Evolution of Dry and Wet Spells Under Climate Change Over North-Eastern North America

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Key Points:

\begin{itemize}
  \item Wet and dry spells future evolution are assessed using two RCMs ensemble: CRCM5-LE and NA-CORDEX.
  \item Modeling uncertainties are accounted for a bigger contribution to the bias than internal variability.
  \item Both internal variability and modeling uncertainties seem to overwhelm the climate change signal.
\end{itemize}

Abstract

Risks associated to extreme hydrological conditions, such as floods and droughts, are expected to increase in future climate because of projected changes in precipitation and temperature. Assessing how wet and dry persisting conditions (or spells) will evolve in future climate is a crucial step in the study of extreme hydrological events. Projected changes over the north-eastern part of North America in the annual number of wet days, wet, and dry spells characteristics (number, duration), and wet spells intensities are analyzed. Two regional climate model ensembles are considered: the multimember ensemble from the Canadian RCM v5 (CRCM5-LE), and 16 simulations from the NA-CORDEX multimodel ensemble both using the Representative Concentration Pathway 8.5 (RCP8.5) scenario. Comparison of observed and simulated wet and dry spells characteristics is first performed in present climate (1971–2000). Regional Climate Model (RCM)s tend to generate too many wet days and wet or dry spells resulting in shorter dry spells and slightly longer wet spells. Modeling uncertainties are accounted for a bigger contribution to the bias than internal variability since the multimodel ensemble dispersion is the largest. Throughout the 21st century, both ensembles project significant trends in winter at higher latitudes resulting in increasing wet day frequency, increasing number of wet spell, longer wet spells and shorter dry spells. For other seasons, internal variability of the CRCM5-LE and differences among the various NA-CORDEX simulations seems to overwhelm the climate change signal. Wet spell intensities increases are projected for all seasons over almost the entire domain. Globally, wetter climate with potential significant hydrological impacts are expected in many regions.

1. Introduction

Risks associated to extreme hydrological conditions, such as floods and droughts, are expected to increase over many regions of the world due to climate change and can threatened many economic sectors, water systems and infrastructures (e.g., water supply, irrigation, agriculture, storm water infrastructures) as well as populations. Global warming will profoundly affect the water cycle. Thus higher temperature will result in greater evaporation and more extreme droughts while a larger moisture holding capacity of a warmer atmosphere may lead to more intense precipitation events (IPCC, 2012; Trenberth, 2011; Westra et al., 2014). An increase in light and extreme events at the expense of dry and moderate events has been highlighted (Rajah et al., 2014). Besides, lasting dry and wet conditions (or spells) can also have huge consequences on hydrological extremes. For instance, Wasko and Nathan (2019) showed that extreme hydrological events may be impacted by moisture conditions. Dry spell duration can be considered as a proxy of antecedent moisture conditions and drier conditions, while wet spell duration and intensity as surrogate of conditions prone to more extreme hydrological conditions (e.g., flooding). Thus, characterizing and assessing the future evolution of dry and wet spells under climate change is therefore crucial and a major step toward the development of adaptation strategies.

Wet spells (WS) are usually defined as consecutive wet days (WD), a day with precipitation more than 1 mm, preceded and followed by a sequence of minimally one dry day (DD) (i.e., with precipitation less than 1 mm, Ye, 2018; Zolina et al., 2010). Dry spells (DS) are similarly defined as a sequence of consecutive DD preceded and followed by WS. Many studies on wet and dry spells (WDS) using observational datasets from many countries, for instance, China (Bai et al., 2007), Switzerland (Schmidtli & Frei, 2005), Greece (Nastos & Zerefos, 2009), India (Singh & Ranade, 2010), and Germany (Zolina, 2014), are available in the literature. Regional differences in WDS characteristics have been reported either within a country or around the world, and linked to the climatic zones (Li et al., 2017; Vinnarasi & Dhanya, 2016). For instance, some
studies have shown that the changes in WD frequency do not entirely explain the observed long term trends in WDS duration over Europe as these changes are mainly related to the clustering of the WD and DD (Zolina et al., 2010, 2013). Tropical regions are characterized by a larger probability of occurrence of 1-day DS over humid regions compared to 3- to 4-day WS in arid regions (Ratan & Venugopal, 2013). Trends in WS and DS duration display complex geographical and seasonal patterns over Europe (Schmidli & Frei, 2005; Zolina et al., 2013). Increasing trends in DS and decreasing trends in WS durations have been reported over central United States (Groisman & Knight, 2008; Groisman et al., 2012). Seasonal trends are observed over south-western United States with increasing trends during the warm and decreasing trends during the cool season for DS duration (McCabe et al., 2010).

Very few studies analyzed projected changes in WDS characteristics under changing climate. Giorgi et al. (2019), using General Circulation Models (GCMs), concluded that the number of light precipitation events (less than 10 mm/day) and WS durations will decrease while the number of DD and DS durations will increase in a future climate. The resolution of GCMs is however too coarse (~150–300 km) for most hydrological applications or to develop relevant adaptation strategies.

Heinrich and Gobiet (2012) analyzed changes in DS and WS over Europe using the Regional Climate Model (RCMs from the ENSEMBLES (Hewitt, 2004) project. Drier conditions are projected for the southern Europe while wetter conditions are reported for northern Europe. The most extreme and significant changes in terms of spell duration, variability, magnitude, and spatial extension arise in the southern and north-eastern part of Europe. However, this study only reported results for climatological drought indices from monthly to multiyearly time scales which is not necessarily relevant for hydrological applications (e.g., for hydrological modeling). A more comprehensive analysis of WDS characteristics, that is, durations, total precipitation, seasonal changes etc., is essential for hydrological applications. It should be noted that Rajczak et al. (2016) showed that RCMs of the ENSEMBLES project display systematic biases for WDS duration over Europe in historical climate with underestimations for DS and overestimations for WS.

More recently, the COordinated Regional climate Downscaling EXperiment (CORDEX, Giorgi et al., 2009) initiative defined a framework for RCMs simulations over various domains. Using CORDEX-Africa simulation ensemble, Dosio et al. (2019) analyzed the projected changes in annual and seasonal maximum WDS duration in future climate for some regions in Africa. For instance, they found significant reduction in precipitation frequency along with longer DS and shorter WS over West Africa and shorter WS over Central Africa. Significant reduction in precipitation frequency during summer resulting in longer DS were also reported over East and Southern Africa. Raymond et al. (2019), using EURO- and MED-CORDEX simulations, showed that the mean number, duration, and spatial extent of very long dry spells (3–31 day events) will increase in future climate in the Mediterranean region. Panthou et al. (2018) studied the impacts of spatial resolution and Mediterranean sea coupling using MED-CORDEX simulations and showed large biases for the 10-year return level of DS duration over the historical period. In another study, Dosio (2016) highlighted that the EURO-CORDEX simulations tend to overestimate the number of wet days and the duration of the longest wet spell and underestimate the longest dry spell in historical period. The same authors also shown that this ensemble projects an increase in the number of wet days and the duration of the longest wet spell as well as a decrease in the longest dry spell in future climate. Finally Jacob et al. (2014) reported a link between the decreasing length of the longest dry spells and the increasing number of dry spells for some regions. All reported studies analyzed multimodel RCM ensemble and only investigate WDS duration biases or/and changes.

This study focuses on the historical biases and trends of various simulated WDS characteristics that can be useful to improve our understanding of the impact of climate change on future extreme hydrological events. Daily WDS characteristics, such as duration, frequency and WS intensity are considered over a domain covering the north-eastern part of North America. A comprehensive analysis of WDS in historical and future climate using stations records and two RCM ensembles is carried out. NA-CORDEX ensemble, which provides an ensemble of multimodel simulations (Mearns et al., 2017) over the North America domain, and the 50-member Canadian Regional Climate Model Version 5-Large Ensemble (CRCM5-LE, Leduc et al., 2019) are considered. Uncertainties in climate models can be partitioned as follows: scenario uncertainty, model uncertainty, and climate internal variability. NA-CORDEX ensemble is used to investigate model uncertainties and how consensual climate change signal is among the various RCM/GCM combinations, while the
multimember ensemble is used to assess the impact of internal variability on climate change signal. Two main questions are addressed: (i) do RCMs adequately simulate WDS characteristics in historical climate?; (ii) how WDS characteristics will evolve under climate change?

The paper is organized as follows. Section 2 introduces the datasets used in this study, describes the WDS characteristics, as well as the methods used to evaluate the RCM performance and to assess the projected trends. Results are presented and discussed in Section 4 and 5, while Section 6 provides the main conclusions and presents the perspective for future works.

2. Region under Study and Datasets

The study region is the north-eastern part of North America (Figure 1), which corresponds to the simulation domain of the Canadian Regional Climate Model Version 5-Large Ensemble (CRCM5-LE, Leduc et al., 2019).

Daily time series at stations operated by Environment and Climate Change Canada (ECCC, 2016) and the Ministère de l’Environnement et de la Lutte contre les Changements Climatiques (MELCC) of Québec, and by the National Oceanic and Atmospheric Administration (NOAA) agency (http://www.ncdc.noaa.gov/data-access/land-based-station-data) for the United States are considered. The stations are selected according to data availability over the 1971–2000 period. Only stations with at least 20 years with less than 5% daily missing values in each 3-month period (December/January/February, DJF; March/April/May, MAM; June/July/August; JJA, and September/October/November; SON) and over the whole year are considered for this study. More severe criteria for station selection (e.g., smaller percentage of missing daily values or larger number of valid years) had also been considered resulting in a drastic reduction of the number of selected
stations. A total of 961 stations are finally selected, 560 (473 from ECCC and 87 from MELCC) located in Canada and 401 in north-east United states (Figure 1). The spatio-temporal coverage of the station network may be an issue and limits our ability to assess the overall performance of climate model. However, station data set remains the most reliable and direct information on past climate. Interpolated gridded datasets may be biased and subject to large uncertainties especially in remote areas (e.g. northern regions) where information remains sparse (Cai et al., 2019). Reanalysis should also be used with caution in remote areas (Diaconescu et al., 2018). The following results should be interpreted keeping in mind the different nature of simulated (areal average) and observed (on-site) values.

Two climate simulation ensembles are used in this study, the CRCM5 large ensemble (CRCM5-LE) and the CORDEX North America ensembles (NA-CORDEX). As part of Climate change and hydrological Extremes (ClimEx) project, a large ensemble (LE) of 50 high-resolution RCM simulations at 0.11° resolution grid (∼12 km) has been produced over the north-eastern part of North America (Figure 1; for details see Leduc et al., 2019). Boundary conditions used to drive the RCM are provided by the Canadian Fourth generation Atmospheric Global Climate Model (CanESM2, Arora et al., 2011; von Salzen et al., 2013). The 50 independent CanESM2-LE simulations (Fyfe et al., 2017; Sigmond & Fyfe, 2016) are simulated under the Representative Concentration Pathway 8.5 (RCP8.5) emission scenario (van Vuuren et al., 2011). Random perturbations of the initial state of cloud-overlap parameters were applied to generate the various ensemble members with all the other simulation settings (e.g., forcing scenario and model parameters) remaining unchanged (Fyfe et al., 2017). This 50-member ensemble has been used as boundary conditions for the 5th generation Canadian Regional Climate Model (CRCM5, Martynov et al., 2013; Šeparović et al., 2013) and is hereafter called CRCM5 Large-Ensemble (CRCM5-LE). A 4-year spin up period was discarded for each CRCM5-LE member, resulting in 146 years of hourly precipitation available at 280 × 280 grid points over the 1954–2099 period. Simulated hourly precipitation have been aggregated at daily resolution. Specific details about CRCM5 dynamics and subgrid model parametrization are presented in Lucas-Picher et al. (2017), while the ClimEx experiment set-up and validation is thoroughly described in Leduc et al. (2019). Considering the high spatial resolution of the CRCM5-LE, grid values are subsampled at a 1/4 ratio meaning that one grid-point is randomly selected among each nonoverlapping block of four grid-points. This leads to almost the same number of grid-points than the other RCMs (Innocenti, Mailhot, Leduc, et al., 2019). CRCM5-LE was used to assess the spatio-temporal structure of extreme precipitation (Innocenti, Mailhot, Frigon, et al., 2019) as well as the response of daily and subdaily precipitation extremes to future warming conditions (Innocenti, Mailhot, Leduc, et al., 2019). Martel et al. (2020) also evaluated the future changes in the frequency and intensities of extreme precipitations using this ensemble. Overall, this data set provides an improved representation of local extreme precipitation events and temperature variability when compared to global climate models (Leduc et al., 2019).

Sixteen simulations from the CORDEX ensemble over the North American domain (NA-CORDEX, Mearns et al., 2017) at 0.22° spatial resolution and using the RCP8.5 emission scenario over the period 1950–2100 are also considered. Table 1 lists these simulations and the five RCMs used to generate the NA-CORDEX ensembles.

3. Wet and Dry Spell Definition and Characteristics

WS is defined as a sequence of consecutive WD, defined as a day with more than 1 mm precipitation, preceded and followed by a sequence of at least one DD, defined as a day with precipitation less than 1 mm. Similarly, DS is a sequence of consecutive DD preceded and followed by WS. These definitions of WD and DD are widely used in the literature (e.g., Groisman & Knight, 2008; Ye, 2018; Zolina et al., 2010) and eliminate the problem of trace precipitation over high-latitude regions (Mekis & Vincent, 2011). Figure 2 illustrates the definition of WS and DS.

Two characteristics are considered for WS (duration and total precipitation depth), and one for DS (duration). Table 2 lists the related seasonal WS or DS indices considered in this study. Biases over the 1971–2000 historical period and trends over the 1954–2099 period are estimated. WDS statistical properties are estimated in terms of the seasonal mean and maximum duration (in days) of WS and DS, and mean intensity (in mm day−1) of WS. The seasonal fraction of WD (in %) and the seasonal number of WDS are also computed. DS, Dry spells; WD, wet days; WDS, wet and dry spells; WS, Wet spells.
4. Comparison of Simulated and Observed WDS Characteristics in Reference Climate

In order to compare WS and DS characteristics from RCM simulations to corresponding values calculated from station records over the reference period, WS and DS indices for each grid point and each simulation are compared to the corresponding values at the closest station. Differences (biases) between mean observed and simulated WS and DS indices are then computed. The statistical significance of these differences is assessed through the nonparametric Wilcoxon rank-sum test (Wilcoxon, 1945; Wilks, 2011) at the 95% significance level. For CRCM5-LE, the difference between recorded and simulated values is significant if at least 90% of the members (i.e., 45 out of 50) display a significant difference at the 95% confidence level.

Differences between CRCM5-LE simulations are associated to internal variability while differences between NA-CORDEX simulations are associated to GCM/RCM structural/model uncertainties. In the case of NA-CORDEX ensemble, dispersion among the various GCM/RCM simulations are mainly related to modeling uncertainties despite that a part of the observed differences may be attributed to internal variability that

| Institute/RCM (reference) | Simulation name | Lateral boundary conditions | Reference |
|---------------------------|-----------------|-----------------------------|-----------|
| CCCma/CanRCM4 (Scinocca et al., 2016) | CanESM2 CanRCM4 | CanESM2 | Arora et al. (2011) |
| Ouranos/CRCM5-OUR (Martynov et al., 2013; Šeparović et al., 2013) | CanESM2 CRCM5-OUR | CanESM2 | Arora et al. (2011) |
| | CNRM-CM5 CRCM5-OUR | CNRM-CM5 | Voilîer et al. (2013) |
| | GFDL-ESM2M CRCM5-OUR | GFDL-ESM2M | Dunne et al. (2013) |
| | MPI-ESM-LR CRCM5-OUR | MPI-ESM-LR | Giorgetta et al. (2013) |
| UQAM/CRCM5-UQAM (Martynov et al., 2013; Šeparović et al., 2013) | CanESM2 CRCM5-UQAM | CanESM2 | Arora et al. (2011) |
| | GEMatm-Can CRCM5-UQAM | GEMatm-Can | Hernández-Díaz et al. (2019) |
| | GEMatm-MPI CRCM5-UQAM | GEMatm-MPI | Hernández-Díaz et al. (2019) |
| | MPI-ESM-LR CRCM5-UQAM | MPI-ESM-LR | Giorgetta et al. (2013) |
| | MPI-ESM-MR CRCM5-UQAM | MPI-ESM-MR | Giorgetta et al. (2013) |
| NCAR Iowa State/RegCM4 (Giorgi et al., 2012) | GFDL-ESM2M RegCM4 | GFDL-ESM2M | Dunne et al. (2013) |
| | HadGEM2-ES RegCM4 | HadGEM2-ES | Collins et al. (2008) |
| | MPI-ESM-LR RegCM4 | MPI-ESM-MR | Giorgetta et al. (2013) |
| NCAR U.Arizona/WRF (Skamarock et al., 2008) | GFDL-ESM2M WRF | GFDL-ESM2M | Dunne et al. (2013) |
| | HadGEM2-ES WRF | HadGEM2-ES | Collins et al. (2008) |
| | MPI-ESM-LR WRF | MPI-ESM-MR | Giorgetta et al. (2013) |

NA-CORDEX, North American COordinated Regional climate Downscaling EXperiment.

Figure 2. Wet and dry spell definition and characteristics.
cannot be assessed since only one simulation (member) is available for each GCM/RCM pair. Dispersion of biases among NA-CORDEX simulations are therefore compared to dispersion of biases among CRCM5-LE members to assess the relative contributions of internal variability and modeling uncertainties and the overall performance of the CRCM5-LE against the other GCM/RCM pairs.

4.1. CRCM5-LE versus Stations

Biases (sim.-obs.) of seasonal WDS mean index values over the 1971–2000 historical period are calculated at each station/grid point pairs and for each CRCM5-LE simulation. The median of the distribution of the 50 biases is then computed. The seasonal observed mean values over the historical period are given by the violin plots for each index. They give some insights about the magnitude of the observed biases compared to the observed historical values.

Figure 3 shows the median bias for the seasonal mean WD fraction and the number of WS of the 50-member CRCM5-LE during the historical period (1971–2000).

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Table 2: Seasonal WS and DS Indices Considered in This Study

| Definition                        | Abbreviation | Unit         |
|-----------------------------------|--------------|--------------|
| Number of WDS                     | NbWS*        | –            |
| Fraction of WD                    | FrWD         | %            |
| Mean WS (DS) duration             | MeanWSDur    | Days         |
| Maximum WS (DS) duration          | MaxWSDur     | Days         |
| Mean WS rainfall intensity         | MeanWSInt    | mm day$^{-1}$|

* Number of DS and WS are equal ± 1

DS, Dry spells; WD, wet days; WDS, wet and dry spells; WS, Wet spells.

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Figure 3. Seasonal ensemble median biases (sim.-obs.) over the 50-member CRCM5-LE of the mean fraction of WD (left panel, in %) and the mean number of WS (right panel) over the 1971–2000 period. Sites with statistically significant bias (90% of the members with significant differences at the 95% confidence level) are represented by black dots and the corresponding fraction of sites is indicated above the color bars. The 10th, 50th and 90th percentiles of the biases are indicated in the color bars. The distribution of the seasonal index values at stations are represented by violin plots at the upper left corner of each map. CRCM5-LE, Canadian Regional Climate Model Version 5–Large Ensemble.
Figure 3 shows that CRCM5-LE globally overestimates the fraction of WD over all seasons, the only exception being the north-west part of the domain in JJA where underestimations are observed while non-significant biases are observed for some other regions and seasons (e.g., south-west part of the domain in SON). Similar patterns are observed for the number of WS although smaller percentages of significant biases are observed for all seasons. The largest biases (in absolute values) are observed in DJF for both the number of WS and the fraction of WD. JJA shows the largest dispersion of bias values over the region while MAM shows the smallest one as shown by the dispersion of the 10th, 50th, and 90th percentiles values. The largest percentage of significant biases occurs in MAM, while SON has the lowest fraction for both indices. In summary, the biases of WD fraction and number of WS display similar spatial patterns for all seasons. Biases in WD fraction and number of WS are mostly overestimations, a result consistent with the known feature that RCMs generate too many wet days (see for instance, Gutowski et al., 2003). The only exception is observed on the western part of the domain in JJA.

Figure 4 shows the seasonal median biases for the seasonal mean DS and WS duration over the 50-member CRCM5-LE in historical climate (1971–2000). Mean DS durations are underestimated by the CRCM5-LE in MAM and JJA over many coastal regions and, to a lesser extent, in SON and DJF. Overestimations are observed in JJA, and, to a lesser extent, in SON, for inland regions with a transition region oriented along the St-Lawrence valley where biases are close to zero. The largest percentage of stations with significant biases is observed in MAM, while the smallest fractions of significant biases is observed in SON.

Biases for WS duration display less contrasted patterns than for DS durations for all seasons, except DJF, with slight overestimations at a majority of stations and larger biases on coastal areas. More significant and widespread overestimations of WS duration are observed in DJF, which also displays the largest percentages of significant biases.

The largest biases in absolute values occur in JJA for DS and DJF for WS. According to the 10th, 50th, and 90th percentiles values, JJA (resp. DJF) shows the largest dispersion of biases over the region for DS (resp. WS) while MAM (resp. SON) shows the smallest one for DS (resp. WS). The largest percentage of stations with significant biases is observed in MAM for DS and DJF for WS while the smallest value appears in SON.

Very similar conclusions to those drawn for the corresponding mean DS and WS durations are obtained for the seasonal maximum DS and WS duration and annual maximum WS duration. Corresponding maps are presented in Figure S1.
In summary, the spatial distribution of biases for the mean DS duration is negatively correlated to the fraction of WD and number of WS biases, while biases for mean WS duration displays no specific spatial pattern. This suggests that CRCM5-LE simulates too many wet days and too short DS. The only exceptions are observed in JJA and, to a lesser extent, in SON for the western part of the domain as already noted in Leduc et al. (2019). In that case, too dry conditions are simulated (underestimation of the number of WD), which results in too long DS while the durations of WS seem adequately simulated.

Figure 5 shows the seasonal 50-member CRCM5-LE median value of the mean WS intensity over the 1971–2000 period. Large underestimations, of the order of 25%–50% of the observed values, are observed in the south-western part of the domain in JJA and SON. Significant underestimations are mainly observed in DJF, the only exception being a region along the coast in the south of the domain where mean WS intensities are overestimated. MAM displays a similar pattern but with much less significant biases. The largest biases values, number of sites with significant biases and bias dispersion are observed in JJA.

### 4.2. CRCM5-LE and NA-CORDEX Ensemble versus Stations

Mean indices over the 1971–2000 period from the two ensembles (50 simulations from CRCM5-LE and 16 simulations from the NA-CORDEX ensemble) are compared to the observed mean indices at stations over...
Taylor diagrams therefore summarizes the agreement between mean simulated and observed values over all station/grid point pairs of the domain. Taylor diagram summarizes three statistics characterizing the differences between the station and corresponding simulated grid point "centered" values ("centered" refers to the difference between at-site values and spatial average values over all sites): (1) the Pearson correlation coefficient measuring the "similarity" between pairs of centered value; (2) the centered root mean square error (CRMSE) which measures the mean square differences between station/grid point mean centered values; (3) the standard deviation of simulated and observed values at all sites (for more details see, Taylor, 2001). Figure 6 presents the Taylor diagram for the mean WD fraction and number of WS over the historical period. Taylor diagram are interpreted as follow. Reference values (station mean value in our case) correspond to the red diamond on the abscissa. Radial distances from the origin are proportional to the standard deviation while azimuthal positions give the correlation coefficient between the simulated and observed values. Finally, the green circular lines correspond to the CRMSE. Therefore, closer a simulated point is to the observed value (red diamond), smaller is the CRCME, larger the correlation and larger the agreement between observed and simulated standard deviation. It is important to remind that these Taylor diagrams measure the agreement between mean simulated and observed WDS characteristics over all station/grid point pairs of the domain.

The standard deviation across stations of the mean fraction of WD is overestimated by CRCM5-LE for all seasons while NA-CORDEX simulations display a much more contrasted pattern, especially in JJA, with...
Correlations and CRMSE are quite similar for both ensembles except in JJA where NA-CORDEX simulations display a wider range of correlation ranging from close to zero to 0.8. Both ensembles globally overestimate the fraction WD except CRCM5-LE in JJA where the median bias is close to 0. The dispersion of median biases among NA-CORDEX simulations is much larger than among the 50 members of the CRCM5-LE. Despite an overall small bias in JJA, Taylor diagram shows large CRMSE values and low correlation for the CRCM5-LE meaning that the spatial distribution of observed WD fraction is rather poorly represented by this ensemble, as seen on the left panel of Figure 3.

Spatial dispersion of the observed number of WS is quite well captured by the CRCM5-LE in DJF and MAM, while it is overestimated in JJA and SON. The spatial distribution of observed mean number of WS is similarly reproduced by both ensembles, with the highest correlations observed in SON and DJF (around 0.8 to 0.9) and the smallest values in JJA and MAM (approximately 0.6). CRMSE are globally higher for CRCM5-LE (especially in JJA), while NA-CORDEX values are more dispersed. Median biases, correlation, CRMSE and spatial variance values are more dispersed among NA-CORDEX simulations than among CRCM5-LE members. Both ensembles globally overestimate number of WS except CRCM5-LE in SON and JJA where the median bias is close to 0. Performances of both ensembles are poorer (larger CRMSE values and smaller correlation) in JJA for WD fraction and number of WS.

Figure 7 presents the Taylor diagram for the mean DS and WS durations over the 1971–2000 period (median biases are also shown).

**Figure 7.** Taylor diagrams for the CRCM5-LE and NA-CORDEX simulations of the seasonal mean DS duration (left panel, in days) and mean WS duration (right panel, in days) over the 1971–2000 period. Black dots refer to the 50-member CRCM5-LE while colored symbols refer to NA-CORDEX simulations. Subplots at the bottoms show the seasonal median biases (sim.-obs.) for each simulation of the NA-CORDEX ensemble, and the box-plots of the 50-member CRCM5-LE median values for DS (left panel) and WS durations (right panel). Red diamond and red line refer to observed values and seasonal median values over all stations are indicated in square brackets at the top of each subplot. CRCM5-LE, Canadian Regional Climate Model Version 5-Large Ensemble; DS, Dry spells; NA-CORDEX, North American Coordinated Regional climate Downscaling Experiment; WS, Wet spells.
Observed spatial dispersion of mean DS duration is underestimated by a majority of simulations in DJF by both ensembles, while overestimated in JJA and SON by CRCM5-LE and underestimated by most NA-CORDEX simulations. Spatial correlation is quite similar for both ensembles with wider range of values for NA-CORDEX. CRMSE is higher for CRCM5-LE ensemble (especially in JJA and SON) while its spread is wider for NA-CORDEX. The median biases have a wider spread for NA-CORDEX ensemble than for CRCM5-LE which is coherent with the Taylor diagrams. Both ensembles underestimate mean DS duration except CRCM5-LE in SON and JJA where the median bias is close to 0. However the Taylor diagram shows rather higher CRMSE values for the CRCM5-LE (especially in JJA) meaning that, despite a global smaller bias, CRCM5-LE locally over or underestimate mean DS duration (which is coherent with the left panel of Figure 4).

The spatial variability of mean WS duration is overestimated for all seasons and almost all simulations. The dispersion within each ensemble is higher for NA-CORDEX in particular in JJA and DJF. Spatial correlation are quite similar for both ensembles (the range is wider for NA-CORDEX) with poorer correlations in JJA (smaller than 0.4). CRMSE is quite similar in MAM and SON (with wider spread NA-CORDEX though). The dispersion of CRMSE values is much wider for NA-CORDEX in JJA and much higher values are observed for CRCM5-LE in DJF (the spread still remain wider for NA-CORDEX). The median biases are more dispersed among the NA-CORDEX ensemble than for CRCM5-LE which is coherent with the dispersion seen in the Taylor diagrams. Both ensembles globally overestimate the mean WS durations. Note that the range of biases of DS duration is larger than the range of WS duration biases.

The conclusions for the maximum DS and WS duration are similar to those for the mean DS and WS duration. The corresponding Taylor diagrams are available (Figure S2).

Figure 8 presents the Taylor diagram for the mean WS intensity over the 1971–2000 period. One can observe that both ensembles performs poorly in JJA especially CRCM5-LE with negative correlation, suggesting a very strong disagreement between observed and simulated patterns of mean WS intensity, as seen in Figure 5 for CRCM5-LE. Otherwise, spatial pattern correlation is quite similar for both ensembles with wider range for NA-CORDEX. CRMSE is similar for both ensembles, except for JJA. Median biases are more dispersed among NA-CORDEX ensemble than for CRCM5-LE. Both ensembles globally underestimate mean DS duration for all seasons, with the exception of a few NA-CORDEX simulations.

In summary, WD frequencies, number of WS, and WS duration are globally overestimated while DS durations are underestimated by a majority of the NA-CORDEX simulations. Also, mean WS intensities are globally underestimated by NA-CORDEX simulations. These results are in agreement with previous studies (e.g., Diaconescu et al., 2018; Jacob et al., 2014) that showed that climate models tend to generate too much precipitation (overestimation of WD frequencies and WS number) leading to overestimation of WS duration, and underestimations of DS duration.

The variability in performances among the NA-CORDEX ensemble is much larger than among the CRCM5-LE ensemble suggesting that model uncertainties dominates internal variability in explaining the differences between observed and simulated values. CRCM5-LE displays an overall performance within the range, or at the margin, of the NA-CORDEX ensemble, except in JJA (and sometimes in SON and DJF) where CRCM5-LE displays a poorer performance than any of the NA-CORDEX simulation. Also, the dispersion of performances among NA-CORDEX simulations is more significant in JJA for all indices suggesting that RCMs inadequately represent precipitation processes during summer. This may be related to the fact that, despite differences in spatial resolution, the convection is not explicitly resolved but parametrized in these models, which can lead to an inadequate simulation of summer convective rainfall.

Assessing the relative contribution of GCM and RCM to total uncertainties and bias is an important but difficult issue. For instance, the CORDEX ensemble is interesting as it coordinates, compiles and gives access to RCM/GCM simulations from many research groups around the world. For now, the available simulations are unfortunately not designed to provide a complete RCM × CM matrix (with several simulations sharing the same RCM or GCM) that could help to assess the relative contributions of GCM and RCM to total uncertainties. Nevertheless, in order to get insight on these relative contributions of RCM and GCM to model performances, various symbols and colors were used to differentiate the GCM (by colors) and the RCM (by symbols) in Figures 6–8. These figures do not however show clear patterns suggesting that either GCMs or
RCMs have the largest contribution to total biases. It can be seen that CRCM5-LE simulations based on the CanESM2-CRCM5 combination have different performances than the CORDEX simulations using CRCM5 model especially in JJA. It is important to note that, although the core of the CRCM5 model is the same in both cases, major differences in simulation setup (spatial resolution and simulation domain) may explain these differences.

5. Projected Changes in WDS

CRCM5-LE and NA-CORDEX ensemble are analyses to assess the projected changes in WS and DS characteristics. Mean seasonal WS and DS indices are estimated at each grid-point for each year over the period 1954–2099 and trends are estimated using the nonparametric Theil-Sen estimator (Sen, 1968) and the nonparametric Mann-Kendall test (Kendall, 1970). Results for the CRCM5-LE are interpreted as significant if at least 90% of the members (i.e. 45 out of 50) display similar results (95% confidence level) i.e., either significant positive, negative or null trend. For NA-CORDEX ensemble, multimodel significance...
of the projected trends is assessed by the degree of agreement between the results of the trend analysis. As suggested by Dosio et al. (2019), results are considered significant if more than 75% (i.e., 12 out of 16) of the simulations show a statistically significant positive, negative or null trend. Therefore, a significant absence of trend (hereafter 0 trend) is assessed when 90% (resp. 75%) of the simulations of CRCM5-LE (resp. NA-CORDEX) display significant null trend. All other cases are interpreted as “uncertain” (no agreement on climate signal due to internal variability for CRCM5-LE or due to different model outcomes for NA-CORDEX ensemble).

Figure 9 presents the seasonal ensemble-median trends for both ensembles over the 1954–2099 period for the fraction of WD. Both ensembles display relatively similar patterns for each season with fewer significant decreasing trends for NA-CORDEX ensemble. Increasing trends are projected in Northern Québec in MAM, SON and DJF while changes remain uncertain for this region in JJA. Decreasing trends are expected at mid-latitudes (between 40° and 55°) and for coastal regions during JJA and SON according to CRCM5-LE and to a lesser extent for NA-CORDEX ensemble. The largest decreases will occur in DJF over the northern part of the domain. Large regions present uncertain trends both for CRCM5-LE (from 37% in SON to 57% in MAM) and NA-CORDEX (from 30% in DJF to 73% in JJA). Uncertain trends are often observed in transition zones between areas with significant positive or negative trends and areas with non-significant trends. A very large part of the domain will experience no change for both CRCM5-LE (from 11% in JJA to 23% in SON) and NA-CORDEX (from 17% in JJA to 47% in MAM).
Figure 10 presents the percentages of grid-points with significant positive (p), negative (n), null (0), or uncertain (U) trends for the mean DS duration (top left), mean WS duration (top right), number of WS (bottom left) and mean WS intensity (bottom right) for both ensembles (NA-CORDEX at the top of each panel and CRCM5-LE at the bottom of each panel) and each season over the 1954–2099 period. CRCM5-LE, Canadian Regional Climate Model Version 5-Large Ensemble; DS, Dry spells; NA-CORDEX, North American COordinated Regional climate downscaling EXperiment; WS, Wet spells.

CRCM5-LE simulations suggest that a significant part of the domain, corresponding to mid-latitude regions, will experience increasing DS duration in JJA (22%) and to a lesser extent in SON (10%; cf. see Figure S3). Such results are not observed for the NA-CORDEX ensemble, as a very small fraction of the domain (less than 1%) display increasing trends in DS duration. According to NA-CORDEX, more than 50% of the domain will see no change in mean DS duration no matter the season while the climate change signal will remain uncertain for the other parts of the domain. However, both ensembles agree and suggest decreasing trends in mean DS duration in DJF and MAM for the northern part of the domain. This result is consistent with the projected increases in the fraction of WD over this region.

Internal variability seems to have an important impact on DS duration trends as more than 45% of the domain displays uncertain trends according to CRCM5-LE. These regions correspond to transition zones between regions with significant or no trends. Results for the seasonal maximum DS duration are very similar to those for the mean DS duration (cf. see Figure S4). For instance, according to both ensembles, extreme DS duration will decrease in the northern part of the domain during DJF while large parts of the domain, mainly in mid-latitude and southern regions, will experience no change according to NA-CORDEX ensemble (from 58% in DJF and JJA to 81% in MAM) and to a lesser extent for CRCM5-LE (17% in JJA to 38% in DJF).

A significant part of the domain (from 55% in DJF up to 91% in JJA) will experience no change in WS duration according to NA-CORDEX ensemble. Both CRCM5-LE and NA-CORDEX suggest increasing trends for WS duration in DJF for northern regions (cf. Figure S5). As for DS duration, more than 45% of the domain for each season, mainly located in transition zones, displays uncertain trends for WS durations for the CRCM5-LE. Results for the annual maximum WS duration are very similar to mean WS duration (cf. see Figure S6). The most notable feature is that both ensembles project significant increasing trends in DJF for extreme WS duration in northern Québec.
Internal variability also plays an important role in the detection of trends for the number of WS since more than 50% of the domain for each season displays uncertain trends for CRCM5-LE. Increase in the number of WS in DJF are projected by both ensembles for northern Québec (cf. Figure S7). Very large fraction of the domain (between 53% in SON to 86% in MAM) will experience no changes in the number of WS according to the NA-CORDEX ensemble. These fractions are much lower for CRCM5-LE. Finally, a very strong and consistent signal over a large fraction of the domain toward more intense WS is projected, ranging from 39% (JJA) to 93% (MAM) for NA-CORDEX and from 26% (JJA) to 79% (MAM) for CRCM5-LE. Uncertain trends are more widespread in JJA and are mostly observed in south-west regions (cf. Figure S8). No regions will experience decreases in mean WS intensity according to both ensembles.

In the following, trends of WDS characteristics are combined to better assess their potential hydrological impacts. For instance, floods can be expected to be more frequent or severe in future climate if the number of WS increases, DS are shorter, WS are longer and more intense. On the opposite, risk of droughts may increase if the number of WS decreases, DS are longer and WS shorter and less intense. Trends for mean DS duration, mean WS duration, and the number of WS are therefore combined. Each grid-point is classified into a “trend class” according to the simulated trends (positive, p; negative, n; null, 0; uncertain, U) of each of the three previous indices. The total number of possible trend class is 64 (4³). For instance, trend class “npp” corresponds to grid-points where 90% (resp. 75%) of the CRCM5-LE (resp. NA-CORDEX) simulations simultaneously display a significant negative trend for mean DS duration, a significant positive trend for mean WS duration, and a significant positive trend of the number of WS.

Figure 11. Seasonal maps of trend classes for CRCM5-LE (left panel) and NA-CORDEX (right panel) ensemble. Classes corresponds to various combination of significant positive (p), negative (n), null (0), or uncertain (U) trends of the mean DS and WS durations, and the number of WS. Percentage of grid-points within each trend class are given in the lower panel. CRCM5-LE, Canadian Regional Climate Model Version 5-Large Ensemble; DS, Dry spells; NA-CORDEX, North AmericanCoordinated Regional climate Downscaling Experiment; WS, Wet spells.
Figure 11 presents seasonal maps of the resulting trend classes for the CRCM5-LE and NA-CORDEX ensemble with the corresponding bar-charts of the percentage of grid-point belonging to each trend class. Only the four classes appearing at more than 5% of grid-points for at least one season and one of the ensembles, and with at least two out of three indices with significant n, p or 0 trends, are considered. Classes where all the indices have significant null (000) or uncertain (UUU) trends were also considered. Finally, a seventh trend class, called “Other,” is defined, including all the other combinations. CRCM5-LE, Canadian Regional Climate Model Version 5-Large Ensemble; NA-CORDEX, North American COordinated Regional climate Downscaling EXperiment.

Spatial distribution and relative importance of the various trend classes significantly differ from one season to the other and between the two ensembles. DJF is the period of the year with the most contrasted results. Three trend classes, apart from the 000 trend class, with significant trends for at least two of the three WDS characteristics are observed in northern regions: npp (shorter DS, longer WS, and increasing number of WS), npU (shorter DS, longer WS, and uncertain changes in the number of WS), and nUp (shorter DS, uncertain changes in WS duration, and increasing number of WS). The only trend class without any uncertain component is npp, the two others, nUp and npU containing uncertain outcomes for WS duration or the number of WS. These results, combined with previous ones suggesting more intense WS, point toward a wetter future climate for these regions with more intense and possibly longer WS, separated by shorter DS, and a larger or unchanged number of WS/DS sequences. The pUn trend class (longer DS, uncertain changes in WS duration, and decreasing number of WS) appears specifically for the CRCM5-LE ensemble in JJA and, to a lesser extent in SON. The regions where this trend class appears in JJA roughly correspond to Ontario (Canada) while it appears along a US region next to Canada border in SON. Given the uncertain trends for the mean WS intensity over these regions (cf. Figure S8), it may suggest drier conditions in future climate for these regions. It is important to note however that these regions are classified in the mixed trend class “Other” by NA-CORDEX, suggesting a weak or no agreement between models.

According to NA-CORDEX ensemble, between 11% and 40% of the domain, depending on season, will see no significant changes of the three WDS characteristics (class 000). However, WS intensity will increase over large fractions of these regions and therefore, despite WDS characteristics remain unchanged, hydrological changes toward more extreme hydrological conditions could be expected for these regions. Projected changes of WDS characteristics remain uncertain for 10%–26% of the domain according to CRCM5-LE (class UUU). Again, internal variability apparently has a considerable impact on our ability to detect a clear climate signal for WDS characteristics. The final outcome in hydrological terms remains uncertain although more intense WS are expected pointing toward an intensification of hydrological events.

A significant fraction of the domain belong to the mixed trend class “Other” for both ensembles. As a reminder, this trend class includes all the marginal cases with no consistent significant changes for two out of the three WDS characteristics and can be interpreted as that there is no consistent signal detected within CRCM5-LE members or between the NA-CORDEX simulations. In the case of CRCM5, this suggests that internal variability largely overwhelms the climate change signal, and for the NA-CORDEX, that the different representations of the climate system from the various GCM/RCM pairs provide inconsistent projections of future WDS characteristics.

6. Conclusions and Perspectives

Future changes in extreme meteorological events may have huge impacts and increased the risk associated to many hydrological hazards. For instance, climate change may increase the risk of flooding if the likelihood of persisting or more intense wet spell occur. Droughts can also become more frequent and last longer because of persisting dry spell and high temperature conditions. This study is a first step toward a more comprehensive analysis of wet and dry spell conditions associated to extreme hydrological conditions.

Two ensembles based on RCMs were used: the CRCM5-LE and the NA-CORDEX ensemble. The first is a multimember ensemble used to assess the impact of the model internal variability on future climate signal. The second one is a multimodel ensemble used to compare and assess the agreement between the various representations of Earth climate system proposed by the various GCM and RCM combinations on the projected climate signal.
Wet spell (WS) was defined as a day or a sequence of consecutive days with precipitation above 1 mm. Dry spell (DS) was similarly defined. Observed and simulated precipitation series were subdivided in WS and DS. Six seasonal indices were computed: mean WS and DS duration, mean number of WS/DS, maximum annual WS and DS duration, mean WS intensity. The fraction of wet days (FrWD) was also computed, a wet day corresponding to a day with more than 1 mm precipitation.

Daily recorded precipitation from 961 stations located within the simulation domain of the CRCM5-LE covering the north-eastern part of North America were considered to assess the performance and bias of the two climate ensembles in historical climate (1971–2000 period).

The main results and conclusions of the comparison of WDS characteristics in historical period are:

1. Wet day frequencies, number of WS, and the WS duration are globally overestimated, while mean DS duration and mean WS intensity are underestimated by almost all simulations
2. No model systematically outperformed the other models
3. The dispersion of performances among the GCM/RCMs models from the NA-CORDEX model is larger than among the CRCM5-LE members suggesting that the contribution to total bias originating from the different model representations is more significant than CRCM5-LE internal variability
4. The performance of the CRCM5-LE is comparable or at the limit of the range of the performances of the NA-CORDEX ensemble, except in JJA where CRCM5-LE is outperformed by NA-CORDEX-NA simulations
5. The dispersion of model performances among CRCM5-LE and NA-CORDEX simulation is wider in JJA for all indices

Many sources of uncertainties can explain the differences between WDS characteristics estimated from simulations and recorded series. For observed series, stations monitoring precipitation are scarce, nonuniformly distributed across regions (especially in Canada), subject to various biases and errors (e.g., systematic bias due to wind undercatch; Mekis & Vincent, 2011). Data quality is also an important issue (Westra et al., 2014). Comparing simulated precipitation with station records also raises the issue of scale mismatch between observed and grid-point values since simulated grid-point precipitations are generally considered as areal average values (e.g., Chen & Knutson, 2008). These may partly explain the differences between recorded and simulated WDS characteristics (especially for WS intensity) making difficult to rigorously disentangle the contribution from mismatching spatial scales errors and model biases and undermining our capacity to assess model performance.

In order to assess the projected changes in WDS characteristics, trend analysis of mean seasonal WDS characteristics over the period 1954–2099 for each CRCM5-LE and NA-CORDEX simulations was carried out. Trends were assessed using the nonparametric Theil-Sen estimator and the nonparametric Mann-Kendall test (at 95% confidence level). Results of the trend analysis from the various CRCM5-LE simulations were then combined. Thus, ensemble trends are significant if at least 90% (resp. 75%) of the members for the CRCM5-LE (resp. NA-CORDEX) display similar significant trend (positive, negative or null). All other cases are defined as “uncertain” as a result of internal variability for CRCM5-LE or models uncertainties for NA-CORDEX. The main results and conclusions regarding the projected changes in WDS characteristics over the 1954–2099 period are:

1. CRCM5-LE and NA-CORDEX ensemble simulate similar significant trends for high latitudes in DJF pointing toward wetter conditions in future climate
2. Significant increases with very large spatial extend of the mean WS intensities are simulated by both ensembles over the entire domain (except in the South West in JJA). Expected increases vary given the ensemble and the season and can range up to 4.8 mm day−1 in DJF over coastal regions
3. Large fractions of the domain will experience no changes in one or many of the WDS characteristics according to NA-CORDEX ensemble
4. The projected trends remain uncertain (in the sense previously defined) for a large fraction of the domain for both ensembles. These regions are often delineated by regions where significant trends, either positive or negative, are projected

In order to better assess the potential hydrological impact of WDS, seasonal trends for mean DS duration, mean WS duration, and mean number of WS were combined. Results show that only a small fraction of
the domain (6% for CRCM5-LE and 4% for NA-CORDEX), located in the northern part ofQuébec, displays concurrent significant trends for the three indices in DJF, showing an agreement between climate projections toward shorter DS, longer WS, increasing number of WD, and also more intense WS. No changes in WDS characteristics are projected for large regions (between 10% and 40% of the domain depending on season). Mean WS intensity is however projected to increase in many of these regions, which could result in more extreme hydrological conditions despite WS and DS durations and numbers remain unchanged. Finally, no consistent signal is detected for both ensembles in many parts of the domain suggesting that internal variability largely overwhelms the climate change signal for CRCM5-LE and intermodel variability provide inconsistent projections of future WDS characteristics for NA-CORDEX.

The previous analysis of precipitation characteristics in terms of potential hydrological impacts is based on mean climatology and future trends of selected WDS indices. However, no distinction was made between liquid and solid precipitation, which can play a key role in the generation of spring flood in the northern part of the domain. Rain-on-snow events can also be important and cause winter floods. A comprehensive analysis of precipitation indices, as well as temperatures, related to such hydrological conditions implies, among others, to assess the performance of the various models in simulating such indices, which can be difficult considering the lack of quality controlled observational solid precipitation records and the multivariate nature of the corresponding indices.

Results have shown that differences in simulated WDS characteristics among the NA-CORDEX multimodel simulations are larger than between multimember CRCM5-LE simulations. Therefore, if internal variability certainly have an impact on the detection of the climate signal (e.g. also see Martel et al., 2018), differences in representations of the climate system provided by the different models remain the major source of uncertainty. This said, despite the domination of model uncertainties, internal variability can certainly “blurred” the climate signal, showing the importance to simulate various initial conditions (members) from the various GCM/RCM combination to assess how the “agreement” between models can be affected by the internal variability. Internal variabilities as simulated by each multimember ensemble will most likely further reduce our ability to assess “consistent” projected changes in WDS characteristics.

One limitations of this study is the definition of “significant projection” when statistical trend tests from the various simulations (either CRCM5-LE or NA-CORDEX) are combined to assess the “significance” of the ensemble. Stricter criteria (e.g., higher number of same sign significant trends for CRCM5-LE or NA-CORDEX) would reduce the number of grid-points with significant trends. Ensemble size may also be a limiting factor. For NA-CORDEX, the limited number of available GCM/RCM simulations prevent a complete coverage of model uncertainties on projected changes for WDS as the NA-CORDEX GCM/RCM simulation matrix remains incomplete (cf., https://na-cordex.org/simulation-matrix.html).

In this study, the climatological biases and trends of WDS characteristics are analyzed in order to provide more insight for impact studies which means that GCM/RCM simulations will be eventually be used as input data in impact models. The climate impacts interpretations/applications are usually derived/calibrated from observational datasets and RCMs would then be used to assess those impacts under climate change. Therefore, biases have to be corrected both in terms of precipitation occurrence and intensity. A natural perspective is to analyze the impact of bias correction (BC) on WDS characteristics. Currently, bias-corrected simulations are available for a subset of the NA-CORDEX ensemble adapted to impact modeling. However, using these bias-corrected simulations in an ensemble analysis may not be appropriate. Indeed, each simulation has been corrected with respect to the same reference data set which necessarily reduce (or at least change) intermodel variability (Vaittina Aayar et al., Accepted). This can undermine the primary added-value of using a simulation ensemble to study the climate variability and their impacts. Combining BC and simulation ensemble need to develop new BC approaches which are able to keep the ensemble variability.

Last but not least, one other way to go further in the analysis of WDS characteristics would be through partitioning and estimating the uncertainty components for simulation ensemble in order to attribute the source of ensemble variability. They can be decomposed into various contributions from these components though ANOVA analysis (e.g., Hingray et al., 2019). Combining such analysis with BC, that is, partitioning and estimating the contributions of the different source of uncertainties before and after BC can help to
evaluate the effects of BC over the different model uncertainties components and which one of them contribute the most to the total bias.

Data Availability Statement

The CRCM5-LE data set for the north-eastern North America domain can be obtained at https://www.climex-project.org/en/data-access. The NA-CORDEX data set are available at https://www.earthsystemgrid.org/search/cordexsearch.html. The daily precipitation data were freely obtained from NOAA Climate Prediction Center (CPC) (http://www.ncdc.noaa.gov/data-access/land-based-station-data). Maximum daily precipitation data (DMPC) for Canada were acquired from Environment and Climate Change Canada (ECCC) and from the MECC of Québec (data available upon request by contacting info-climat@melcc.gouv.qc.ca).

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