PROJECTIONS OF FUTURE EXTREME RAINFALL EVENTS USING STATISTICAL DOWNSCALING IN MALAYSIA

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Specially dedicated to my beloved parents *Mama and Abah*, my beloved sister, *Syazana Abdul Halim* and brothers *Abdul Shahnaz Abdul Halim and Abdul Shahin Abdul Halim,* my beloved husband, *Mohd Noreffendy Jayah* and my adorable kids *Umar, Ulya and Zara*.

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ABSTRACT

Climate change is one of the greatest challenges for water resources management. Intensity and frequency of extreme rainfalls are increasing due to enhanced greenhouse gas effect caused by climate change. A lot of research has been done in developing innovative methods for assessing the impacts of climate change on rainfall extremes. Climate change strongly depends on General Circulation Model (GCM) outputs since they play a pivotal role in the understanding of climate change. However due to their coarse resolution, statistical downscaling is widely applied to match the scale between the GCM and the station scale. This research proposed to establish statistical downscaling model that was able to generate hourly rainfall data for future projection of hourly extreme rainfall in Peninsular Malaysia. An Advanced Weather Generator (AWE-GEN) built on stochastic downscaling principles was applied for simulating hourly rainfall data. The model construction involved 40 stations over Peninsular Malaysia with observations from 1975 to 2005. To account for uncertainties, an ensemble of multi-model namely GFDL-CM3, IS-CM5A-LR, MIROC5, MRI-CGCM3 and NorESM1-M were obtained from the dataset compiled in the WCRP's, CMIP5. The projections of extreme precipitation were based on the RCP 6.0 scenario (2081-2100). To address the problem of unavailability of rainfall data at remote areas over Peninsular Malaysia, this research also examined the spatial variability of rainfall and temperature parameters using Locally Weighted Regression. Results of the AWE-GEN showed its capability to simulate rainfall for Peninsular Malaysia. Both hourly and 24 hour extreme rainfall showed an increase for future. Extremes of dry spell was projected to decrease in future whereas extremes of wet spell was expected to remain unchanged. Simulations of present climate using interpolated parameters showed promising results for the studied regions.

ABSTRAK

Perubahan iklim adalah salah satu cabaran terbesar bagi pengurusan sumber air. Intensiti dan kekerapan hujan ekstrim semakin meningkat disebabkan peningkatan kesan gas rumah hijau yang disebabkan oleh perubahan iklim. Banyak kajian telah dilakukan dalam membangunkan kaedah inovatif untuk menilai kesan perubahan iklim ke atas hujan ekstrim. Perubahan iklim sangat bergantung kepada output Model Edaran Umum (GCM) kerana ia memainkan peranan penting dalam pemahaman perubahan iklim. Walaubagaimanapun, oleh kerana resolusi GCM yang kasar, kaedah penurunan statistik digunakan secara meluas untuk padanan skala antara GCM dan skala stesen. Kajian ini mencadangkan untuk membina model penurunan statistik yang mampu menjana data hujan seterusnya mengunjur hujan ekstrim pada selang masa satu jam di masa depan untuk Semenanjung Malaysia. Kaedah Penjana Cuaca Termaju (AWE-GEN) yang dibina atas prinsip stokastik digunakan untuk simulasi data hujan setiap jam. Pembinaan model melibatkan 40 stesen di Semenanjung Malaysia dengan data cerapan dari tahun 1975 hingga 2005. Bagi mengambil kira ketidaktentuan, pelbagai model iaitu GFDL-CM3, IS-CM5A-LR, MIROC5, MRI-CGCM3 dan NorESM1-M telah diperolehi daripada WCRP’s, CMIP5. Unjuran hujan ekstrim adalah berdasarkan senario RCP 6.0 (2081-2100). Bagi menangani masalah ketiadaan data hujan di kawasan terpencil, kajian ini juga mengkaji ubahan ruang parameter hujan dan suhu dengan menggunakan kaedah Regresi Tempatan Wajaran. Keputusan hasil AWE-GEN menunjukkan keupayaan untuk menjana simulasi hujan di seluruh Semenanjung Malaysia. Kedua-dua siri hujan ekstrim bagi satu jam dan 24 jam menunjukkan peningkatan pada masa akan datang. Musim kering ekstrim dijangka berkurangan sementara musim hujan ekstrim dijangka kekal tidak berubah. Hasil bagi simulasi iklim semasa menggunakan parameter berinterpolasi menunjukkan keputusan yang agak memberangsangkan bagi rantau kajian.

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LIST OF ABBREVIATIONS

ANN	-	Artificial Neural Network
AOGCM	-	Atmospheric Ocean General Circulation Model
AR1	-	Autoregressive Lag-1 model
AWE-GEN	-	Advanced Weather Generator
CGCM2	-	Canadian Coupled General Circulation Model
CMIP3	-	Coupled Model Intercomparison Project Phase 3
CMIP5	-	Coupled Model Intercomparison Project Phase 5
CTS	-	GCM control period
DID	-	Malaysia Drainage and Irrigation Department
ENSO	-	El Niño-Southern Oscillation
FC	-	Factors of change
FUT	-	GCM future period
GCM	-	General Circulation Model
GFDL-CM3	-	NOAA Geophysical Fluid Dynamics Laboratory, United States
GHG	-	Greenhouse gas
HadCM3	-	Hadley Centre Coupled Model, Version 3
INT	-	Interpolated
IPCC	-	Intergovernmental Panel on Climate Change
IPSL-CM5A-LR	-	Institut Pierre-Simon Laplace, Paris
LARS-WG	-	Long Ashton Research Station-Weather Generator
LGCV	-	Local Generalized Cross-Validation
LWR	-	Locally Weighted Regression
MA	-	March-April
MCMC	-	Markov Chain Monte Carlo

MIROC5 - Atmosphere and Ocean Research Institute (The University of Tokyo), National Institute for Environmental Studies, and Japan Agency for Marine-Earth Science and Technology, Japan
MJO - Madden-Jullian Oscillation
M-K - Mann-Kendall
MM5 - Fifth-Generation Penn State/NCAR Mesoscale Model
MMD - Malaysia Meteorological Department
MRI-CGCM3 - Meteorological Research Institute, Japan
NCEP - National Centers for Environmental Predictions
NEM - Northeast monsoon
NorESM1-M - Norwegian Climate Centre, Norway
NSRP - Neyman-Scott Rectangular Pulses
OBS - Observations
PDFs - Probability density functions (PDFs)
RCM - Regional Climate Model
RCP - Representation Concentration Pathways
SDSM - Statistical Downscaling Model
SLP - Sea-level pressure
SO - September-October
SRES - Special Report on Emission Scenarios
SST - Sea Surface Temperature
SWM - Southwest monsoon
WCRP - World Climate Research Programme

LIST OF SYMBOLS

$\overline{D}_0$ - Observed mean distance between each station and their nearest neighbor

d_i - Distance between station i and its nearest station

$\overline{D}_E$ - Expected mean distance for the stations given a random pattern

z_{ANN} - Score for the statistic for average nearest neighborhood

y_i - Observed values of the response variable for individual i

$\hat{y}_i$ - Predicted values of the response variable for individual i

t - Test statistic for t-test

$C_h(h)$ - Coefficient of variation

$\rho(h)$ - The lag-1 auto-correlation

$\kappa(h)$ - Skewness

$\Phi(h)$ - Probability that an arbitrary interval of length is dry

λ^{-1} - Mean storm origin arrivals for precipitation *(h)*

β^{-1} - Mean waiting time for cell origins after the origin of the storm for precipitation *(h)*

η^{-1} - Mean duration of the cell for precipitation *(h)*

μ_c - Mean number of cell per storm for precipitation [-]

α - Shape parameter of the Gamma distribution of rainfall intensity for precipitation [-]

θ - Scale parameter of the Gamma distribution of rainfall intensity for precipitation (mm h^{-1})

M_0 - Mean fair weather cloudiness for cloud cover

σ_m - Standard deviation fair weather cloudiness for cloud cover

ρ_m - Lag-1 autocorrelation of mean fair weather cloudiness

$\gamma = \varsigma$ - Cloudiness decay rate (h-1)

J_1 - Length transition period (h)

B - Regression coefficients of deterministic component of temperature first order differential equation for air temperature

$\overline{dT_h}$ - Mean random temperature deviate

ρ_{dT} - Lag-1 aoutocorrelation random temperature deviate

$\sigma_{dT,h}$ - Standard deviation random temperature deviate

dT - First step temperature ($^\circ$C)

μ_0 - Ozone for solar radiation (cm)

μ_n - Nitrogen dioxide for solar radiation (cm)

α_Λ - Angstrom turbidity parameter for solar radiation

$\omega_{\Lambda 1}, \omega_{\Lambda 2}$ - Single scattering albedos for solar radiation

ρ_g - Surrounding ground albedo for solar radiation

β_Λ - Angstrom turbidity parameter for solar radiation

LWP_R - Liquid water path with cloudiness for solar radiation (g/m2)

$a_i, i = 0,1,2,3$ - Regression coefficients of deterministic component of vapor pressure

$\overline{d\Delta e}$ - Average of vapor pressure deficit deviations

$\sigma_{d\Delta e}$ - Standard deviation of vapor pressure deficit deviations

$\rho_{d\Delta e}$ - Lag-1 autocorrelation of the process

$c_i\,(i=0,\ldots,4)$ - Regression coefficients of deterministic component of wind speed

$\overline{dW_s}$ - Average wind speed deviation

σ_{dW_s} - Standard deviation of wind speed

ρ_{dW_s} - Lag-1 autocorrelation of the process of wind speed

γ_{dW_s} - Skewness of wind speed

$\overline{P}_{atm}$ - Average atmospheric pressure

$\sigma_{P_{atm}}$ - Standard deviation of atmospheric pressure

$\rho_{P_{atm}}$ - Lag-1 autocorrelation of the process of atmospheric pressure

$\overline{P}_{yr}$ - Average annual precipitation (mm)

$\sigma_{P_{yr}}$ - Standard deviation of annual precipitation

$\rho_{P_{yr}}$ - Lag-1 autocorrelation of the process of annual precipitation

$\gamma_{P_{yr}}$ - Skewness of annual precipitation

μ_h - Mean at a given aggregation time interval h

$\gamma_{h,l}$ - Covariance at a given aggregation time interval and h lag l

ξ_h - Third moment of precipitation process

$\mu_{\mathrm{Pr}}(h)$ - Mean of precipitation

$\sigma^2(h)$ - Variance of precipitation

$\rho_{\mathrm{Pr}}(h)$ - Lag-1 autocorrelation of precipitation

$\kappa_{\mathrm{Pr}}(h)$	-	Skewness of precipitation
$\Phi_{\mathrm{Pr}}(h)$	-	Probability that an arbitrary interval of length is dry
$\mu_T(h)$	-	Mean of temperature
$\upsilon, i = 1, \ldots, 5$	-	Precision parameters
μ	-	Present temperature
v	-	Future temperature
υ_0	-	Natural variability
k	-	Number of GCM
ϕ	-	Degrees of freedom
h	-	Aggregation time interval (hourly)
N	-	Total number of stations
w_i	-	Weight of training data
n	-	Training data
K_i	-	Biweight kernel function
$D_{\max}$	-	The largest of the n distances to the interpolation point
$n_{\min}$	-	Minimum number of training data
ε	-	Random error
b_0 and b_1	-	Coefficients of LWR equation

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CHAPTER 1

INTRODUCTION

1.1 Introduction

Climate change is a crucial problem as it requires us to adapt our activities to uncertain future climate scenarios. Several sectors such as water resources, agriculture, energy and tourism face the severe impacts caused by climate change. Climate change and global warming occur when the global atmospheric concentrations of carbon dioxide (CO2), methane (CH4) and nitrous oxide (N2O) increases due to human activities. Consequently, the observed global average temperatures has also been increasing since the mid-20th century due to the rise of anthropogenic greenhouse gas (GHG) concentrations (IPCC, 2007). The warming has been shown to affect many natural systems which includes notable changes in snow, ice and frozen ground, increased runoff and changes in both terrestrial and marine ecosystems (Tangang *et al*., 2012), changes in rainfall and risks of flooding (Willem *et al*., 2011) and changes of occurences of extreme precipitation (Huang *et al*., 2011). Besides that, the notable changes in marine and freshwater ecosystems are also related to changes in temperature. Among the major impacts of global warming are the increased frequency and intensity of extreme rainfall events (Sen Roy, 2009; Cheng *et al*., 2011). Extreme rainfall is one of the main causes of natural disasters such as flooding. Therefore, to date, considerable attention has been paid to the modeling of extreme rainfall for preventive measures of massive flooding as well as for projecting future extreme rainfall (Chu *et al*., 2012). This has led to numerous collaborations between meteorologist and hydrologists to establish hydrological model of spatial and temporal precipitation extremes.

General Circulation Model (GCM) are widely used in providing outputs of global climate across the world which consist of hydrometeorological variables such as precipitation, air temperature, relative humidity, wind speed, geopotential height and cloud cover. GCM is a numerical model which comprises of different earth frameworks; for example, air, sea, surface area and ocean ice. Information on the important processes about global and continental scale atmosphere can be projected by GCM for future atmosphere under different emission scenarios. Despite numerous uncertainties in different GCMs (Chu *et al*., 2010), these outputs provide hydrologists with the desired information. Unfortunately, GCMs are usually at resolution that is too coarse for many climate change impact studies (Fowler *et al*., 2007; Hessami *et al*., 2008; Hashmi *et al*., 2009; Chu *et al*., 2010; Hashmi *et al*., 2010; Fatichi *et al*., 2011). The internal relationships between the model's variables produced from GCM also may not always be the same as those found in the observational data. As a result, their simulations of current regional climate can often be inaccurate for sub-grid scales (Chu *et al*., 2010; Guo *et al*., 2011).

The discrepancy between the GCM scale and the scale that is required for most impact studies has led to the development of downscaling methodologies. In order to match the scale between the GCM outputs and hydrological process at smaller scale, downscaling must be employed. In particular, downscaling is used to model the hydrometeorological variables, at a smaller scale from a large scale. There are two approaches for downscaling: dynamical downscaling and statistical downscaling. Dynamical downscaling or known as Regional Climate Model (RCM) simulates climate at resolution of 50 km or less where the GCMs provide the boundary conditions to RCMs (Fowler and Wilby, 2010). Meanwhile, statistical downscaling is an empirical method that defines the statistical relationships between the large-scale climate features and the hydrological variables (Wilby *et al*., 2004; Sunyer *et al*., 2011). There are various discussions and debates on these two approaches. However, statistical downscaling requires less computational effort and is cheaper to employ (Wilby and Wigley, 2000; Huang *et al*., 2011). Advantages of statistical downscaling also include the opportunity to use ensemble GCM results which takes into account average results from more than one model. Projections from ensemble model is better as compared to projections from individual model where the uncertainties from different GCM models could be taken into account (Wibig *et al*., 2015).

Previously, future projections are based on Special Report of Emission Scenarios (SRES) scenarios. All SRES scenarios are non-intervention scenarios with an increasing forcing path during the 21st century while Representative Concentration Pathways (RCP) span a large range of stabilization, mitigation and non-mitigation pathways (Rogelj *et al*., 2012). There are some similarities and differences between temperature projections for SRES scenarios and RCPs. As stated in Rogelj *et al*. (2012), the RCP 8.5 is equivalent to SRES A1F1 scenario which represent high-emission, non-mitigation future where by 2100 the range of temperature is between 4.0 to 6.0 ºC. RCP 6.0 temperature projections are equivalent to SRES B2. Likewise, RCP 4.5 temperature projections are equivalent to SRES B1. However, the lowest RCP scenario is basically different from the SRES scenario. In spite of having similarities, there are some particular differences between these two scenarios in terms of the rate of median temperature rises.

For instance, the median temperatures in RCP 8.5 rise slower than in SRES A1F1 during the period between 2035 and 2080, and faster during other periods of the 21st century. On the other hand, the median temperatures in RCP 6.0 rise faster than in SRES B2 during the three decades between 2060 and 2090 while slower during other periods of the 21st century. Similarly, the median temperatures in RCP 4.5 rise faster than in SRES B1 until mid-century, and slower afterwards. RCP scenarios are more focusing on process begins with pathways of radiative forcing, yet not detailed socioeconomic narratives or scenarios as in SRES scenarios. Table 1.1 summarizes the definition of each RCP scenarios which will be the baseline of the future climate condition. The basis of the scenario name is according to their 2100 radiative forcing level based on the forcing of greenhouse gases and other forcing agents.

Table 1.1: Definition of RCP scenario

Name	**Radiative forcing**[1]	**Concentration**[2]	**Pathway**	**SRES temperature anomaly equivalent**
RCP 8.5	>8.5 W/m^2 in 2100	> approx. 1370 CO_2-eq in 2100	Rising	SRES A1F1
RCP 6.0	Approximate 6 W/m^2 at stabilization after 2100	Approximate 850 CO_2-eq (at stabilization after 2100)	Stabilizing without overshoot	SRES B2
RCP 4.5	Approximate 4.5 W/m^2 at stabilization after 2100	Approximate 650 CO_2-eq (at stabilization after 2100)	Stabilizing without overshoot	SRES B1
RCP 2.6-PD[3]	peak at approximate 2.6W/m^2 before 2100 and then decline	peak at approximate 490 CO_2-eq before 2100 and then decline	Peak and decline	None

[1] Approximate radiative forcing levels were defined as ±5% of the stated level in W/m^2. Radiative forcing values include the net effect of all anthropogenic GHGs and other forcing agents.

[2] Approximate CO_2 equivalent (CO_2-eq) concentrations. The CO_2-eq concentrations were calculated with the simple formula Conc = 278 * exp (forcing/5.325). Note that the best estimate of CO_2-eq concentration in 2005 for long-lived GHGs only is about 455 ppm, while the corresponding value including the net effect of all anthropogenic forcing agents (consistent with the table) would be 375 ppm CO_2-eq.

[3] PD = peak and decline.

1.2 Problem Statement

Malaysia experiences massive floods occurred during monsoon seasons and flash floods brought by convective rainfall occurred during intermonsoon seasons. Flash floods are frequently associated with convectional storms which tend to be of short durations (IASH, 1974; Jamaluddin, 1985). Major concern on flash floods include structural and erosional damage, loss of life and property and disruption of socio-economic activity (Jamaluddin, 1985). This is an indication that Malaysia will face a higher probability of damages from extreme rainfall in the future. Thus, understanding the patterns of extreme rainfall and their future behaviour is of importance to policy makers in Malaysia.

Malaysia currently ranks 52nd in the Climate Change Performance Index 2015 according to their emissions level, emissions development, renewable energy, efficiency and policy (CCPI, 2015). The change of rainfall patterns as well as temperature changes in future might be useful inputs to policy makers to initiate the mitigation and adaptation strategies in order to adapt with the future uncertain climate change. Due to the weaknesses of GCM as mentioned earlier, downscaling is used to match the scale between the GCM and the station scale since the GCM scale is much coarser compared to station scale. Two approaches of downscaling known as dynamical and statistical are extensively applied by the climatologist and hydrologist. In this study, the statistical downscaling approach will be adopted. There are three types of statistical downscaling methods: regression, weather typing scheme and weather generator. Weather generators involve stochastic process (Wilks and Wilby, 1999) that can be used to produce long time series of simulated weather variables and simulating future climate by perturbing weather parameters or by fitting to perturbed statistics (Michelle *et al.*, 2012). This study uses the hourly rainfall data as inputs to the weather generator. Research done by Fatichi *et al.* (2011) have demonstrated the capacity of an hourly climate generator in reproducing a wide set of climate statistics over a range of temporal scales including extreme variables. This method adopts stochastic models, often referred as stochastic downscaling. The absence of such methodology being used in climate projections for Malaysia is the basis of undertaking this study. Projection of future extreme rainfall events for the country is crucial, and the appropriate method for that purpose needs to be developed.

1.3 Aim and Objectives of Research

The overall aim of this research is to establish the statistical downscaling model that is able to generate hourly rainfall data at present climate and project the future hourly extreme rainfall in Peninsular Malaysia. This research also aims to examine the potential of spatial variables in the model for simulation of ungauged sites using locally weighted regression.

The objectives of the research are:

1. To study on statistical downscaling model focusing on the Advanced Weather Generator (AWE-GEN) method.
2. To explore the ability of AWE-GEN method in projecting future extreme rainfall events in Malaysia using new model parameters.
3. To investigate and determine spatial interpolation methods using physical elements as variables for simulating extreme rainfall events for ungauged sites.

1.4 Scope of Research

This research will focus on one of the statistical downscaling model which is the weather generator. The weather generator that will be used in this research is the hourly AWE-GEN which combines the physically-based and stochastic approaches. The precipitation that will be considered in this research is hourly rainfall. Other meteorological data required in this study are hourly air temperature, hourly wind speed, hourly relative humidity, hourly atmospheric pressure, hourly cloud cover and hourly solar radiation. Hourly rainfall, temperature, wind speed and relative humidity data are from the Malaysia Meteorological Data (MMD). Meanwhile, hourly atmospheric pressure, cloud cover and solar radiation are adopted from Fatichi *et al*. (2011). Data will be limited to sites in Peninsular Malaysia. GCMs realizations will be obtained from the dataset compiled in the World Climate Research Programme’s (WCRP’s), Coupled Model Intercomparison Project phase 5 (CMIP5). An ensemble of multi-model (i.e. more than one GCM model will be used) in this study. They are GFDL-CM3 (United States), IS-CM5A-LR (Paris), MIROC5 (Japan), MRI-CGCM3 (Japan) and NorESM1-M (Norway). RCP 6.0 scenario will be used for future projections.

1.5 Significance of Research

Recognizing the needs and significance of having adequate rainfall data, this research attempts to propose a suitable hourly weather generator model which could generate a wide set of climate statistics over a range of temporal scales, from extremes to low-frequency inter-annual variability for the whole of Peninsular Malaysia. Such information would be beneficial especially to hydrologists and environmentalists. Moreover, realizing the importance of understanding and predicting climate change, this research also attempts to simulate the future climate scenarios, as inferred from climate models, using the proposed model. The proposed model is able to quantify uncertainties by estimating the weighted averages based on outputs of different climate models using Bayesian theories. Having insufficient climate data is a critical problem in hydrological studies (Ming Kang and Fadhilah, 2012). Thus, the output of this study which will be simulated time series of climate data will be able to alleviate this problem. This study will also extend the application of AWE-GEN by interpolating the AWE-GEN parameters to simulate weather time series at remote areas where meteorological data do not exist. This will be invaluable for hydrological studies done in such locations.

1.6 Summary

This chapter discusses issues of climate change occurring around the world, including Malaysia. Problems related to climate change which are of concern to the policy makers were also discussed. GCM ouputs which provides information on climate at global scale need to be downscaled to finer scale in order to match scale required for hydrological modeling at local scale. Therefore, statistical downscaling will be applied in this study. This chapter outlined the aim and the objectives of the research, the scope and the significance of the research. Therefore, Chapter 2 will cover the literature reviews of rainfall studies as well as statistical downscaling studies. In addition to that, past researches done on spatial interpolation methods will also be discussed in Chapter 2. Next, the methodology to be applied in this research will be discussed in detail in Chapter 3 including the theories and assumptions involved. The discussions of results will be given in Chapters 4, 5 and 6. Finally, conclusion and recommendations will be discussed in Chapter 7.

7.3 Recommendations for Future Work

Further research could identify the best fit distribution to represent rain cell intensity in AWE-GEN besides the Gamma distribution. For instance, Weibull, Generalized Pareto, Exponential and Mixed-Exponential distributions could be fitted to the rain cell intensity. Malaysia has different seasonal variation of rainfall and different geographical where local climates are affected by the presence of mountain ranges throughout Malaysia which can be divided into three groups which are the highlands, the lowlands, and coastal regions. For the spatial interpolation methods, further research could also identify the relationship between the rainfall and temperature parameters with longitude and latitude of the stations.

Furthermore, other variables such as geographical and seasonality factors could be incorporated in LWR in order to establish a more robust interpolation model for Peninsular Malaysia. Moreover, besides rainfall and temperature, other parameters such as solar radiation and wind speed could also be considered to be incorporated in the model. The range of future changes of extreme climate under certain level of radiative forcing with certain level of economic and population growth would be more beneficial for climatologists and meteorologists for designing the mitigation plan and coping with the future risks. Further research could also project future extreme precipitation under other different RCP scenarios such as RCP 2.6, RCP 4.5, RCP 6.0 and RCP 8.5. The results from the different scenarios could be assessed and a range of future values developed to give a more comprehensive projection of future extreme values.

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