiskers represent 99.3% coverage defined by the horizontal bars, and the plus signs indicate the outliers. NVAP-M data are obtained from the daily value. Model and reanalysis values are calculated from the daily mean (DMean) and daily max (DMax), those ones indicated by a cross on the median.

that NVAP-M has systematically lower mean maxima than ERA-Interim TCW and TCWV. The differences between the two datasets are larger than the differences between TCW and TCWV arising from inclusion or exclusion of cloud water and ice.

b *Model Evaluation*

1 SIMULATIONS DRIVEN BY ERA-INTERIM

The two CRCM4 simulations driven by ERA-Interim, NA45_ERA and QC15_ERA, have very similar annual cycles of monthly PW (Fig. 1), as well as the distributions of daily PW (Fig. 2 from DMean and DMax), despite their differences in resolution and domain (see Table 1). Both are similar to ERA-Interim's TCW and TCWV and share common features with the reanalyses' differences with NVAP-M (where its DMean (DMax) outliers are smaller (comparable or slightly larger) than NVAP-M's outliers (Fig. 2), as well as with their general behaviour of the maximum annual daily values (Fig. 3)). Both simulations overestimate the ten largest values from NVAP-M by a little more than 11% (mean basin value) from DMax and underestimate around 5% from DMean. The inter-basin variability is captured well by the model, as can be seen from the mean annual daily maximum PW (Fig. 4). CRCM4 values are closer to ERA-Interim than to NVAP-M, with the same wettest (Mattagami) to driest (Manic-5 and Nelson) basins.

It is interesting to note the correspondence of over- and underestimation years between CRCM4 and ERA-Interim in Fig. 3, even if the differences in CRCM4's annual daily maximum from NVAP-M are usually larger than ERA-Interim's. Figure 5 shows the correlation of the 22 annual maximum values for the 1988-2009 period with ERA-Interim's TCW. As expected, ERA-Interim TCWV has a nearly perfect correlation. Even if the CRCM4 is driven by those reanalyses, we do not expect the model to reproduce the observations perfectly or in this case its driving data; hence, it is not surprising that the model has lower correlation values, considering that here we examine the maximum event per year. In such a specific data comparison, the internal variability of the model can also play a role, even if it is limited by either the spectral nudging (NA45_ERA) or the small domain size (QC15_ERA).

The impact of higher resolution cannot be studied directly because NA45_ERA and QC15_ERA also differ in domain. However, from Fig. 2 we can see that the effect of these differences is limited for DMean but is considerable for DMax when looking at higher percentiles and outliers. Such a feature could be attributed to the increase in resolution, producing more localized features and, thus, more extreme values. When considering the annual daily maximum of precipitable water, we find that the simulation with the finest resolution (QC15_ERA) produces the highest value most years, as can be seen in Fig. 3. However, the "one maximum event per

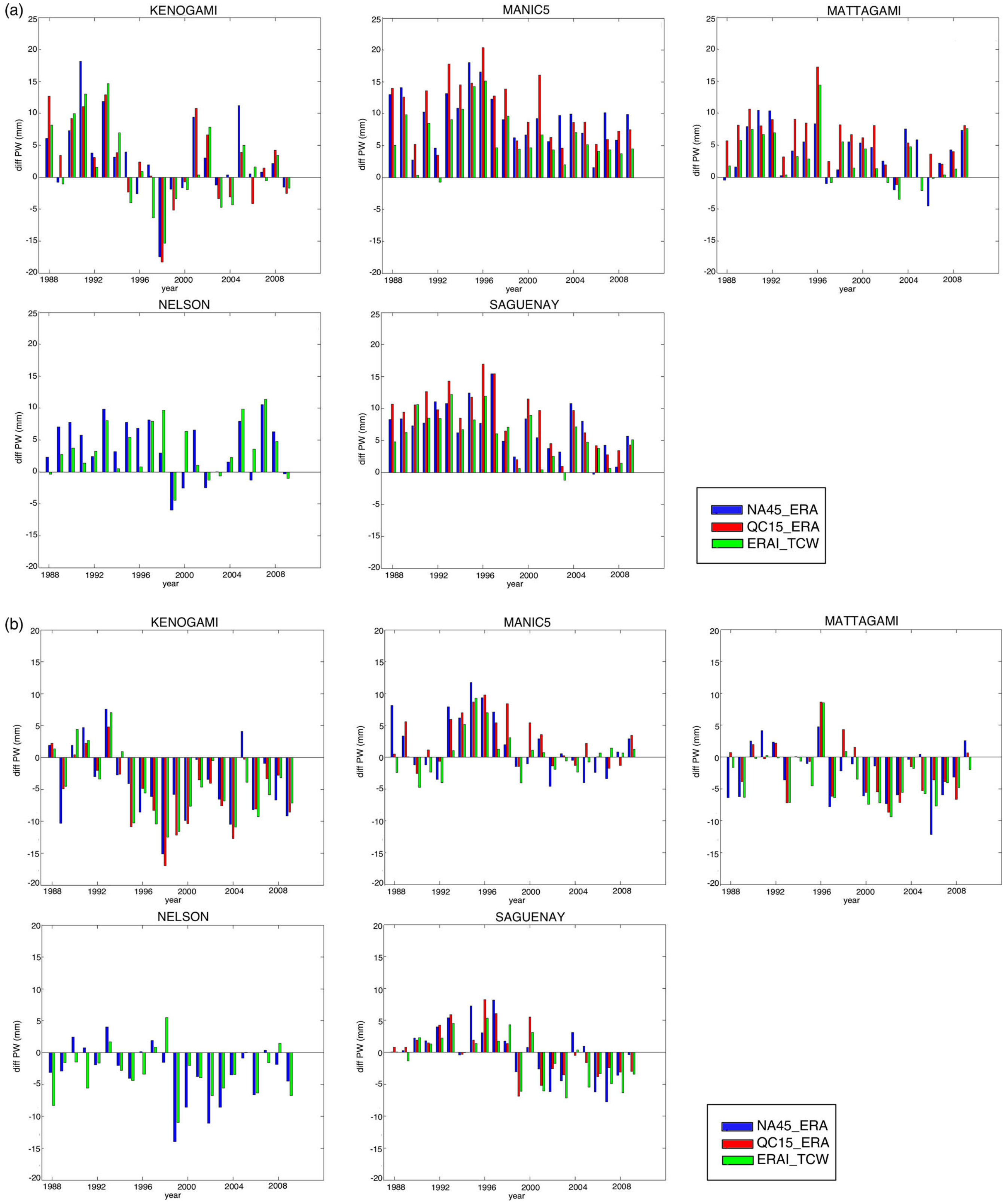

Fig. 3 Annual differences (mm) of Amax (annual daily maximum) precipitable water from the NVAP-M dataset used as a reference over the 1988–2009 period for each of the five study basins. Results are shown from CRCM4 simulations named NA45_ERA (blue) and QC15_ERA (red), both driven by reanalysis data, and for ERA-Interim reanalysis TCW (green). Model and reanalysis values are obtained from the annual maximum of (a) DMax and (b) DMean.

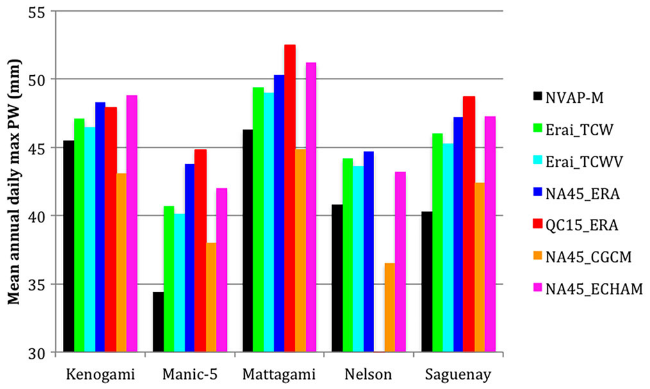

Fig. 4 Mean values of Amax (annual daily maximum) precipitable water (mm) for 1988–2009 over each basin. Reanalysis and CRCM4 simulation values were obtained with the daily maximum value (DMax).

year" factor also plays a role and for some basins, higher values produced by the lower resolution NA45_ERA for just a few years (1991 and 2005 on Kenogami, for example) are sufficient to influence the overall mean (where Fig. 4 gives slightly larger NA45_ERA than QC15_ERA values on Kenogami).

The resolution, along with the domain size, also influences the statistical significance of the correlation of the 22 annual daily maximum values (Fig. 5). With respect to the synchronicity between simulations and observations, the PW in QC15_ERA for the four basins displays a significant correlation with ERA-Interim TCW values, reaching values as high as 0.84 for Mattagami, whereas for NA45_ERA only two out of the five basins have significant correlations. It is difficult to separate the effect of resolution from the domain size, as discussed above, but it is well known that small domains tend to better replicate the driving data and generally lead to an increase in correlation. However, the presence of spectral nudging should help the larger-domain simulations to follow the driving data more efficiently. More simulations should have been performed to correctly evaluate this topic.

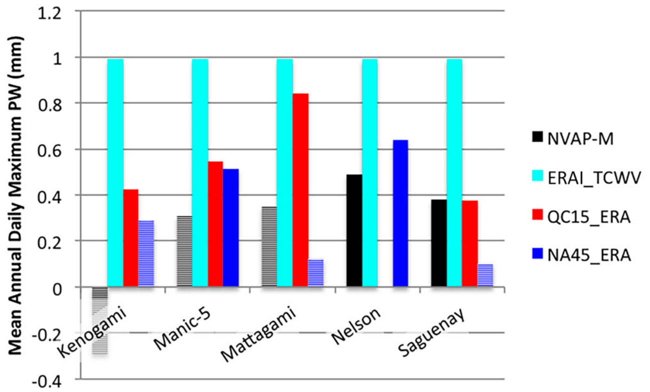

Fig. 5 Correlation of the 22 annual daily maximum values (from the 1988–2009 period) with ERA-Interim TCW over each basin. Bars with horizontal stripes indicate non-significant values.

2 SIMULATIONS DRIVEN BY GLOBAL MODELS

For the two GCM-driven simulations, NA45_CGCM and NA45_ECHAM, annual cycles (Fig. 1), distributions (Fig. 2), and mean values of annual daily maximum PW were evaluated (Fig. 4). Both simulations showed the signal of the driving model strongly. The simulation driven by CGCM3 has smaller values of total PW throughout the year for all basins, and the distributions have smaller values. This behaviour can also be seen in Fig. 4, in which NA45_CGCM always has a value lower than all other simulations and reanalysis values. The largest values are also underestimated compared with those from NVAP-M: a 4% basin-mean value when calculated with DMax and more than a 22% basin-mean value with DMean. This behaviour of the CRCM4-CGCM3 is consistent with a known cold and dry bias in this region, this bias being specific to the interactions of those models (Paquin, 2010; Paquin et al., 2014). The values from NA45_ECHAM, driven by ECHAM5, are much closer to those from NA45_ERA in particular and to the observations in general (ERA-Interim particularly), for the annual cycle, the distributions as well as mean values of Amax PW (Figs 1, 2, and 5).

4 Conclusions

Dam managers have used empirical estimations of PW to evaluate PMP and PMF for years. Recently, they have begun to move away from empirical formulations and instead use data produced by climate models to estimate how these variables will evolve in the future. The evaluation of model output in the current climate using observations is required to ensure that the values of PW are comparable to observations. In this analysis, we compared PW from CRCM4 simulations with NVAP-M daily observations and ERA-Interim reanalysis values over five basins located in eastern Canada. ERA-Interim provides both the total amount of water and vertically integrated water vapour—which are almost identical—and thus enabled us to conclude that vertically integrated water vapour is dominant. NVAP-M has smaller daily values than ERA-Interim for all basins, and this behaviour is general because it is found in both the annual cycle and the distribution (all percentiles). The correlation between the two sets of observations for the annual maximum daily values is significant for only two of the five basins, with values under 0.5. ERA-Interim was used to drive CRCM4 simulations, and the evaluation shows that the model has a clear tendency to be closer to its driving data than to NVAP-M data. The DMean (DMax) computed PW for ERA-Interim and CRCM4 showed behaviours similar to NVAP-M for mean (extreme) characteristics. The difference in the top 10 values of daily PW calculated from DMean (DMax) in ERA-Interim is about -8% (5.5%) of the mean value of the top 10 events. The use of NVAP-M is highly desirable because it represents the state of the art in observational datasets, but the potential underestimate of sub-daily extremes should be kept in mind. The CRCM4 driven by ERA-Interim is able to reproduce the interannual and inter-basin variability. The increased resolution (from 45 to 15 km) of the CRCM4 results in extremes that are larger, without much influence on the mean behaviour of PW. The simulation driven by CGCM3 reproduces a well-known dry bias, whereas the one driven by ECHAM5 does not show a systematic bias. Overall, our evaluation shows that CRCM4 is able to reproduce the major characteristics of the observations well, including annual daily maximum and basin variability and can, therefore, serve as a tool to provide PW data that could be used for PMP and PMF studies. Such a conclusion can be extrapolated to RCMs in general, even though particular features of each RCM-GCM combination will remain an issue to be considered in any study.

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Disclosure statement

No potential conflict of interest was reported by the authors.

ORCiD

D. Paquin http://orcid.org/0000-0002-1353-930X

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