IOSR Journal Of Applied Physics (IOSR-JAP)
e-ISSN: 2278-4861.Volume 13, Issue 4 Ser. II (Jul. – Aug. 2021), PP 05-15
www.Iosrjournals.Org

Derivation of Relative Humidity and its Associated Parameters from Measured Temperatures and Pressures Using Nimex-1 Data

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Abstract:
Background*: The moisture content of the atmosphere can be expressed in various units. These units can be used in the prediction of various events in the atmospheric boundary layers. The inadequacies in the measurement of atmospheric parameters, limits in-depth and valuable research from being carried out. In a bid to cushion these effects on research, various methodologies have been employed in addition to making suitable assumptions that enable the use of available measured parametric data to generate data and results for which unmeasured parameters would have served same purpose. The measurement of wet bulb temperature and dry bulb temperature from meteorological stations would rather have made this study parochial, save for various methodologies used in the calculation of dew-point temperature. Large dependence of diurnal variability of moisture parameters with dew point temperature makes it imperative for its calculation and development of an alternative but suitable technique in its estimation. Diurnal variability of meteorological parameters over the course of a day and season and the need to improve on the accuracy of calculation of these parameters first and foremost, then to proffer an alternate method of estimation of parameters which could be used interchangeably or more so serve as a check on calculated parameters forms the pedigree of this work.*
Materials and Methods*: A simple method to estimate diurnal vapour pressure is evaluated, assuming that recorded minimum temperature approximates our estimated dew-point. Using wet bulb and dry bulb temperatures for 14 days, this methodology showed that vapour pressure, humidity and vapour pressure Deficit D, can be computed to a reasonable accuracy.*
Results*: The results show good agreement between calculated and estimated values of e and RH, and not for D. Correlation is very high for e, moderate for RH, but poor for D. More advanced methods could be used to evaluate* T_d. *However, such methods would require additional data and assumptions which could be used to validate and refine our analysis This methodology showed that vapour pressure, humidity and vapour pressure Deficit D, can be computed to a reasonable accuracy*
Conclusion: *It is worthy to note that even with available observed humidity parameters, these are typically subject to drift and of course suffer data-gap. The temperature base methodology as shown in this work or from more advanced methods would serve as a supportive and easy quality- control measure to at least flag for further inspection periods where the RH measurements are absent or rather questionable. Hence, minimum temperature values can be used to compute vapour pressure e, relative Humidity RH, and Vapour pressure Deficit D at night/ morning hours.*
Key Word*: Relative Humidity RH; Vapour Pressure e; Vapour pressure Deficit D, Dew Point Temperature*

Date of Submission: 18-07-2021 Date of Acceptance: 03-08-2021

I. Introduction

The capability of water, acting as a transporting medium of heat after its absorption and release over long distance with the same ability to transport other species, being the key medium for chemical transformation makes it (water) imperatively unique in our daily life. Human activities are mainly concentrated on the lowest end of the boundary layer which contains a greater percentage of water. The atmospheric water content is helpful for chemical processes of soluble and solute species in the atmosphere which encompasses: absorption of gases in the atmosphere; product and kinetics of several chemical atmospheric transformation reactions, as well as the deposition of nutrients and pollutants to the biosphere.[1, 2]

Temperature is also used as measure of human discomfort[3] and can even be used to estimate such things as lifting condensation level [4]

Moisture content is expressed in various units. Amongst these include; the actual water vapour pressure *e* (kPa), which expresses the partial pressure of water vapor in air. At any given temperature T, water vapour in the atmosphere cannot exceed the saturation vapour pressure e_s (T) by any significant amount.

Dew point temperature (T_d) is defined as the temperature to which air has to be cooled (at constant pressure) to reach its saturation vapour pressure, thus, $e(T)=e_s(T_d)$.
Relative humidity (RH) is closely related to these variables (e, e_s and T_d). It is defined in two forms based upon either air ratio or vapour pressure (Bohren – based definition).

$$RH = \frac{e}{e_s(T)} = \frac{e_s(T_d)}{e_s(T)} \qquad 1$$

RH could be expressed in percentage or fraction of vapour pressure. As a final consideration for this work, the vapour pressure Deficit D (kpa) which is defined by the difference between saturation and actual vapour pressure shall be discussed. The Vapour pressure deficit D is defined as

$$D = e_s(T) - e_s(T_d) \qquad 2$$

Where the terms are as defined above.
Vapour pressure Deficit D is one of the key controls on the opening of stomata in plants and is thus an important factor for evapotranspiration, plant respiration and biomass production [5, 6] and for the uptake of harmful pollutants such as Ozone through the stomata [7].
The main objective of this work is to evaluate whether such an assumption could perform satisfactorily in Western Nigeria. Secondly, was to focus on the humidity parameters around nighttime/ morning hours, since this corresponds to the time of when dew tends to form.
The data used in this study were NIMEX 1 data generated from NIMEX experiment carried out in 2004 at Obafemi Awolowo University, Ile-Ife of Osun State, Nigeria.

The basis of the methodology presented here rest on a basic hypothesis:
The measured daily minimum temperature T_{min}, is a reasonable estimate of the dew point temperature, T_d, (and hence of water vapour pressure, e) of the air at that time of the day. The hypothesis is validated in the discussion below, but when true, T_{min} gives a good estimate of e. The approximate value of the vapour pressure estimated by this methodology will be denoted as e_a and the approximated RH and vapour pressure Deficit as RH_a, D_a, respectively;

	Measured	**Estimated**
Dew-point temperature	$T_d = T_d(t)$	$T_d = T_{min}$
Vapour pressure	$e = e_s(T_d)$	$e_a = e_s(T_{min})$
Relative humidity	$RH = e / e_s(T)$ $= e_s(T_d) / e_s(T)$	$RH_a = e_a / e_s(T)$ $e_s(T_{min}) / e_s(T)$
Vapour pressure Deficit	$D = e_s(T) - e$	$D = e_s(T) - e_a$

Where $T_d = T_d(t)$ indicate temperature is a function of time

The assumption presented in section 3.2, is intended as approximations and neither assumption hold true everywhere .Kimball et al. (1997) has discussed the validity and limitations of T_{min} base methods for the United States & Alaska. Some points shall be reviewed here.

The rule of thumb used in weather forecasting is equivalent to saying that RH approaches 100%. This approximation is widely used for a number of applications [5,6,8,9] and follows from the physical meaning of T_d, which relates to the temperature at which dew forms. Cooling of the surface at night (due to outgoing long wave radiation) takes place everywhere, at least in the absence of strong advective effects. As the air cools, air temperature approaches T_d. If the temperature falls close to T_d, water starts to condense, and further heat loss results in greater condensation rather than falling temperatures .In extreme circumstances, temperature may fall below T_d but under normal conditions air temperature remains above or equal to T_d. [10]

Nocturnal cooling frequently causes RH to approach 100%, during the night in a wide range of climates [6]. Of course, many exceptions occur and such exceptions are seen in most days used in this study. For example, Fig 1 illustrates the range of RH values found for each of the synoptic hours for one of the days considered in this work. Indeed, it is obvious that many of the night time/ morning RH values lie below 100%, with values around and above 90% with 100% out of the range.

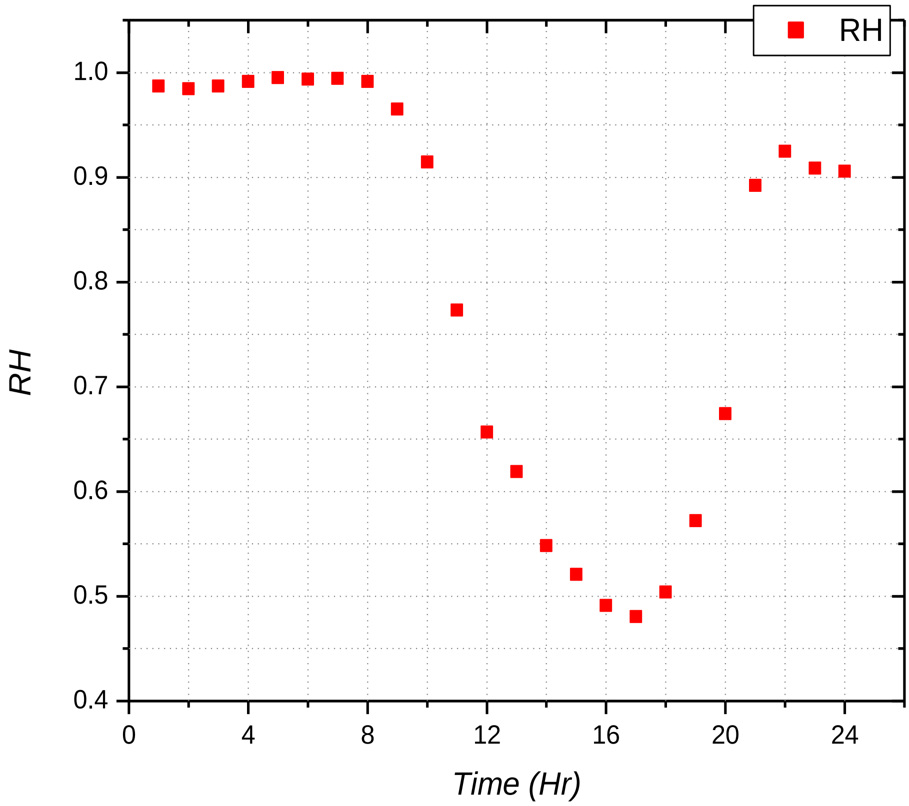


Figure 1: Daily variation of RH

One reason for this is that air temperatures measured at screen height of above 2m are usually greater than temperatures at the surface [11]. In Dyer and Brown (1997) model for example, dew formation was assumed to start when RH exceeded 90%, but air temperature decreased after this time, and they indeed assumed that T_{min} was equivalent to T_d.

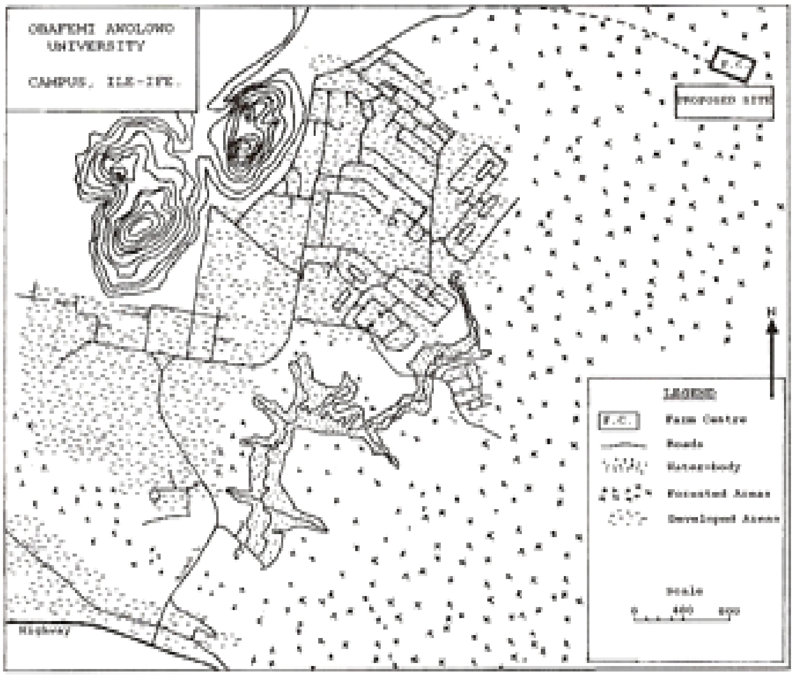
A number of situations can give rise to low RH at night. Windy conditions for example can mix warm, dryer, air from aloft down towards the surface and temperature might not fall sufficiently for RH to reach 100%. As another example, at mountain-sites, meteorological stations are often affected by topographic flows, or simply by air masses advected into the site which have little contact with the ground surface, so values of RH<100% are quite common[12]

Over sea-areas, the cooling of the surface at night is usually less than over land, since mixing of the surface layers prevents the build-up of a strong gradient near the air-sea boundary and the sea has a high heat capacity.

II. Material And Methods

For the evaluation of the Minimum Temperature based methods, meteorological data was extracted from NIMEX 1 data which was generated from NIMEX 1 project conducted in the farmland of the Obafemi Awolowo University, Ile-Ife, Osun State which is in the South-West region of Nigeria. This experiment took place between February and March 2004. Plate 3.1 shows the outlaying areas of the school campus located on 7.55^{o} N; 4.56^{o} E. Figure 2, is a digital photograph of the measuring setup/ station.

Figure 2: Site plan



These data were quality controlled by the various participating institutions involved in the field project work and include instantaneous wet and dry bulb temperatures (T), air pressure (Press), night-time temperature (T_{min}), all measured at around 2m above the ground T_{min} is the minimum of temperature found during 12 hours from 21 GMT of the previous day to 9 GMT of the current day. Other parametric values (e, RH, and D) were calculated and results are shown in the further pages of this work. Dew-point was calculated from observed values, using the equations displayed in subsequent sections of this work. The estimation methods with the highest correlation coefficient was used to generate the dew point temperature as was not measured during the NIMEX 1 field project.

Table 1: A table of some instruments used for the NIMEX 1 field measurement

Parameter	Device and Model	Manufacturer	Accuracy
Air temperature (wet and dry bulb)	Frankerberger psychrometer	Theodor Friedrichs	$\pm$ 0.05°C
Air Pressure	Capacitive Barometer	Ammonit	1hPa
Data acquisition	Data logger CR10X	Campbell Scientific	Not applicable
Data acquisition	Laptop computer	Not applicable	Not applicable

Dew-point temperature was first calculated in this work from observed nighttime/ morning hours wet bulb and dry bulb temperature values using the equation below (after "Magnus" or "Magnus-Tetens" approximation for the saturation vapor pressure of water in air as a function of temperature).

$$T_d = \frac{237.7 \, X \, r(T, RH)}{17.27 \, X \, r(T, RH)} \quad ---------- (a)$$

$$where \; r(T, RH) = \frac{17.27 \, T_{dry}}{237.7 \, X \, T_{dry}} + \ln\left(\frac{RH}{100}\right) \quad ----- (b)$$

$$RH = 100 \, X \left(\frac{e}{e_s}\right) \quad ------------ (c)$$

$$e_s = 6.112 e^{17.67 T_{dry}/(T_{dry}+243.5)} \quad -------- (d)$$

$$e = e_w - P_{sta}(T_{dry} - T_{wet}) \, X \, 0.00066 \, (1 + 00115 T_{wet} \quad ---------- (e)$$

$$e_w = 6.112 \, e^{17.67 T_{wet}/(T_{wet}+243.5)} \quad --------------- (f)$$

$$T_d = Dew - point\ temperature$$
$$RH = Relative\ Humidity$$
$$e_s = Saturation\ Vapour\ Pressure$$
$$e = Actual\ Vapour\ Pressure$$
$$e_w = Wet\ bulb\ vapour\ pressure\ (T_w)\ \ where\ T_w is\ wet\ bulb\ temperature$$
$$P_{stn} = Atmospheric\ pressure\ at\ Station$$

Saturation Vapour Pressure e_s equation (as recommended by Alduchov and Eskridge, 1996) used was:

$$e_w(T) = \ 6.1094\ X\ e^{17.625T/(243.04+T)} - - - - - - - - - - - (g)$$
$$e_s(T) = e_{wa} = 1.00071 e^{4.5\ X\ 10^{-6}p}\ X\ e_w(T) - - - - - - - - - - - - (h)$$

P is atmospheric pressure in hPa, and T is in ^{o}C. Equation (h) makes a small correction for the fact that air is a mixture of water vapour and dry air.

e was estimated simultaneously using calculated T_d value in place of T in the afore equation. The computations are attached to the appendix of this work. RH and D were then calculated. In computation of estimated values of *e*, RH and D denoted by e_a, RH and D, recalling our earlier stated assumption that $T_d \sim T_{min}$ in nighttime / morning hours, we replace T_d with T_{min} and perform the same calculation to generate values for the afore mentioned parameters which were stored in a table also attached in the appendix of this work.

Suitable analytic techniques and plots were employed using two software namely; Origin 6.1 and Minitab to generate results from which conclusion were arrived at.

III. Result

For each day, we have calculated *e*, RH and D term, and estimated e_a, RH_a, and D_a for all hours, which were averaged to give daily values used in the computation of this work. The computation of considered variables (*e*, RH and D) were done using equations stated in the chapter three section of this work. The mean value of calculated and estimated parameters are denoted by µ and μ_a respectively; 'a' and 'b' refers to intercept; E_a and E_b being errors of 'a' and 'b'; SD as Standard Deviation and R^2 as Correlation Coefficient.

Table 2 illustrates the statistical mean for all the 14 days generated by taking the mean of the hourly values.

Table 2: General Statistics for 14 days

	µ	μ_a
e	25.77	29.35
RH	0.85	0.98
D	4.31	0.76

Considering fig 3a, b and c, which are scatter plots for e against e_a; RH against RH_a and D against D_a, respectively for 14 days considered, it is worthy to note that two points show quiet some large scatter or rather large discrepancies from other points. These points corresponds to days 66 and 67 respectively. This is observed for all the scatter plots for the considered variables.

In table 3, statistical mean of calculated and estimated values; a, b, E_a, E_b, SD and R^2 are generated from a linear fit shown in fig 4a, b, c of daily values of considered parameters for the first twelve (12) days. Days 66 and 67 were isolated in this work because they are considered to be erroneous for the purpose of analysis (plot of linear fit) in this work.

Table 3: Statistics for 12 days

	µ	μ_a	a	b	e_a	e_b	SD	R^2
e	28.32	29.88	-1.75	1.12	0.16	4.60	1.05	0.91
RH	0.93	0.98	0.83	0.16	0.06	0.06	0.01	0.61
D	2.25	0.72	0.42	0.14	0.18	0.07	0.28	0.52

From table 2 and 3, some mean values differ. More so, the slope (b) is less than 1.2 for all days with RH and D showing positive intercepts, and negative for *e*. Correlations are fairly moderate for D, moderate for RH, but rather better for *e*. These average results hide some rather significant variations between days. We shall discuss these in the sections following this.

The key success of this method depends upon the relationship between the minimum and dew-point temperatures, as displayed in Fig 5. All the days show negative differences between dew-point temperature and minimum temperature with only day 57 having a difference of zero (o), day 61 with -0.05. Generally, the differences are less than 2^{o}C, with the largest variation displayed by days 66 and 67.

Fig 6a, b and c, shows daily variation of calculated and estimated parameters for the upper plot and temperature (T, T_{min}, T_d) variation for various temperature values as the lower plot. Considering the lower plot first in Fig 6a, it shows minimum temperature T_{min}, dew-point temperature T_d, and actual night/ morning temperatures T for all days in ^{o}C. If our assumption were fulfilled perfectly, T_{min} and T_d would be identical. We observe that T_{min} lies above T_d for most days, with the exception of days 57 and 61 where the two plots intersect or equal or better said, have a difference of approximately Zero (0). The upper plot illustrates corresponding calculated values of *e* along side with

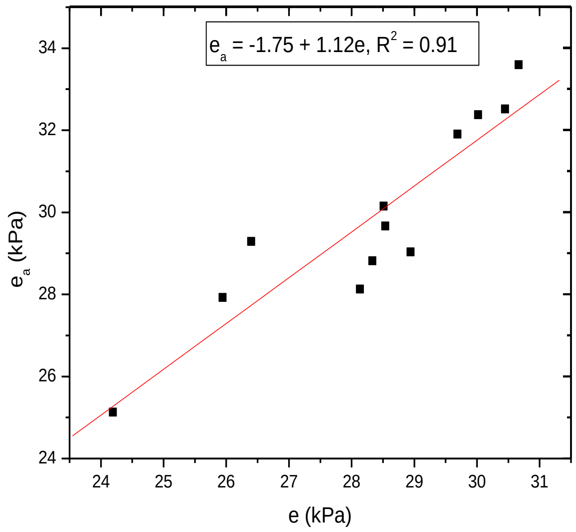


Figure 4a: Linear fit of e against e_a

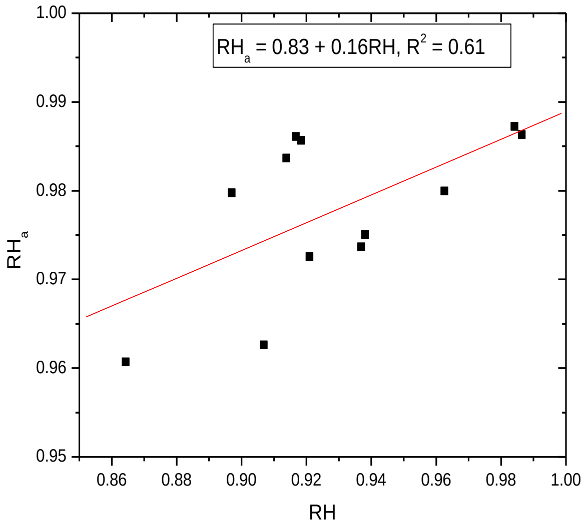


Figure 4b:Linear fit of RH against RH_a

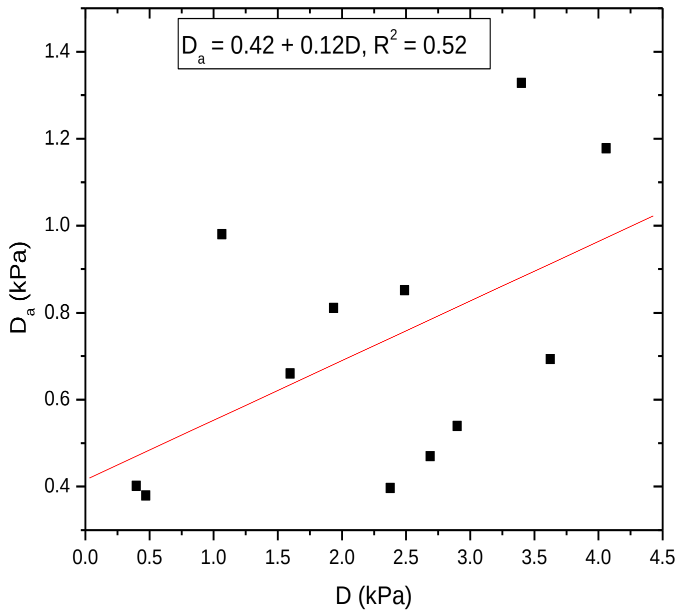


Figure 4c: Linear fit of D against D_a

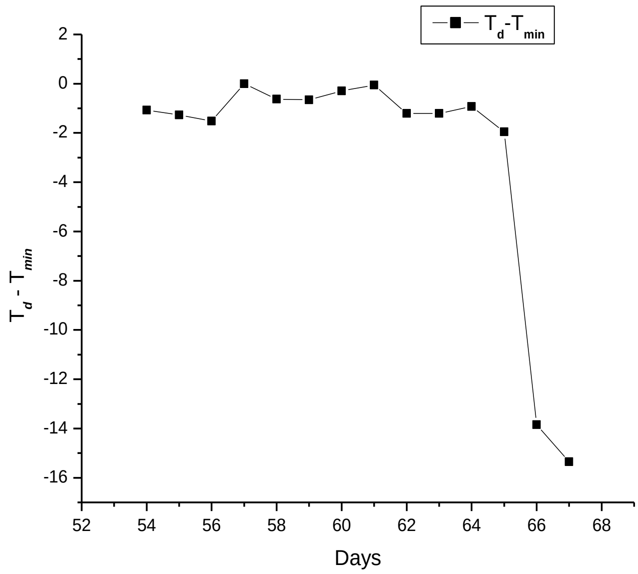
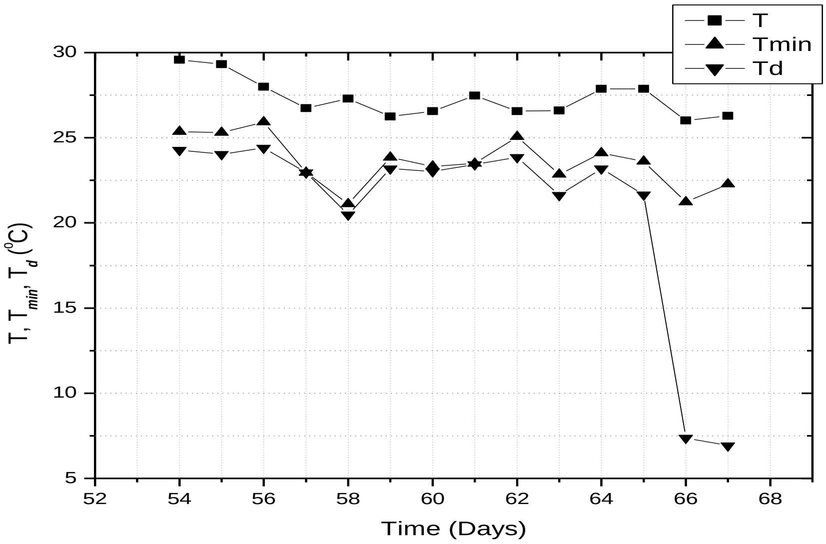


Fig 5: Difference Between Dew-Point Temperature T_d And Minimum Temperature T_{min}

the estimated *e*. The plot shows that the estimate of e follows the calculated value of e to a good degree for all days with a maximum difference of 3^{o}C, with exception of days 66 and 67, which displays large discrepancies between *e* and e_a well over 13^{o}C.

From Fig 6b, the plot of RH_a does not follow too well with RH except for days 57 and 61 were they record same value, which also corresponds to the point where $T_d = T_{min}$. Days 66 and 67 show usually large discrepancies too.



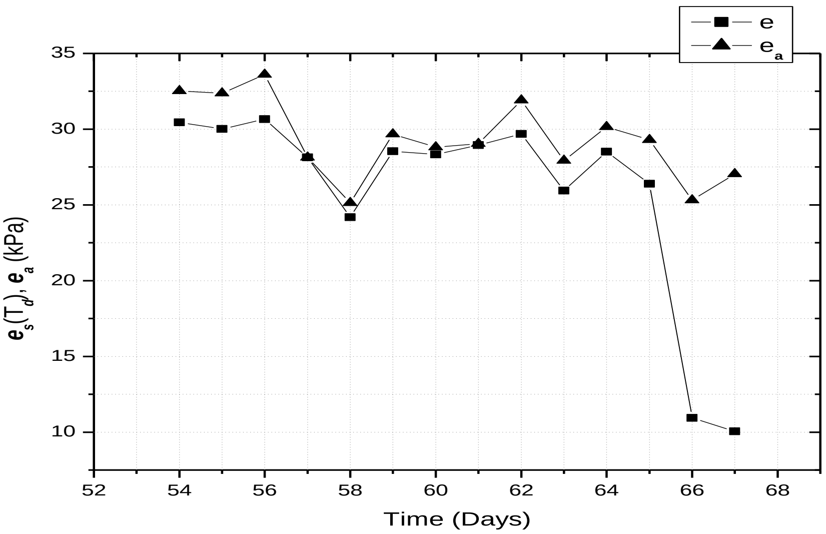
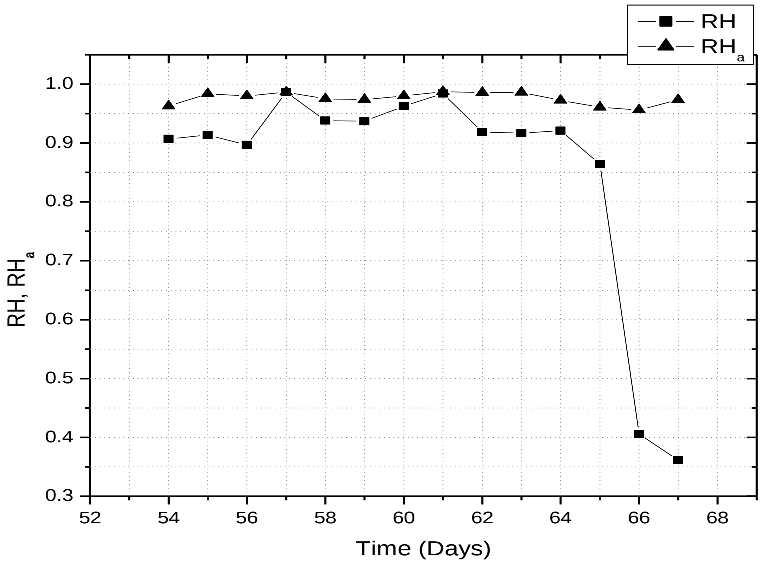


Fig 6a: Comparison of Calculated and Estimated *e* For 14 Days

D and D_a in Fig 6c show a similar but opposite plot of Fig 6b, with large discrepancies existing in days 66 and 67 too.

With due reference to fig 4a, b, c, the value of our coefficient of correlation is justified considering the movement both plots (e and e_a; RH and RH_a; D and D_a) in fig 6a, b and c respectively.



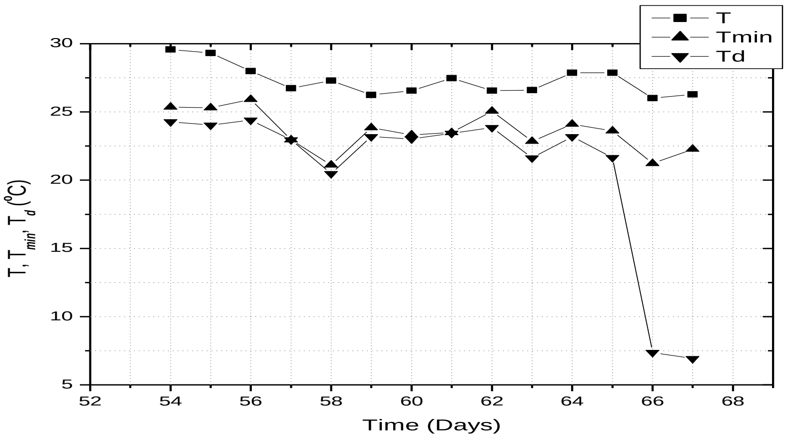
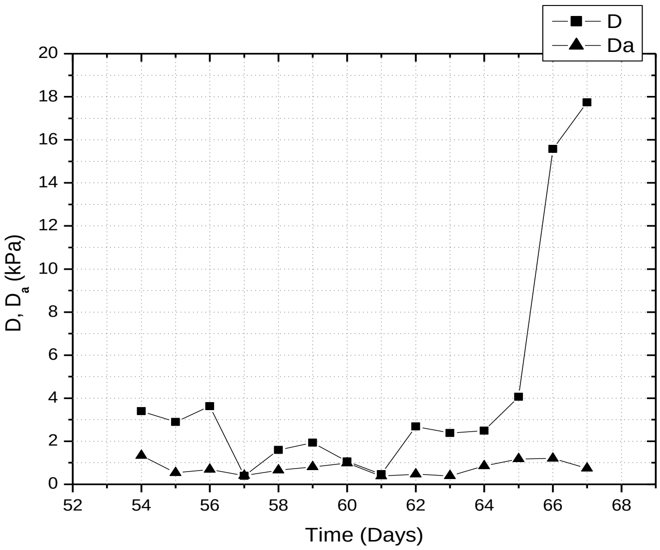


Fig 6b: Comparison of Calculated and Estimated RH For 14 Days



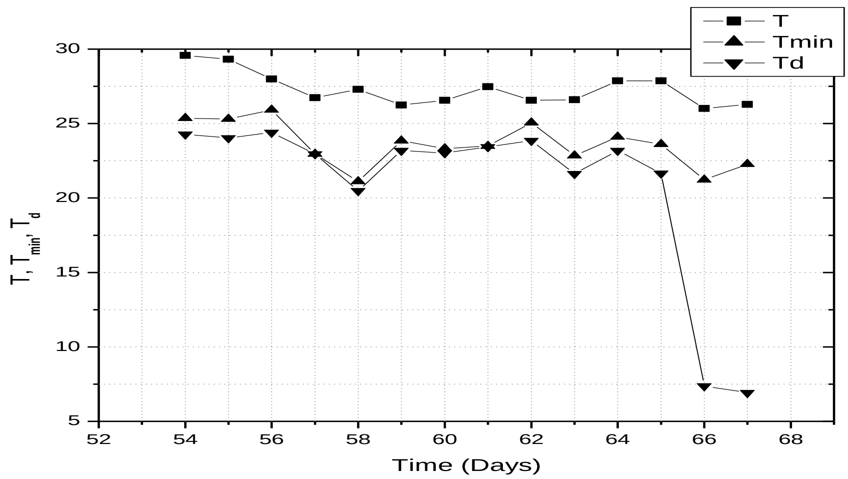


Fig 6c: Comparison of Calculated and Estimated D For 14 Days

IV. Discussion

As noted in the earlier section of this work, an assumption was made in our methodology which for brief is "T_{min} approaches T_d, or equivalently that RH approaches 100% at night". The difference between T_d and T_{min} are usually some few degrees with a mean standard deviation of 4.59°C.

Many factors some discussed in earlier chapters will lead to situations were RH is less than 1 when expressed as a fraction or 100% in percentage as seen in this work at nighttime.

It is worthy to note that days of high RH corresponds to days with $T_{min} \sim T_d$, or rather having differences of about 0.1°C at most or less and much lower RH values with days showing high discrepancies in $T_d - T_{min}$ above 10°C. This could be expressed as shown below;

Days of $T_{min} > T_d$ equivalent to $RH_a > RH$

Days of $T_{min} >> T_d$ equivalent to $RH_a >> RH$

Correlation is fairly moderate for D, moderate for RH, and good for *e*. Large discrepancies shown for days 66 and 67 in most of the plot is due to the large difference between T_d and T_{min}.

V. Conclusion

In this study, we set to test the validity that night/ morning temperature values can be used to assess changes on Vapour pressure *e*, Relative Humidity RH, and Vapour pressure Deficit D over the course of a day. The methodology has been tested using data for 2 weeks from

NIMEX-1 field experiment, carried out in 2004 at the Obafemi Awolowo Uninversity Campus, Ile Ife of Osun State, Nigeria. The results show good agreement between calculated and estimated values of *e* and RH, and not for D. Correlation is very high for *e*, moderate for RH, but poor for D. More advanced methods could be used to evaluate Td. However, such methods would require additional data and assumptions which could be used to validate and refine our analysis.

In conclusion, it is worthy to note that even with available observed humidity parameters, these are typically subject to drift and of course suffer data-gap. The temperature base methodology as shown in this work or from more advanced methods would serve as a supportive and easy quality- control measure to at least flag for further inspection periods where the RH measurements are absent or rather questionable. Hence, minimum temperature values can be used to compute vapour pressure *e*, relative Humidity RH, and Vapour pressure Deficit D at night/ morning hours.

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Akwuegbu, C. Ozochi, et. al. “Derivation of Relative Humidity and its Associated Parameters from Measured Temperatures and Pressures Using Nimex-1 Data.” *IOSR Journal of Applied Physics (IOSR-JAP)*, 13(4), 2021, pp. 05-15.