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ESTIMATION OF SOME THERMODYNAMIC METEOROLOGICAL VARIABLES FROM MEASURED METEOROLOGICAL DATA

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Abstract

Appropriate studying of the meteorological conditions via the continuous measurements and analysis of the various meteorological variables can make a difference for the survival and prosperity of the human race. In this study, measured meteorological variables from an implemented device together with reanalysis data from ERA-Interim and NASA were used to estimate four addition thermodynamic meteorological variables (TMVs) using appropriate formula and statistical tools for Auchi area of Edo State, Nigeria. The annual average measurement values from the implemented device for the average temperature, relative humidity and mean sea level pressure are 27.60°C, 73.20% and 1012.28 mbar respectively. While that of the estimated TMVs are 21.90°C, 26.83, 0.017 kg/kg and 27.89°C for the dew point temperature, vapour pressure, specific humidity and virtual temperature respectively. Delightfully, the values were in conformity with those of the reanalysis data. These TMVs are very importance in atmospheric thermodynamics because they deal with the processes of heat to work transformation and their reverse that occur in the atmosphere of the earth which result to weather/climate as the case maybe, and they form the basis for cloud Micro-Physics and convection parameterizations that are used in numerical weather/climatic models and also in numerous climate considerations.

Key Words: *Agriculture, Environmental hazards, Variables, Weather*

Introduction

Weather has always been a universal concern that plays a major role in our everyday lives (Devaraju *et al*., 2015; Donald, 2009; Ukhurebor and Azi, 2018). Weather measurements and monitoring potentially help in keeping track of different meteorological variables which hold great importance and have several applications in agricultural, transportation, construction, military operations, radio signal transmission, solar devices and many other personal and industrial aspects of human lives

(Devaraju, 2015; Ukhurebor and Azi, 2018; Ukhurebor and Umukoro, 2018; Ukhurebor *et al.,* 2018; Ukhurebor and Odesanya, 2019; Ukhurebor *et al.,* 2019; Akhilesh *et al*., 2015). Man has always tried in finding out the causes of different meteorological conditions within his environs and possibly monitors what the weather would be at any given time. Appropriate studying of the meteorological conditions can make a difference for the survival and prosperity of the human race (Ukhurebor *et al*., 2017a; Ukhurebor *et al.,* 2017b; Ukhurebor *et al.,* 2017c; Ukhurebor *et al*., 2017d).

Weather measurements and monitoring have developed over the centuries and a lot of knowledge and information have been gathered that have helped in understanding the meteorological conditions of the universe ((Ukhurebor *et al*., 2017a; Ukhurebor *et al*., 2017b; Ukhurebor *et al.,* 2017c; Ukhurebor *et al*., 2017d; World Meteorological Organization, 2008).

There are many factors that influence weather, some of which are visible and others invisible. These factors include but not limited to the following; latitudinal location, proximity to water bodies, solar distance, air masses, air pressure, elevation, etc (Moore, 2017; Ukhurebor and Abiodun, 2018).

In this study the measured meteorological variables from an implemented device were used to estimate four addition TMVs; the dew point temperature, vapour pressure, specific humidity and virtual temperature which are very importance in atmospheric thermodynamics.

Materials and Methods

Weather Monitoring Device

The weather monitoring device was implemented in such a way that it can be used remotely and the readings are displayed on the user-friendly LCD display in numerical digital values and can also be sent to computer through the programmed micro SD card or/and through the serial port (the Arduino SD Card Module). In this implementation a full set of meteorological variables can be acquired within few seconds which is relatively fast compare to some other meteorological monitoring devices that require meteorological variables to be logged every hour or thereabout. However, the user has the option of choosing the frequency of meteorological variables that will be logged, measured, recorded, stored and displayed. The acquired meteorological variables are displayed on LCD for the respective meteorological values. In addition, the meteorological variables for each day are saved on the micro SD card in Microsoft Excel format on a separate file with each file created with a file name that corresponds to the date and time when the meteorological data were acquired. The user also has the option to stop the meteorological variables acquisition process at any time by interrupting the routine.

After the construction and implementation processes were completed testing was carried out. It was found that the weather monitoring device was working properly. For quality assurance andvalidation purposes; measurements of temperature, relative humidity and atmospheric pressure were done at the Centre for Atmospheric Research (CAR), Ayangba, Kogi State Nigeria for one week (between 1st to 8th November, 2016). The results from the recalibration and comparison, show that there is a good agreement between the values from the implemented device and that from CAR. They had correlation coefficient (λ) of 0.98, 0.97 and 0.96 for the temperature, relative humidity and atmospheric pressure respectively. This shows that the implemented device works with minimum error. Details of the implemented device is contained in Ukhurebor *et al.* (2017b).

Area of Study

Edo University Iyamho (EUI) is very close to Auchi, Edo State, Nigeria. Auchi is located around latitude "7°06'752.6"N and longitude 6°26'36.0"E" with an elevation of 188m above sea level. The area has a humid tropical climate which is characterized by wet and dry seasons. The vegetation is that of the Savannah and relative undulating topography (Ukhurebor and Azi, 2018; Ukhurebor and Umukoro, 2018; Ukhurebor *et al*., 2018). Figure 1 shows the map of Nigeria indicating the study area (Auchi) as adopted from Edo State Ministry of Lands and Surveys, Benin City, Nigeria.

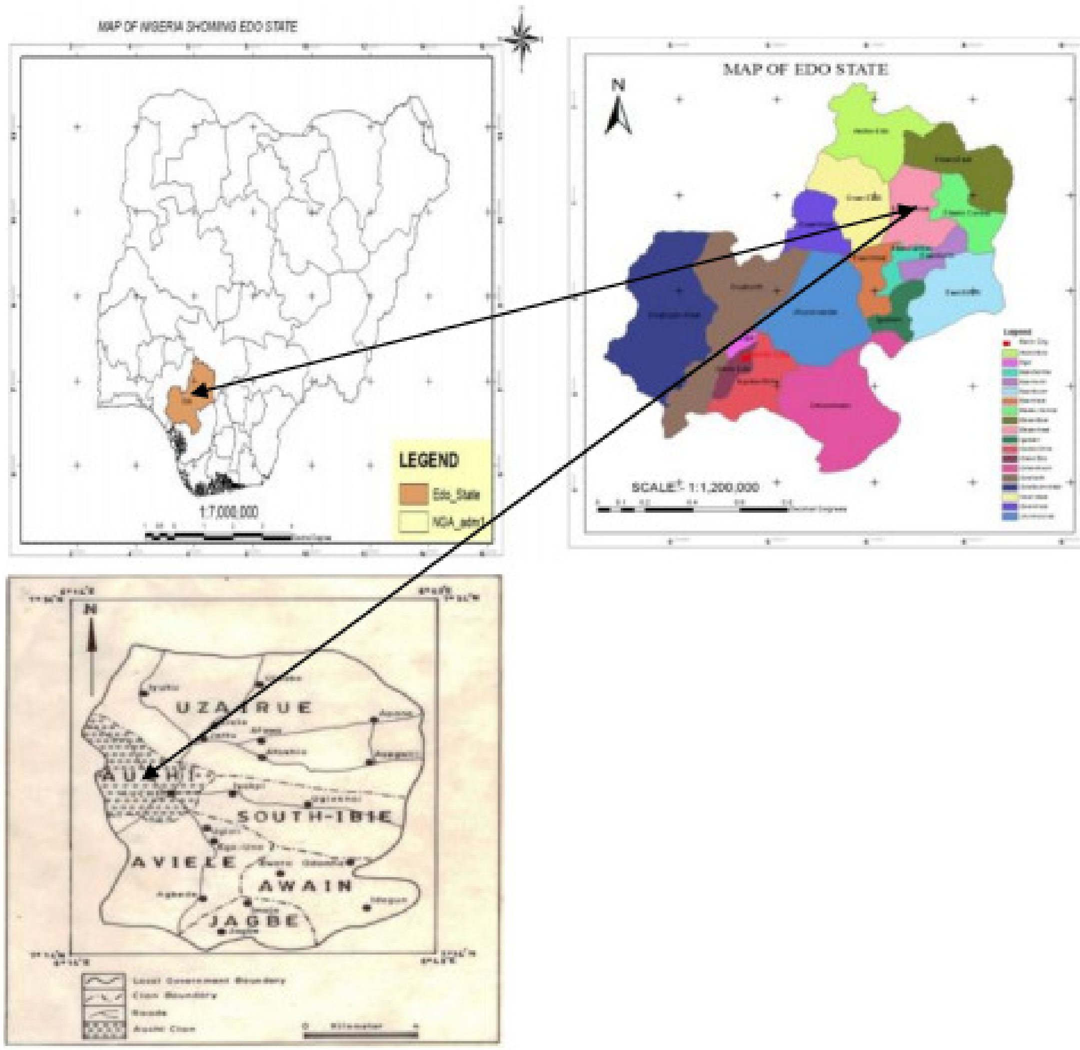

Fig. 1: Map of Nigeria indicating the Study Area (Auchi)

Measurement of the Meteorological/Weather Variables

The fixed measuring method was employed for the measurements of the various meteorological variables at the administrative block of EUI for continuous measurements from January to December, 2017. As stated earlier, the weather monitoring device measure four meteorological variables; temperature (^oC), atmospheric pressure (mbar), relative humidity (%) and light intensity (lux) and the records cover 24 hours each day from 00 hour to 2300 hours local time. Measurements were done at intervals, with average values for each day copied from the micro SD card to the computer from the implemented meteorological monitoring device.

The Dew Point Temperature

The dew point is that temperature at which air must be cooled to undergo saturation with the water vapour present in the air (Wallace and Hobbs, 2006). Its measurement is somehow related to humidity. The higher the dew point the greater the moisture present in the air. Normally, the dew point temperature (T_d) is always less than the air temperature this is due to the fact that relative humidity cannot exceed 100%. Higher relative humidity indicates that the dew point is closer to the current air temperature (Lawrence, 2005). A maximum relative humidity implies that the dew point is close if not equivalent to the current temperature and the air would be maximally saturated with water. When the moisture content remains constant and temperature increases, relative humidity decreases, but the dew point remains constant (Wallace and Hobbs, 2006; Lawrence, 2005).

Dew point is measure with devices called hygrometers over a wide range of temperatures. Manual devices of this sort can be used to calibrate other types of humidity sensors and automatic sensors may be used in a control loop with a humidifier or dehumidifier to control the dew point of the air in a building or in a smaller space for a manufacturing process. We can also approximate it using the Magnus-Tetens formula. Its estimation can be using the Magnus-Tetens formula in Eqn. 1 (Wallace and Hobbs, 2006; Lawrence, 2005; Monteith and Unsworth, 2013):

There is also a simpler approximation that allows conversion between the dew point, temperature, and relative humidity. This approach is accurate to within about ±1 °C as long as the relative humidity is above 50%.

$$T_d = \sqrt[8]{\frac{Rh}{100}}\left(112+0.9T\right)+\frac{T}{10}-112 \quad (1)$$

Where Rh is the relative humidity and T is the temperature.

Vapour Pressure

Vapour pressure which is also known as equilibrium vapour pressure is the pressure exerted by a vapour in thermodynamic equilibrium with its condensed phases (solid or liquid) at a given temperature in an isolated system (Wallace and Hobbs, 2006; Lawrence, 2005; Monteith and Unsworth, 2013). It has to do with the tendency of particles to escape from either the liquid or solid. In meteorological term vapour pressure means the partial pressure of water vapour present in the atmosphere. We can either have the actual vapour pressure (e) and saturated vapour pressure (e_s). Vapour pressure is measured in the standard units of pressure. The SI is the Pascal (Pa); which is equivalent to Nm^{-2} or $kgm^{-1}s^{-2}$.

The Antoine equation is a mathematical expression of the relation

between the vapor pressure and the temperature of pure liquid or solid substances.
We can estimate these from the formula from Eqn. 2 and 3 (Wallace and Hobbs, 2006; Lawrence, 2005; Monteith and Unsworth, 2013):

$$e = 6.11 \times 10^{\left(\frac{7.5T_d}{237.3+T_d}\right)} \quad (2)$$

$$e_s = 6.11 \times 10^{\left(\frac{7.5T}{237.3+T}\right)} \quad (3)$$

The relative humidity is connected to the vapour pressure by Eqn. 4:

$$Rh = \frac{e}{e_s} \times 100 \quad (4)$$

According to Monteith and Unsworth (2013); Wallace and Hobbs (2006), the dew point temperature can also be estimated by Eqn. 5 and Eqn.:

$$T_d = \frac{237.4 \ln\left(\frac{e_s \times Rh}{611}\right)}{7.5 \operatorname{In} 10 - \ln\left(\frac{e_s \times Rh}{611}\right)} \quad (5)$$

and

$$T_d = \frac{234.5 \times In\left(\frac{e}{6.112}\right)}{17.67 - \left(\frac{e}{6.112}\right)} \quad (6)$$

Humidity

Humidity is a basically used to describe the amount of water vapour present in air. It indicates the likelihood for precipitation, dew or fog to be present. The amount of water vapour needed to achieve saturation increases as the temperature increases. As the temperature of a parcel of air decreases it will eventually reach the saturation point without adding or losing water mass. The amount of water vapour contained within in a parcel of air can vary significantly (Wallace and Hobbs, 2006; Lawrence, 2005; Monteith and Unsworth, 2013).
Three primary measurements of humidity are widely employed: absolute, relative and specific.

Absolute Humidity/Vapour Density

This describes the water content of air. In a system of moist air, it is the ratio of the mass of water vapour present to the volume occupied by the mixture, which is the density of the water vapour component expressed in either grams per cubic meter or grams per kilogram.

Relative Humidity

This is the ratio of the vapour pressure to the saturation vapour pressure with respect to water expressed in % indicating a present state of absolute humidity relative to a maximum humidity given the same temperature.

Specific Humidity

This is also known as moisture content and it is our major concern here. It is the ratio of water vapor mass to total moist air parcel mass. As temperature decreases, the amount of water vapor needed to reach saturation also decreases. As the temperature of a parcel of air becomes lower it will eventually reach the point of saturation without adding or losing water mass (Wallace and Hobbs, 2006; Lawrence, 2005; Monteith and Unsworth, 2013). It can be expressed mathematically as:

$$q = \frac{m_v}{m_t} \quad (8)$$

m_v and m_t are the water vapour mass and total moist air parcel mass respectively.
We can therefore express q as:

$$q = \frac{m_v}{m_v + m_d} \Rightarrow \frac{\frac{m_v}{m_d}}{\frac{m_v}{m_d} + \frac{m_d}{m_d}} = \frac{w}{w+1} \quad (9)$$

Since the mixing ratio w is:

$$w = \frac{m_v}{m_d} = \frac{e_s \times 0.622}{e - e_s} \qquad (10)$$

This implies that the specific humidity is approximately equal to the mixing ratio which is the ratio of the mass of water vapour in an air parcel to the mass of dry air (m_d) for the same parcel as expressed mathematically in Eqn. 10 (Wallace and Hobbs, 2006; Lawrence, 2005; Monteith and Unsworth, 2013).

Virtual Temperature

Virtual temperature is mostly used in atmospheric thermodynamics processes to assume air parcels behave approximately adiabatically and ideally. It is the temperature of a dry air mass that has the same air density of the mixture of dry air and water vapour at the same pressure. Since the atmosphere is a mixture of dry air and water vapour, to determine the influence of air humidity on air density, meteorologists introduce virtual temperature so as to translate the influence of atmospheric water vapour on air density into something comparable to the influence of temperature on air density.

We can estimate it using the formula of Eqn. 11 or 12 (Wallace and Hobbs, 2006; Lawrence, 2005; Monteith and Unsworth, 2013):

$$T_v = T\left(1 + 0.608 \times w\right) \qquad (11)$$

or

$$T_v = \frac{T + 273.15}{1 - 0.379 \times \left[\dfrac{6.11 \times \left(\dfrac{7.5 \times T_d}{273.7 + T_d}\right)}{P_s}\right]} \qquad (12)$$

Virtual temperature is basically used in adjusting convective available potential energy (CAPE) soundings for assessing available convective potential energy from skew-T log-P diagrams. The errors associated with ignoring virtual temperature correction for smaller CAPE values can be quite significant. Thus, in the early stages of convective storm formation, a virtual temperature correction is significant in identifying the potential intensity in tropical cyclogenesis.

Results and Discussion

Meteorological Variables

As stated earlier, the fixed measuring method was employed for the measurements of the measured meteorological variables at the administrative block of EUI for continuous measurements for the entire 2017.

The ERA-Interim data is a global atmospheric reanalysis data from the European Centre for Medium-range Weather Forecasts (ECMWF) which covers from 1979 to date with horizontal resolution of 0.75° × 0.75° and 60 vertical levels from ground to 0.1 hPa (Dee *et al*., 2011). After proper registration the required data were extracted using the Climate Data Operator (CDO). Daily data for 2017 and monthly data for 1987-2017 for temperature, relative humidity and surface pressure were obtained.

The Modern-Era Retrospective analysis for Research and Applications (MERRA) which was undertaken by the National Aeronautics and Space Administration data (NASA) is a reanalysis data which covers from 1979 to date with horizontal resolution of 0.5° × 0.5° and 72 vertical levels from ground to 0.01 hPa (Rienecker *et al*., 2011). Daily data for 2017 and monthly data for 1987-2017 for temperature, relative humidity and surface pressure were obtained.

Four TMVs (dew point temperature, vapour pressure, specific humidity and virtual temperature) were estimated using the appropriate equations from the measured, ERA-Interim and NASA data. Three (temperature, relative humidity and mean sea level pressure) essential climate variables (ECV) out of the four measured meteorological variables were used.

The atmospheric/surface pressure readings from the three different sources was reduced to the mean sea level pressure (MSLP) so as to make the readings of different sources comparable by cancelling out altitude-dependent differences. The reduction to the mean sea level was performed on all atmospheric/surface pressure readings based on information about the atmospheric/surface pressure (*P*), altitude (*h*) and temperature (*T*) data obtained. Eqn. (13) was used for the reduction to the mean sea level (Ji *et al*., 2018):

$$P_{(mslp)} = P \times \left[1 - \frac{0.0065 \times h}{T + 0.0065 \times h \times 273.15}\right]^{-5.257} \quad (13a)$$

$$= 0.03414 \times \frac{Ph}{(273.15 + T)} \quad (13b)$$

The average monthly measurements for 2017 of each of the measured meteorological variables are contained in Table 1.

Table 1: Average Measured Meteorological Variables for 2017

Month	Temperature (°C)	Relative Humidity (%)	MSL Pressure (mbars)
Jan	28.20	42.70	1010.64
Feb	31.80	48.20	1012.42
Mar	30.10	68.70	1013.38
April	29.30	85.20	1013.18
May	28.40	92.10	1011.64
June	26.30	92.40	1012.49
July	25.00	95.30	1013.66
Aug	26.60	78.60	1013.41
Sept	25.50	78.40	1014.80
Oct	25.70	68.90	1012.26
Nov	27.80	68.20	1010.10
Dec	26.50	58.30	1009.38
Average	27.6	73.20	1012.28

The average monthly reanalysis data from ERA-Interim and NASA for 2017 of each of the considered meteorological variables are contained in Table 2 and 3 respectively.

Table 2: Average ERA-Interim Meteorological Variables for 2017

Month	Temperature (°C)	Relative Humidity (%)	MSL Pressure (mbars)
Jan	28.41	65.76	1010.02
Feb	29.08	61.49	1009.52
Mar	27.10	76.92	1009.10
April	27.31	78.52	1009.82
May	26.37	83.66	1011.42
June	25.23	89.37	1012.43
July	23.81	91.77	1014.40
Aug	23.53	92.48	1013.37
Sept	24.30	90.46	1012.87
Oct	25.17	89.78	1011.44
Nov	26.36	86.29	1010.47
Dec	27.47	76.54	1010.10
Average	26.25	81.92	1011.23

Table 3: Average NASA Meteorological Variables for 2017

Month	Temperature (°C)	Relative Humidity (%)	MSL Pressure (mbars)
Jan	26.12	63.93	1010.13
Feb	27.06	58.24	1009.69
Mar	27.78	73.85	1008.92
April	26.98	80.07	1009.43
May	26.45	84.43	1010.89
June	25.67	85.10	1011.78
July	25.67	85.97	1011.78
Aug	24.55	88.28	1012.44
Sept	24.82	88.13	1012.25
Oct	25.66	85.74	1011.07
Nov	25.53	79.25	1010.39
Dec	25.31	69.56	1010.46
Average	25.97	78.62	1010.77

Climatic data were also obtained from ERA-Interim and NASA for a period of thirty-one years (1987-2017) and the average yearly data are presented on Table 4 and Table 5 respectively.

Table 4: Average ERA-Interim Meteorological Variables for 1987-2017

Month	Temperature (°C)	Relative Humidity (%)	MSL Pressure (mbars)
Jan	27.91	66.40	1010.19
Feb	27.94	71.76	1009.68
Mar	27.42	79.94	1009.28
April	26.84	84.63	1009.51
May	25.97	88.36	1010.99
June	24.61	92.29	1012.71
July	23.65	93.58	1013.50
Aug	23.58	92.74	1013.29
Sept	23.92	93.75	1012.59
Oct	24.79	91.73	1011.49
Nov	26.41	85.78	1010.41
Dec	27.72	74.10	1010.30
Average	25.90	84.59	1011.16

Table 5: Average NASA Meteorological Variables for 1987-2017

Month	Temperature (°C)	Relative Humidity (%)	MSL Pressure (mbars)
Jan	24.73	60.09	1010.61
Feb	26.49	63.55	1009.67
Mar	27.24	72.40	1008.91
April	27.03	79.15	1009.00
May	26.34	83.04	1010.46
June	25.29	85.84	1012.15
July	24.48	86.89	1012.77
Aug	24.34	86.76	1012.55
Sept	24.62	87.56	1011.97
Oct	25.08	86.39	1011.00
Nov	25.31	77.49	1010.37
Dec	24.43	65.67	1010.85
Average	25.45	77.90	1010.86

Estimation of the TMVs

The various measured meteorological variables were used to estimate the dew point temperature, vapour pressure, specific humidity and virtual temperature. The average monthly estimated variables from the 2017 measured variables of each of the considered thermodynamic meteorological variables are contained Table 6.

Table 6: Average Estimated TMVs for 2017

Month	Dew Point Temperature (°C)	Vapour Pressure	Specific Humidity (kg/kg)	Virtual Temperature (°C)
Jan	14.3356	16.3603	0.0102	28.3775
Feb	19.5363	22.7329	0.0141	32.0794
March	23.6482	29.3349	0.0182	30.4427
April	26.5311	34.7474	0.0215	29.6964
May	26.9912	35.6495	0.0221	28.7948
June	24.9659	31.6272	0.0295	26.6232
July	24.1923	30.1823	0.0187	25.2929
Aug	22.5235	27.3071	0.0169	26.8746
Sept	21.4566	25.5689	0.0158	25.7517
Oct	19.5422	22.7286	0.0141	25.9248
Nov	21.3988	25.4908	0.0158	28.07340
Dec	17.6163	20.1949	0.0125	26.7063
Mean	21.8948	26.8270	0.0174	27.8865

The average mean and average SD results of the meteorological variables are presented in Table 7.

Table 7: Average Mean and Average SD of the Meteorological Variables

	Measured, 2017		ERA-Interim, 2017		NASA, 2017		ERA-Interim, 1987-2017		NASA, 1987-2017	
	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD
Temp. (^{0}C)	27.5690	2.0506	26.2316	2.03275	25.8806	1.2191	25.8968	1.7117	25.4470	1.0512
Relative Humidity (%)	73.2011	16.7547	82.0415	13.1570	78.8888	11.6414	84.5883	9.4591	77.9014	10.0855
MSLP (mbar)	1012.2800	1.5920	1011.2590	1.9068	1010.9160	1.6605	1011.1620	1.5162	1010.8590	1.2981
Dew Point Temp. (^{0}C)	21.8948	3.7250	22.6342	2.0660	21.7370	2.7422	22.9891	0.8550	21.1814	2.2596
Vapour Pressure	26.8270	5.8142	27.6362	2.8211	26.2560	3.7901	28.0966	1.4321	25.3240	3.2792
Specific Humidity (kg/kg)	0.0174	0.0051	0.0141	0.0029	0.01230	0.0032	0.0175	0.0009	0.0157	0.0021
Virtual Temp. (^{0}C)	27.8865	2.0810	26.5097	2.0434	26.1421	1.2394	26.1767	1.7294	25.6947	1.0713

Supposedly, these estimated TMVs and other meteorological parameters are critical in atmospheric thermodynamics and agricultural and environmental sustainability issues (Salack *et al.,* 2018; Ukhurebor *et al*., 2020; Habib *et al*., 2001; Nwankwo *et al.,* 2020; Ukhurebor and Siliko, 2020).

Also, from the other analysis carried out, it has been shown that the data from the three different sources (measured, Era-Interim and NASA) were close statistically with little variation and the estimated TMVs were also close as well.Though, there was some level of inconsistencies between the reanalysis meteorological data (ERA-Interim and NASA) and ground measured meteorological data. According to Ukhurebor *et al.* (2020), there are two possible reasons that could be responsible for these inconsistencies; "the sensitivity nature of the sensors (sensors errors) used for the implementation of the device used for the ground measurement, and even the uncertainty surrounding reanalysis satellite meteorological data".

Hence, this affirmed the results of Salack *et al.* (2018); Ukhurebor *et al.* (2020) and Habib *et al*. (2001), that meteorological data particularly satellite reanalysis meteorological data are accompanying with some level of reservations or/and errors in the form uncertainties which need to be suitably accounted for.

Conclusion

This study demonstrates the use of some measured meteorological variables from an implemented device in Auchi area of Edo State, Nigeria to estimate four addition TMVs such as dew point temperature, vapour pressure, specific humidity and virtual temperature. These TMVs are very critical in atmospheric thermodynamics due to the role they play in the processes of heat to work transformation and their reverse that occur in the atmosphere of the earth which result to weather/climate as the case maybe. They form the basis for cloud Micro-Physics and convection parameterizations that are used in numerical weather/climatic models and also in several climate considerations. It is believed that the results obtained will assist in providing the appropriate panacea to mitigating weather induced environmental hazards, hereby improving agricultural and economic efficacy and throughput, as well as enhancement of scientific research.

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