Potential of the coupled WRF-Hydro modeling system for flood forecasting in the Ouémé-river basin (Benin, West Africa): an assessment with the Stochastic Kinetic-Energy Backscatter Scheme

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Abstract

Since 2000s, most of West-African countries and particularly Benin have experienced an increased frequency of extreme flood events. In this study we focus on the case of the Ouémé-river basin in Benin for the period 2008-2010. To investigate on how to early warn flood events in this basin, the coupled atmosphere-hydrology model system WRF-Hydro is selected. Such a coupled model allows to explore the contribution of atmospheric components into the flood event, and its ability to simulate and predict accurate streamflow. The potential of WRF-Hydro in correctly simulating streamflow in the Ouémé-river basin is assessed by forcing the model with operational analysis datasets from the ECMWF. Atmospheric and land surface processes are resolved at a spatial resolution of 5km. The additional surface and subsurface water flow routing is computed at a resolution 1:10. Key parameters of the hydrological module of WRF-Hydro are calibrated offline, and tested online with the coupled WRF-Hydro. The uncertainty of atmospheric modeling on coupled results is assessed with the stochastic kinetic-energy backscatter scheme (SKEBS). WRF-Hydro is able to simulate the discharge in Ouémé river on offline and fully-coupled modes with a Kling-Gupta Efficiency (KGE) around 0.70 and 076 respectively. In fully-coupled mode the model captures the flood event that occurred in 2010. A stochastic perturbation ensemble of 10 members for three rain seasons shows that the coupled model performance in terms of KGE is from 0.14 to 0.79. This ability in realistically reproducing observed discharge in the Ouémé-river basin demonstrates the potential of the coupled WRF-Hydro modeling system for future flood forecasting applications.

1. Introduction

In its 5th report, the Intergovernmental Panel on Climate Change (IPCC) stresses the increment of the number of extreme weather events for the 21st century due to climate change (IPCC, 2014). Tropical countries of West Africa are threatened particularly by climatic hazards, such as droughts, floods, high winds, elevation of the sea level, etc. Droughts and floods are the most important in terms of damages and impacts. Countries in West Africa such Benin, Burkina Faso, Cote d'Ivoire, Niger, Senegal, and Togo have suffered from catastrophic floods (Hounkpè et al., 2015) with severe consequences as loss of life, property and damage. For example, a case of the Ouémé-river in September-October 2010, Benin experienced dramatic flooding, which affected 680,000 people, leading to 43 deaths (UNHCR, 2010).

Such damaging floods make it necessary to improve hydrological forecasts in order to reduce the vulnerability of regional and local communities. Identifying the drivers of change in flood regimes in West African watersheds is a complex task due to the heterogeneity of the region and the changing hydrological functioning of watersheds as a result of human activity. Nka et al., (2015) found that there is significant trend in terms of flooding magnitude and frequency in West Africa with two main patterns: the Sahelian showed increasing flood trends, whilst some Sudanian area presented decreasing flood trends.

Flood events analysis are usually performed with hydrological models. Such models use precipitation input from different sources: radar, remote sensing, rain gauges or simulated precipitation from numerical weather models. The operational global weather forecast centers routinely provide relatively coarse precipitation forecasts with resolutions of 16–27 km (e.g. Givati et al., 2016).

Because these kind of forecasts could not provide necessary details of complex, intense precipitation structures led by the mesoscale orography, land-surface heterogeneities, and land-water contrasts (Fiori et al., 2014), Givati et al., (2012) used the Weather Research and Forecast (WRF) model to provide high-resolution precipitation forecasts of 1.3 - 4 km horizontal resolution. They found that the WRF model was able to provide precipitation forecast both in terms of amount and spatial distribution. This output from the WRF model (here the upper-Jordan-River basin) was used as forcing to run the Hydrological Model for Karst Environment (HYMKE). Similar experiments were set in different areas and the authors showed that the precipitation estimates with WRF is able to reproduce the spatial distribution of precipitation, but may underestimate the magnitude of the heavy precipitation events when compared to rain gauges or global observation datasets.

Several studies (Bouilloud et al., 2010; Chen, Fei ; Dudhia, 2001; G. Seuffert, P. Gross & Wood, 2002; Jasper, Gurtz, & Lang, 2002; Marty, Zin, & Obled, 2013; Moreno, Vivoni, & Gochis, 2013; Zabel & Mauser, 2013) have shown the benefits of choosing coupled atmospheric-land-surface models for estimating temperature and precipitation in different areas. Wagner et al., (2016) investigated and evaluated simulations with a fully coupled atmospheric-hydrological model (WRF-HMS) and uncoupled model for various meteorological variables and showed a better performance for the fully coupled model against the uncoupled; whilst another study led by Senatore et al., 2015 compared a one-way forced implementation of the WRF-Hydro system to a fully 2-way coupled instance of WRF/WRF-Hydro in order to assess the impact of 2-way coupling on simulated precipitation and streamflow. They found that the two setups performed well for the precipitation, but the matching to observed data was higher for the two-way coupled WRF/WRF-Hydro simulation in terms of statistical performance criteria.

To assess the advantages and limitations of one-way versus two-way coupled modeling systems for flood prediction over Ayalon basin (Israel), Givati et al., (2016) used both a hydrological model (Hydrological Engineering Center-Hydrological Modeling System, HEC-HMS) and the WRF-Hydro modeling system. The models were forced by observed, interpolated precipitation from rain-gauges within the Ayalon basin, and with modeled precipitation from the WRF atmospheric model. Comparing simulations with the one-way coupled WRF model and the two-way coupled WRF/WRF-Hydro modeling system, they found that the use of two-way atmospheric- hydrological coupling has the potential to improve precipitation and, therefore, hydrological forecasts for early flood warning applications.

It is important to acknowledge here that the model uncertainty in simulating precipitation can be relatively high. Model uncertainty can for example be evaluated with a model ensemble (e.g. Errico et al., 2002). Berner et al., (2009) developped the Stochastic Kinetic Energy Backscatter scheme (SKEBS) within the WRF model in order to generate such an ensemble.

The goal of the present study is to develop a model system able to simulate flood events in the Ouémé-river basin, Benin, West Africa, in order to be used for potential flood prediction later. According to successful examples in the literature, we use the atmospheric-hydrological modeling system WRF-Hydro for this purpose. Section 2 gives the characteristics of the study area as well as different sources of dataset used. The modeling approach, including calibration and evaluation of the model offline, the coupled modeling, and ensemble generation, is detailed in section 3. Results are provided in section 4, whilst section 5 is dedicated to a summary and conclusion.

2. Study area and observation datasets

The study area is in West Africa, located between latitudes 0°N and 18°N and longitude 7°W and 12°E, as displayed in Fig. 1. This also constitutes the setup of the WRF domain. This region is bordered in the South by the Gulf of Guinea, in the north by Mali and Niger. Nigeria highlands form the eastern boundary while the Mauritania, Mali and Ghana form the western limit. The annual mean temperature is about 18°C, but the monthly mean can be more than 30°C over the southern part of Sahara. Rainfall pattern over this region is mostly affected by ocean currents and local features such as topography. In terms of climatic zones West Africa is characterized by mainly three different regions: the first region covers the Sahel and is characterized as a semi-arid zone located from western Senegal to eastern Sudan between 12°N and 20°N. The second zone is the Sudano-Saherian and the third zone comprise Guinea coast, which is characterized by a bimodal mode driven by the Inter-Tropical Divergence (ITD). The basin is located in the Benin republic.

The republic of Benin is in the inter-tropical zone (between 06°10′N and 12°25′N), that has a wet and dry tropical climate (Hounkpè et al., 2015). It contains the interested rivers (Savè and Bétérou) on which we focus in this study (see Fig. 1). The Ouémé catchment at Savè (resp. Bétérou : inner-catchment to Savè) outlet covers an area of 24.800 km^2 (resp. 10.475 km^2). It is located between 7º58-10º12N and 1º35-3º05E, and represent 47 % of the whole Ouémé-river (Le Barbé et al., 1993). The seasons correspond to the periods of dominance of the wet tropical continental air masses. The seasonal distribution of rainfall follows the direction of the ITD and varies almost proportionally with distance from the coast. Therefore, Bétérou has a unimodal precipitation regime (May to October), whilst the southern part of Savè catchment has transitional regime (April and October, with some time a short dry in August). The average annual rainfall between 1960 - 2007 is 1200 mm at the Bétérou rainfall station, and

1100 mm at Savè. The flow dynamic is characterized by a high discharge during the rainy season. The maximum flow between May and September over the period 1960-2007 is in the order of 270 m^3/s at Bétérou and 480 m^3/s at Savè outlet. From November to May almost all the rivers dry up and the averages of low flows is about 5m^3/s at Savè, and 2m^3/s at Bétérou. The annual mean temperature range is between 24ºC and 33ºC.

A particular focus in our assessment is on the year 2010, known as the year when Ouémé-river experienced a dramatic flooding. Hounkpè et al., (2015) showed that the maximum values of discharge recorded during period 1989-2009 is less than 1400 m^3/s at Savè, and 650 m^3/s at Bétérou. Analysis of station data for period 1960-2007 showed that the peaks of discharge at Savè (resp. Bétérou) are about 910 (resp. 470), 1067 (resp. 560), and 1200 (resp. 640) m^3/s respectively for 5-, 10-, and 20-year return period.

The discharge and precipitation station data used in this study were collected over Savè and Bétérou outlets of Ouémé-river basin. The 3-hourly satellite estimates of Tropical Rainfall Measuring Mission (TRMM, 3B42 v7 derived daily at 0.25° horizontal resolution, 1998-near-present; Huffman et al., 2007) dataset and, the daily Climate Hazards Group Infrared Precipitation with Stations (CHIRPS; chirps- v2.0 at 0.05° horizontal resolution; 1981-near-present; Funk et al., 2015) is used for model evaluation.

3. Method

3.1. Weather Research and Forecasting (WRF) and WRF/WRF-Hydro model setups over West-Africa

The Weather Research and Forecasting (WRF) version 3.7.1 is utilized both for WRF-only and fully-coupled WRF/WRF-Hydro modeling over the research area. In the following, the fully coupled WRF/WRF-Hydro is referred as WRF-H. It is a non-hydrostatic, mesoscale Numerical Weather Prediction (NWP) and atmospheric simulation system. Table 1 shows the different physics schemes and experimental details. The setup uses one domain at 5-km spatial resolution covering the area 7ºW-12ºE, 0º-18ºN and 400x400 grid points, with 30s as numerical simulation time step. The vertical structure of the domain consists of 50 levels, from the surface up to a 10 hPa pressure top. The option of land use categories "Moderate Resolution Imaging Spectroradiometer (MODIS, 20 classes; Friedl et al., 2002)" is selected. The Noah LSM model (Chen Fei and Dudhia Jimy, 2001) is used as the column land surface physics model.

For purposes of hydrometeorological simulations with WRF-H, the WRF domain is additionally coupled with routing processes at 500 m resolution with 4000 × 4000 grid points in east-west and north-south directions. The fully coupled mode simulations are performed for 3 years, from January 2008 to December 2010, with January-February 2008 as spin-up period. The driving data is the operational analysis dataset from European Centre for Medium-Range Weather Forecasts (ECMWF) which provides the initial and lateral boundary conditions. Both WRF-H and WRF-only components of the coupled modeling system share the same physics parameterizations Table 1.

3.2. Calibration of Weather Research and Forecasting-Hydro in offline mode

The uncoupled WRF-Hydro model consists of a variety of parameters (e.g. Kerandi et al., 2018), which usually require calibration. Since the aim of the research is to evaluate the performance of WRF-Hydro to simulate discharge, and therefore analyze its predicting skills about floods, the calibration is performed based on discharge at the Savè catchment outlet.

The WRF model is run over the domain displayed in Fig. 1a in order to generate atmospheric input data for the uncoupled WRF-Hydro calibration. To reduce the computation cost for the calibration, the simulation domain (Fig.1a) is reduced to the subdomain shown in Fig.1b. This inner-domain (0.5ºW - 4.5ºE, and 0º-13ºN, 100x150 grid points) contains the research area (Ouémé-river basin), where floods are frequently recorded.

Fig. 2 shows the comparison between the simulated WRF-only and observed dataset. The weekly WRF precipitation for the Savè catchment is relatively close to that derived from CHIRPS (Fig. 2a) and TRMM (Fig. 2a), with the mean coefficient of determination (R^2) equal to 0.64, and 0.59 respectively. The agreement between the two observed datasets (CHIRPS and TRMM) is about 0.87 for R^2.

Since the investigation is on the potential of WRF-H (model coupled with WRF) for flood predictive, the available WRF precipitation at the highest spatio-temporal resolution is used to force the uncoupled WRF-Hydro model. In particular, the hourly output of WRF at 5-km spatial resolution are used as meteorological forcing data which contain necessary variables such as incoming shortwave radiation (W/m^2), incoming longwave radiation (W/m^2) Specific humidity (kg/kg), air temperature (K), surface pressure (Pa), u and v components of near surface wind (m/s), and liquid water precipitation rate (mm/s). The meteorological forcing data needed by the Noah LSM (land surface hydrological modeling system) are prepared as hourly gridded data. The Noah LSM static data (topography, land cover, soil type) are too coarse for a WRF-Hydro application. Additional datasets from the Shuttle Elevation Derivatives at Multiple Scales (HydroSHEDS) data base (Lehner et al., 2008 , e.g. high-resolution topography and channel network) are considered to accurately route water across the landscape through overland, subsurface or channel flow.

For calibrating the model WRF-Hydro 3.0, we focus on selcted sensitive parameters highlighted in previous works, such as REFKDT, SLOPE, RETDEPRTFAC, OVROUGHRTFAC, and MannN. Applying a stepwise approach, following previous WRF-Hydro studies (Arnault et al., 2016; Givati et al., 2016; Senatore et al., 2015; Yucel et al., 2015), we first focus on the parameters controlling the total water volume, namely infiltration factor (REFKDT) and surface retention depth (RETDEPRT, see Table 2). It is noted that REFKDT is a tunable parameter that significantly impacts surface infiltration and hence the partitioning of total runoff into surface and subsurface runoff; increasing REFKDT decreases surface runoff. Since there is not a historical range to estimate these parameters over the interested domain, the study tasks to calculate them from 0.1 to 10 with 0.1 increments. The second step of the calibration is to evaluate the coefficient governing deep drainage (SLOPE); the same method used in case of REFKDT and RETDEPRTFAC for selecting the optimum value is applied, by testing values from 0.1 to 1.0 with 0.1 as increment. The adjustment of the roughness parameter, which controls the overland flow is performed from the default value to the optimum one.

Sensitivity tests are additionally done on the surface and channel roughness parameter (MannN), which controls the shape of the hydrograph. The two efficiency criteria Kling–Gupta efficiency (KGE), and Correlation coefficient (Corr) are used to evaluate the model performance within the calibration process.

In order to harmonize the uncoupled and coupled setups, the uncoupled simulations use the same time step as the WRF-only and WRF-H simulations (30s). The calibration of the model is performed using hourly dataset input, and the focus is on the performance skill in reproducing daily discharge in the sub-catchments. One year calibration is considered as sufficient to evaluate the basic parameter sensitivities (e.g. Senatore et al., 2015). WRF-Hydro is calibrated on P_1 (2008) and validated on P_2 (2009-2010), where P_1 and P_2 are the shared periods containing into the whole study period named P (2008-2010).

3.3. Evaluation of model uncertainty with the Stochastic kinetic energy backscatter scheme

The *Stochastic Kinetic Energy Backscatter scheme* (SKEBS; Berner et al., 2015; Berner et al., 2009; Shutts, 2005), which primarily acts on the dynamical tendencies at the lateral boundaries, is activated into WRF-H for the fully-coupled simulation (WRF-H-SKEBS). The SKEBS technique provides several advantages over perturbation techniques that only perturb the initial state. The method aims to represent model uncertainties associated with scale interactions that take place in the real atmosphere but are absent in a truncated numerical model (Leutbecher et al., 2017). SKEBS perturbs the model fields by adding random, amplitude perturbations (noise) to the horizontal wind and potential temperature tendency equations at the lateral boundaries for each time step (Judt & Chen, 2016). An ensemble of 10 members using the WRF-H-SKEBS model is generated for each rain season of the period P (2008-2010).

4. Results

4.1. Calibration and evaluation of WRF-Hydro offline

The calibration is performed for the Savè catchment for the parameters REFKDT, SLOPE, RETDEPRTFAC, OVROUGHRTFAC, and MannN, using both KGE, and Corr as efficiency criteria. Efficiency criteria results of the optimization of those parameters are listed in Table 2. Furthermore, the calibrated Manning's coefficient (MannN) for the river channel routing used are set as 1.75 for stream order 1, 1.70 for stream order 2, 1.65 for stream order 3, 1.60 for stream order 4, and 1.55 for stream order 5. It can be seen that the observed discharge hydrograph at Savè is reasonably well reproduced with KGE, and Corr equal to 0.63, and 0.67, respectively, between March and December 2008 (Fig. 3.a). As in Arnault et al., (2016) for the case of the Sissili in West-Africa, we find that the model discharge performance is highly sensitive to parameter REFKDT. In our case, the result is also very sensitive to the parameter SLOPE. In all subsequent simulations, the calibrated parameters for the Savè catchment are held as such.

The calibrated model is evaluated offline for the period P_2 (Fig. 3b). The above-mentioned efficiency criteria allow us to evaluate the performance of the model. It can be noticed that it fairly well simulates the trend and peaks of the observed discharge, even slightly better in comparison to the calibration period, with model efficiencies KGE of 0.86 and Corr of 0.87. This enhanced performance for the validation period is related to the much higher discharge peak in 2010, i.e. the flooding year, which is fairly well reproduced by the model. Globally, for the simulation period P, WRH-Hydro in offline mode is able to simulate discharge with KGE and Corr equal to 0.70 and 0.74.

4.2. Evaluation of WRF-H

The calibrated model parameters are used for online WRF-Hydro model (referred as WRF-H), to assess the performance of the calibrated model to simulate discharge and precipitation in the research area.

4.2.1. Precipitation simulations

The agreement skills of WRF-H is evaluated for precipitation both temporally and spatially for the rainy season of the period 2008-2010 according to the research interest (flood). The Fig. 4 exposes comparison between the weekly precipitations from WRF-only, WRF-H, and observed datasets. The R^2 in Fig. 4a, which compares WRF-H and WRF-only, is equal to 0.88. This shows clearly that WRF-only and WRF-H simulate differently precipitation, which was already illustrated by Givati et al., 2016; Naabil, 2017; Senatore et al., 2015. Fig. 4b and 4c compare WRF-H with CHIRPS and TRMM and it illustrates a good agreement between these datasets. The slightly better agreement of CHIRPS (compared to TRMM) with WRF-only (Fig. 2b) and WRF-H (Fig. 4b) could be explained by the high resolution of both CHIRPS and WRF-H precipitation. Indeed, the comparison between Fig. 2 and Fig. 4 illustrates that WRF-H performs slightly better than WRF-only in term of weekly precipitation. The Fig. 4d enhances this results with Corr equal to 0.68 between WRF-H against 0.59 between WRF-H and TRMM.

Klein et al. (2015) showed that the high variability of precipitation in West Africa results from a large uncertainty in WRF simulations. This uncertainty is investigated in details in section 4.3. by modifying boundary conditions with a stochastic perturbation. The difference between simulated precipitation and CHIRPS is analyzed in Fig. 5 and 6. Fig. 5 presents the monthly trend of precipitation and shows that precipitation records during the two last months (August and September) in 2010 are highest in comparison to 2008 and 2009. The simulated precipitation WRF-H follow well the trend of the observation CHIRPS. Fig. 6 presents the spatial distribution of precipitation in domain D2 during the rainy season period June to September (JJAS) in 2010 (the flooding year). The difference between the two models (Fig. 5c) shows either WRF-H underestimated or overestimated simulation in comparison to WRF-only, depending on the location (as in Wagner et al., 2016). The mean precipitation in domain D2 is about 864 mm for WRF-only, and 947 mm for WRF-H. This means that WRF-H increases the simulated precipitation from WRF-only by about 1%. The observed precipitation in this domain is about 817 mm i.e. less than simulated precipitation from both WRF-only and WRF-H. Similar results are obtained for the Savè catchment, with a seasonal spatial-averaged precipitation of 1049 mm for WRF-H, 998 mm for WRF-only and 977 mm for CHIRPS.

4.2.2. Discharge simulations

Discharge results are displayed in Fig. 7a, showing the daily time series of simulated (green) and observed (red) stream discharges and related WRF-H precipitation (blue) for the period 2008-2010. A good agreement can be seen between the observed and the simulated hydrographs, and an approximate good representation of the peaks of discharge as well as hydrograph shapes, as quantified by the performance measures KGE and Corr, equal to 0.76 and 0.84, respectively. This better performance, in comparison to the offline simulation, could be explained by the time step of the meteorological data in fully-coupled mode, which is 30s and not hourly as in offline mode. Since the objective of the study is to evaluate the performance of WRF-H to simulate the discharge, and therefore to predict potential floods, the study focuses on the ability of the model in reproducing only the rainy seasons. We obtain from Fig. 7 for Savè's a KGE equal to 0.22, 0.64 and 0.80 for the rain seasons of 2008, 2009 and 2010, respectively, which gives solid information about the model’s simulation skills. It is noted that the model has a better performance in 2010.

The robustness of the calibrated WRF-H over Savè is evaluated in a second catchment, i.e. the Bétérou (Savè’s inner-catchment), which is illustrated at Fig. 7b. Fig. 7b shows that WRF-H reproduces well the discharge trend as well as the peaks, so that WRF-H can also be used successfully for this inner-catchment. Table 3 illustrates the discharges peaks obtain for basins during the three years.

WRF-H is able to capture the flood event which occurred in September-October 2010 over Savè as well as over Bétérou. In particular, although the predicted highest discharge peak occurs earlier than in the observation at Savè and Bétérou. The second "weak" peak in 2010, which could amplify damage intensities of the flood in the study area, is also well reproduced. According to results from Fig. 5, this second “weak” peak should resulted from the highest precipitation simulated and observed in September 2010. The first important peak at Save in 2010 is also reflected from the highest simulated precipitation of August 2010.

4.3. Evaluation of uncertainty of WRF-H

In order to evaluate the forecasting uncertainties of WRF-H, a stochastic kinetic-energy backscatter scheme (SKEBS: Berner et al., 2015, 2009; Shutts, 2005) is used and activated in WRF-Hydro; it is referred as WRF-H-SKEBS. The purpose here is that the SKEBS approach adds random perturbations with prescribed spatial and temporal decorrelations. In particular, SBEKS produces perturbation into the lateral boundary conditions. The amplitude of the stochastic perturbations is chosen as the default in WRF-H. An ensemble of 10-member is performed for this task. Both stochastic physics and initial condition perturbations into WRF-

H-SKEBS result in an ensemble spread for the three rainy seasons. Fig. 8 shows that WRF-H-SKEBS has a relatively large impact on precipitation and discharge results in the study region. The ensemble also results in a large range of simulated discharge performance, as can be seen in Table 4.

This demonstrates the sensitivity of WRF-H to lateral boundary perturbations, and confirms the uncertainty of the model regarding discharge and precipitation simulations, which is of uttermost importance for flood forecasting.

5. Summary and conclusion

The study explores the abilities of the fully coupled WRF-Hydro modeling system to simulate discharge and precipitation in Ouémé-river in West-Africa. The model has been calibrated in offline mode for one year, and tested for two years using hourly outputs from WRF simulations. Optimized parameters from the calibration were used to perform the fully coupled WRF-Hydro model, which was used to investigate the performance skills over the study area.

The evaluation of simulated precipitation showed its good performance skills, and provides confirmation about the uncertainty of WRF-H to simulate precipitation (Klein et al., 2015; Miguez-Macho et al., 2007). WRF-H also showed a good performance to simulate discharge, with a KGE equal to 0.76 for the period 2008-2010. The robustness of WRF-H has been assessed at Bétérou, an inner-catchment of Ouémé-river at Savè, where it provided a good agreement with respect to observed discharge, with a KGE equal to 0.66. Additionally, WRF-H was able to capture the flood event which occurred in 2010 over both Savè and Bétérou. Indeed, in the WRF-Hydro simulation in fully-coupled mode the atmospheric and hydrological processes are simulated in a consistent way, which enhances the confidence in the results.

The uncertainty of predictability skills of WRF-H with respect to discharge in Ouémé-river at Savè was performed with an ensemble of 10 members using a random perturbation scheme. Results showed the large sensitivity of simulated discharge to perturbations introduce into the atmosphere. In summary, WRF-H is considered as a suitable model for evaluating discharge prediction uncertainties in the Ouémé river, and we encourage the implementation of the model for further basins in West Africa.

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