IOSR Journal of Environmental Science, Toxicology and Food Technology (IOSR-JESTFT)
e-ISSN: 2319-2402,p- ISSN: 2319-2399.Volume 13, Issue 1 Ver. I (January. 2019), PP 44-56
www.iosrjournals.org

Monthly and Daily Variations in down ward Long wave Radiation and Its Relationship with Atmospheric Temperature and Water Content in desert and Mediterranean Climates

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Abstract: *Knowledge of downward atmospheric radiation in the range λ= 4–100 μm is vital for several applications. In this study, longwave (LW) radiation datafrom desert (Riyadh, Saudi Arabia) and Mediterranean (Adelaide, Australia) climates are used to characterize seasonal and daily variations.*
At both sites, the LW radiation shows a maximum in summer and a minimum in winter. The monthly changes in the LW radiation were about 22% for Adelaide, and 36% for Riyadh. When considering these seasonal variations, it was found that during winter and summer, the variations inLW radiation were confined to between 2% and 4%. However, during the transition seasons (spring and autumn) the LW radiation varies considerably. In Adelaide, spring and autumn change by about 8% and 10% respectively. In Riyadh, the LW radiation varies by about 12% in both seasons.
At both sites, the LW radiation has aminimum value in the early morning, around 06:00 local time, and reaches its maximum at around 13:00. The daily changes in the LW radiation were 13.5% for Riyadh and 10% for Adelaide.
Obviously, the monthly and diurnal variations of the LW radiation closely follow the temperature variations rather than the water content.
The influence of screen temperature (T) and atmospheric moisture on LW radiation are examined for each site. The screen level water vapour pressure (e) and the precipitable water vapour (PWV) areusedas two different representative measuresof the atmospheric water contents. PWV is calculated using radiosonde observations from both sites. It is clear thatthe LW radiation correlates better with T than e, and better correlation between LW and e was apparent in Adelaide than in Riyadh. When using the PWV as a measure of thetotal atmospheric water content, the correlation between LW radiation and this variable improves significantly for both sites.
Regression analyses are carried out between LW radiation and temperature and water vapour pressure at screen level (T, e), LW radiation and screen temperature and PWV (T, PWV) for eachsite individually, and data arecombined from both sites. Statistical indicators such as mean bias error (MBE), root mean square error (RMSE), mean percentage error (MPE), and student t-tests are used to assess these regressions. Both schemes give good predictions for the measured data, although the model containing(T, PWV) shows better statistics (better predictions) for the three datasets in comparisons with the model using (T, e). For instance, the model containing (T, e) gives a RMSE of 19.38 Wm^{-2} for Riyadh, 20.52 Wm^{-2} for Adelaide, and 22.419 Wm^{-2} for the combined data from both sites. Using the scheme comprising (T, PWV) reduces the RMSE values by 16% for Adelaide, 34% for Riyadh, and 14% for the combined data.
Finally, several previously developed models areused to calculate the LW radiation for the three datasets (Adelaide, Riyadh, and the combined data from both sites). Nineteen models with different functional forms and different meteorological variables areselected and used. We find that the predictability of these models varies from one dataset to another. While some models show adequate prediction forone site, they fail forthe other. However, some models give reasonable estimates when the measured data from both sites are combined.

Keywords: *Meteorology; Longwave Radiation; Climate; PWV; Screen temperature; monthly variations; daily variations.*

Date of Submission: 12-01-2019 Date of acceptance: 27-01-2019

I. Introduction

Downward longwave (LW) radiationis due to absorption and emission caused by greenhouse gases (GHG) in the infrared wavelengths (λ= 4–100 μm). Among these gases are water vapour, carbon dioxide and certaintrace gases such as ozone and methane. The amount of emitted radiation depends on the distribution of

these gases (Angstrom 1915; Idso and Jackson 1969; Berdahl and Fromberg 1982; Heitor et al., 1991). The determination of LWradiation is of great importance in several applications such as atmospheric science, meteorology, radiation budget studies, and climatological studies (Stephens 1984; Wild et al., 2001.LW radiation data can be obtained usingmeasuring equipment such as pyrgeometers. However, due to the cost of maintenance and the necessary calibration proceduresof thistype of equipment,LW data are always not obtainable (e.g., Berdahl and Fromberg 1982; Miskolczi 1993;Philipona et al., 2001; Duarte 2006).

Empirical correlations between LW radiation and easy-to-measure meteorological variables are usually conducted when thesedata are scarce. Several modelshave been developedusing this approach.Temperature and water vapour arethe most commonly used variables in these models, and different functional forms have been suggested to calculate the LW radiationunder different climatic conditions (Berdahl and Martin 1984; Dilley and O'Brien 1998; Crawford and Duchon 1999; Jin et al., 2006 ;Ruckstuhl et al., 2007; Bilbao and De Miguel 2007; Dupont et al., 2008;ViAdex-Mora et al., 2009).

In this study, LW radiation data from a Mediterranean climate (Adelaide,Australia)and a desert climate (Riyadh, Saudi Arabia)are used to study and characterize the seasonal and diurnal variations inthe LW radiation. Additionally, the effects of temperature at screen level and atmospheric water contents (at screen level and integrated over the whole atmospheric profile) under clear skies areestablishedfor both sites. Several previously proposedmodels will be assessed in terms of their predictability for the three datasets.

II. Experimental Data and Methodology

2.1 Description of Sites

Adelaide (34.9 S, 130.6 E,4 m) is located in the southern part of the Australian continent and can bedescribed as having a Mediterranean climate. Adelaide is characterized bywarm-to-hot,dry summers (December to February),and mild-to-cool winters (June to August) with moderate rainfall.The mean daytime temperature is about 31°C, althoughthere are several occasions when it experiences maximum temperatures of 42°C or above. During winter, the temperature ranges between 6–15°C with frequent frosts,mainly in the valleys of the Adelaide Hills.

Riyadh(24.35 N,46.42 E, 620 m)is the capital, largest and most populatedcity in Saudi Arabia. It is located in the centreof the Arabian Peninsula, and has a hot, arid, desert climate. In summer, very low humidity is usually recorded in Riyadh, and the mean daytime temperature is between 43–46 °C, with some days when the temperature exceeds 51°C. During winter, the climate is warm, with cool, windy nights. The mean temperatureat nightis between 10–14°C, and zero temperatures are rarely seenin Riyadh. The large temperature variations betweentheseasons in Riyadh are due to the arid conditions and the prevalence of continentality. Riyadhisalso characterized by a high frequency of dust storm events and occurrences of moderate rain fall,particularly during the pre-monsoonseason.

2.2 Observational Data

The data used in this study comprises LW radiation measurements, surface meteorologicaland radiosonde observations.

For the Adelaide site, LW radiation at 4–50 μmwas measured for the period between 2003 and 2006,using the CGR1pyrgeometer developed by KippandZonen(2000). The detector wasinstalled at Kent Town weather station (centre of Adelaide City, approximately 10 km from the coast) and measured the hemispherical LW radiation with a sampling frequency of 1 Hz, collected as 30minute averages.

Standard meteorological observations of ground temperature, dew point temperature, air pressure and cloud data were obtained from Adelaide Airport (8 km from the city centre) and records were made by the AustralianBureau of Meteorology.

LW radiationand meteorological measurements for Riyadh city, for the period between 2014 and 2016, were obtained from the King Abdulaziz City for Science and Technology (KACST) station installed on the rooftop of the Applied Physics Centre building at KACST. The LW radiation was measured using the CGR4pyrgeometer from Kip and Zonen (2013). The measurements were acquired with a sampling frequency of 10 Hz and stored as10min averages. Metrological parameters were measured using the Skye Mini Metstation (Skye Instruments, 2013). For consistency, hourly averaged data from both sites were considered.

Clear sky timeswereselectedbased on the cloud information provided by the Australian Bureau of Meteorology (ABM)and the Saudi Presidency of the Environment (SPE). The cloud coverage was required tobeless than twooctaduring the course of measurements.

Table 1 presents the mean, maximum, minimum and standard deviation values of the LW measurements and some metrological data for both Adelaide and Riyadh.

The mean temperature (T) in Riyadh is 10^{o}C warmer than forAdelaide. In addition, the mean LW radiation in Riyadh is about 69 W/m^2 higher than that measured in Adelaide. In contrast, the mean relative

humidity (RH) in Adelaide is four times higher than in Riyadh. The mean total atmospheric water content in Riyadh is slightly higher than that found in Adelaide.

Table1. Basic statistical parameters for screen level temperature, pressure, relative humidity, precipitablewater vapour and LW radiation during clear sky periods for Adelaide (22610 hours for screen level parameters and 945 hours for PWV data) and Riyadh(1141 hours for screen level parameters and 780 hours for PWV data)during the periodsconsidered

		T [°C]	*e [mbar]*	*RH [%]*	*P [mbar]*	*PWV [mm]*	*LW [Wm-2]*		*T [°C]*	*e [mbar]*	*RH [%]*	*P [mbar]*	*PWV [mm]*	*LW [Wm-2]*
Mean	*Adelaide*	*18.51*	*10.35*	*52.31*	*1017.59*	*16.20*	*325.47*	*Riyadh*	*29.5*	*8.33*	*12.00*	*939.23*	*18.57*	*393.63*
Standard Deviation		*7.39*	*3.51*	*22.19*	*7.04*	*7.80*	*37.34*		*9.25*	*3.52*	*19.26*	*3.90*	*6.55*	*47.25*
Minimum		*-0.10*	*0.49*	*2.00*	*993.80*	*4.24*	*248*		*3.41*	*1.71*	*3.37*	*929.53*	*2.64*	*247.47*
Maximum		*43.00*	*26.60*	*100.0*	*1039.*	*59.95*	*472*		*45.98*	*21.97*	*99.99*	*951.09*	*41.59*	*589.80*

2.3 Methodology

We first consider the diurnal and monthly behaviours of the LW radiation and the meteorological variables, primarilythe temperature and the water contents.The mean values of these variables were classified into 12 bins to studytheir monthly variations and into 24 bins to investigate the daily variation.

The relationship between themeasured LW atmospheric radiation, temperature and the water content was then investigated for each site separately and by combining the data from both sites. Statistical estimators such as the mean percentage error (MPE), mean bias error (MBE), root mean square error (RMSE), student t-test and correlation coefficient (R)were used to assess the association between these variables.

The effect of the atmospheric water content on LW radiation was investigated using the screen level vapour pressure and the total integrated water content, namely the PWV Radiosondemeasurements provided by ABM and SPE for the considered periods were used to calculate the PWV values for each site as follows(e.g., Maghrabi and Clay 2010):

$$PWV = \int_0^z \rho_v(z)dz \qquad (1)$$

whereρv is the absolute humidity at level z.For each radiosonde profile, the required data were extracted at every available atmospheric level, and Equation (1) was integrated to calculate the PWV for the whole atmospheric profile. The calculated statistical parameters for this variable for each site are given in Table 1.

III. Results and Discussion

3.1 Monthly Variation

Figures 1 to 4 present the monthly and diurnal variations inLW radiation, air temperature,vapour pressure and PWV for the two sites.The monthly and diurnal variations inthe LW radiation and air temperature are typicalforthe climatesofAdelaide (southern hemisphere) and Riyadh (northern hemisphere) and are comparable to the observed pattern in other places withthe same climate (e.g., Alados-Arboledas, and Jimenez, 1988andSicartet al, 2010 for northern hemisphere; and Barbaro et al 2010, for southern hemisphere).

Monthlyvariations aregenerally characterized by high LW radiation and temperatures in summer and low values in winter.The variations inthe LW radiation, air temperature, vapour pressure, and PWV in Adelaide were 22%, 158%, 59% and 45% respectively. LW radiation showsa maximum in January (356 $\pm W/m^2$); between February and March,itdrops by about 17 Wm^2 (6%), and thendecreases graduallyuntil it reaches aminimum (about290W/m^2) in winter.The monthly patterns for the three meteorological variables are similar to that of the LW radiation. It shouldbenotedthat the temperature between May and June fellby 46%, while the PWV dropped by about 38% between February and March.The LW radiation pattern reflects the effect of the local climate onboth temperature and moisture. While the variations in LW radiation during winter and summer were2% and 3% respectively, the variations in spring (7.8%) and autumn(9.7%) were larger.

The monthly variations inLW radiation, temperature, vapour pressure and PWVfor Riyadh were 36%, 24% 146% and 78%, respectively. The LW radiation pattern in Riyadh is somewhat similar to that of Adelaide, as it follows the trend of air temperature. However, it varies considerably throughout theseasons. For instance, in spring (March to May) and autumn(September to November), the LW radiation changes by about 12%, whereas it ranges between 3%–4% during the winter and summer seasons. Additionally, largechanges in the LW radiation are evident between the last and the first months of a transition season. For instance, the change in LW radiation between February and March (transition from winter to summer) and between November and December (transition from autumnto winter) was about 15%.Theselarger variations during thetransition seasons reflect the effect of the instability inthe atmospheric conditions during these times. For instance, spring in Riyadhbegins with continuous episodes of dust storms.

The seasonal pattern inthe vapour pressure and PWV in Riyadh is different from that in Adelaide,as it somewhat fails to follow that of the temperature. The vapour pressure decreases slowly from December until it reaches aminimum of 5.2 mbar in July. It then increases to amaximum in November,and decreases by about 68% to reach a value of about 7.8 mbar in December.

The monthly variation inthe PWV shows two minima and two maxima. The first minimum inPWV occursin February (12.5 mm),anditthen jumps by about 73% to reach the first maximumin March (22 mm). It then decreases to the second minimum (15.4 mm) in July. An increasing trend is then shown inthe PWV, to reach the second maximum (25.7 mm) in October. It is noticeable that the PWV increases by about 31%between September and October.

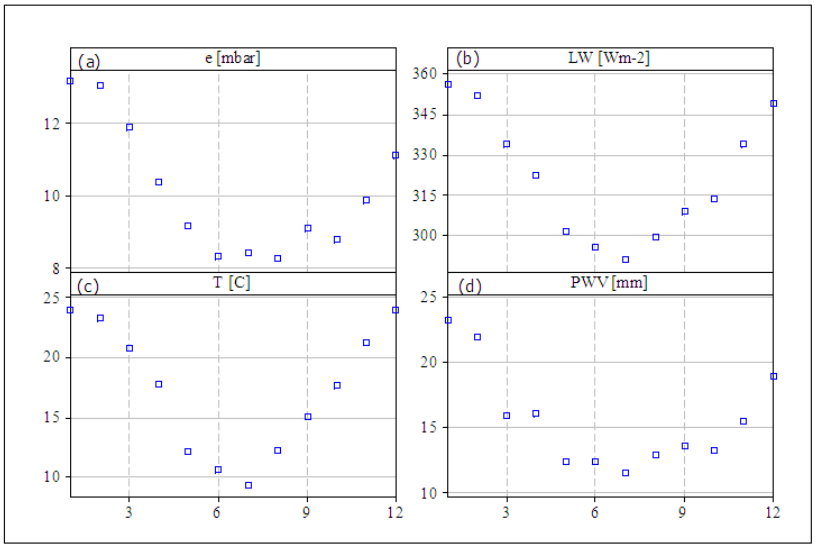

Fig.1. Monthly cyclesin:(a) screen level vapour pressure; (b) LW radiation; (c) screen level temperature; and(d)PWV for the Adelaide site

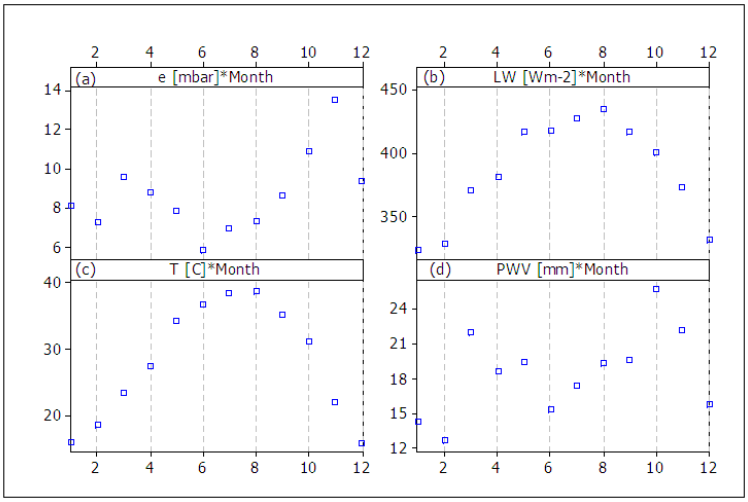

Fig.2. As **Fig. 1,** but for the Riyadh site.

3.2 Diurnal Variations

Figures3 and 4 indicate the daily variations inLW radiation, vapour pressure and air temperature for both sites. It is clear that the daily variation in the LW radiation follows that of the temperature. Both variables have minimum values in the early morning (06:00 local time), and these then gradually increase to reach a maximum at around 13:00. The two variables then start to decrease graduallyafter 13:00 in Riyadh, although they plateau around their maximum values for between two and three hours in Adelaide. The daily variations in temperature and LW were 34% and 13.5% respectively for Riyadh, and 87% and 10% for Adelaide.

In Riyadh, water vapour pressure varies by about 18%, and in Adelaide by 14%. In Riyadh, it shows a gradual increasing trend from 15:00 local time, reaching its maximum at around 05:00. It then decreases slightly to aminimum of 7.5 mbar at 14:00. In Adelaide, the variation inthe water vapour pressure isentirely different from Riyadh. It increases from 9.5 mbar at 05:00 to reach amaximum of 11 mbar at 20:00, andit then decreases again.

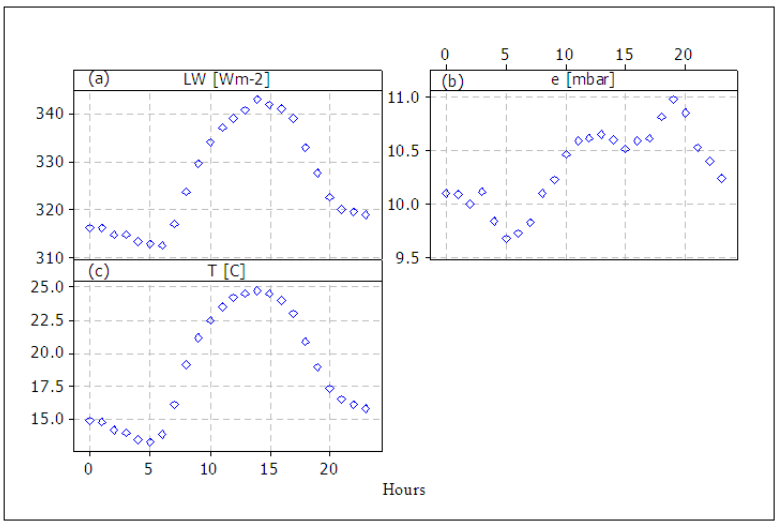

Fig.3. Hourly variation in: (a) LW radiation;(b) screen level vapour pressure; and (c) screen level temperature, for the Adelaide site.

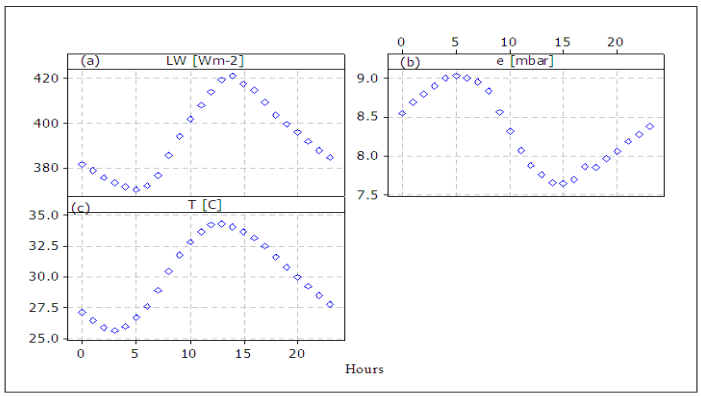

Fig. 4. As **Fig 3**, but for the Riyadh site.

3.3 Relationship between LW Radiation, Screen Level Temperature and Water

Figures 5 and 6show the hourly data forthe LW radiation,plotted against the screen temperature and water vapour pressure for Riyadh and Adelaide, respectively. It is clear that the LW radiation atboth sites has a better correlation with screen temperature than withwater vapour pressure. The correlation coefficient and the RMSEbetween the LW radiation and the screen temperature were0.88 and 22 Wm^{-2} respectively for Riyadh,and 0.81 and 22 Wm^{-2} for Adelaide. However, LW radiation shows a better correlation with the vapour pressure in Adelaide than that found in Riyadh. For Adelaide, the correlation coefficient was 0.4, andthe RMSE was 35 Wm^{-2}, whereas the correlation coefficient and RMSE for Riyadh were0.2and 48 Wm^{-2} respectively.

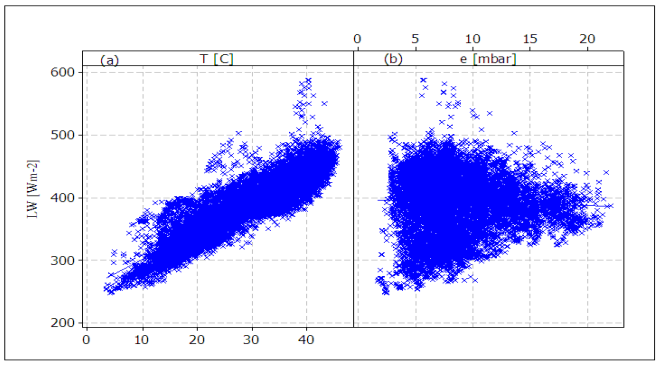

Fig.5. Scatter plot for(a) LW radiation and screen temperature; and (b) LW and screen level vapour pressure for the Riyadh site

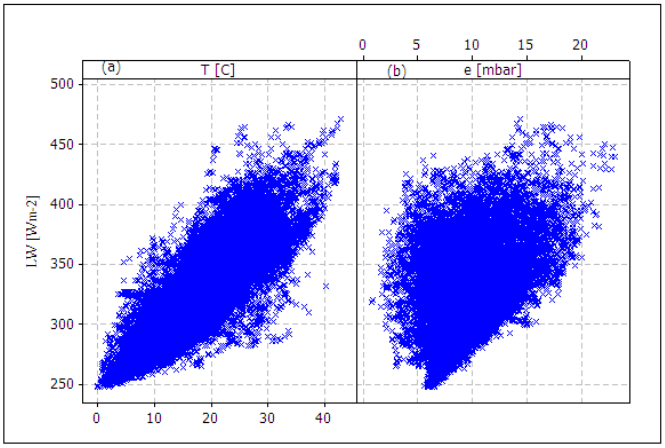

Fig. 6.As **Fig. 5**, but for the Adelaide site.

Regressionanalyses were carried out forLW radiation data and both variables for Riyadh, Adelaide, andthe combined data from both sites;thesegave the following equations:

$LW(T,e) = 222.9171 + 4.8409 \times \mathrm{T} + 2.9826 \times \mathrm{e(Riyadh)}$ (2)

$LW(T,e) = 229.804 + 3.8252 \times \mathrm{T} + 2.4045 \times \mathrm{e(Adelaide)}$ (3)

$LW\ (T,e) = 222.6917 + 4.8592 \times T + 1.734 \times e\mathrm{(Both\ sites)}$ (4)

The regression results and the statistical indicators for these equations are given in Table 2. In all cases, the slopes of the regression between the measured and the predicted values are close to one; MBE is very small; the MPE is less than 0.5%; and t-values are less than the critical values (less than one) at a 95% level of significance for (n−1) degrees of freedom. The RMSE was 19.38 Wm^{-2} for Riyadh(5% of the mean), 20.52Wm^{-2} for Adelaide(5% of the mean), and 22.419 Wm^{-2}(6% of the mean) for the combined data.

Table2. Statistical results forthe regression analyses (Eqs.2 to 4) between the hourly LW radiation and the screen level temperature and water vapour pressure for the three datasets

	Riyadh	Adelaide	Combined Data
MBE	-0.0003	0.0003	-0.0001
MPE	-0.24	-0.36	-0.38
RMSE	19.38	20.52	22.38
R	0.85	0.78	0.86
Slope	0.89	0.76	0.84
t-values	0.002	0.002	0.001
n-1	11392	22568	33961

The relationship between the measured and calculated LW radiation inthe three models is depicted in Figure 7. It is clear that all the models predict the measured data with good accuracy. For most cases, about 95% of the predicted LW radiation data are in close agreement with the measured data. The failure of the models to predict the measured data in some situations may be due to theuncertaintiesassociated with measurements ofthe meteorological variables and/or LW radiation. Other atmospheric parametersnot considered here, such as the effects of atmospheric aerosols, wind speed and high level clouds, may have major influences on the LW radiation in some situations (Riodran et al., 2005; Sugita and Brutsaert 1993). Moreover, the day/night variations inthe atmospheric boundary layer may affect the contribution of the screen level water contents to the absorption and re-emission of LW radiation (Kruk et al., 2010).This explanation will be justified in the following section when the total atmospheric water content, PWV, is used instead of the screen level water.

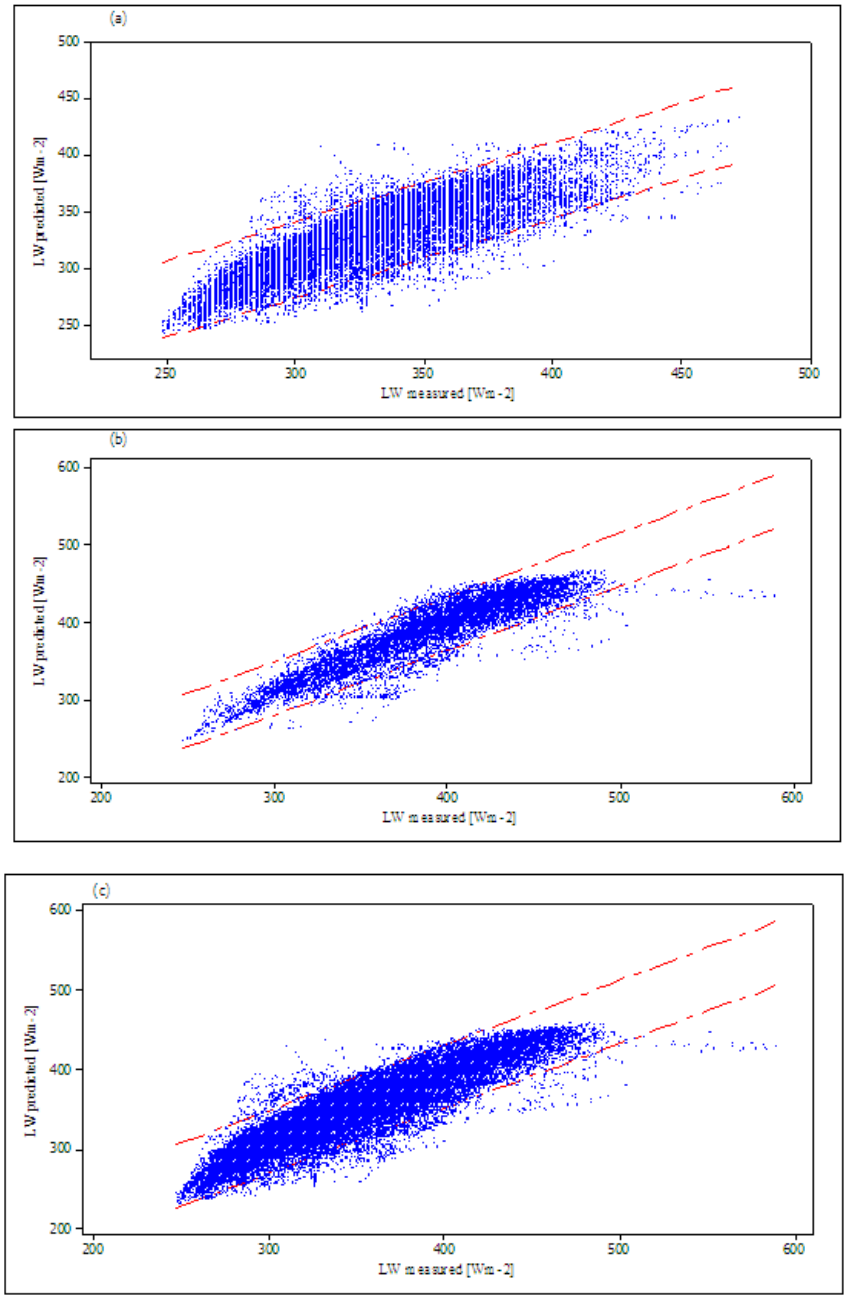

Fig.7. Scatter plot ofthe measured and predicted LW radiation for: (a)Adelaide data; (b) Riyadh data; and (c) combined data from both sites.The dashedred lines representthe 95% confidence interval

3.4 Relationship between LW Radiation, Screen Level Temperature and Total Water Content

Precipitable water vapour (PWV) is generallyused as an actual measure ofthe total moisture in the atmosphere. Several researchers have suggested that PWV is a more suitable variable forinvestigating the real influence of the atmospheric water on LW radiation (Dilley and O'Brien 1998; Prata 1996; Dupont et al., 2008). In this section, the dependence of the LW radiation on PWV will be investigated, andan alternative scheme formodelling the LW radiation using the screen temperature and the PWV will be developed.

Radiosonde data from both sites overthe considered time periods were used to calculate the PWV using Equation (1). A total of 945 PWV data points from the Riyadh site and 780 from the Adelaide site were available for the purpose of this work. The basic statistics of the calculated PWV data are given in Table 1. The corresponding meteorological variables and LW radiation data for the times that have PWV datawere selected.

The mean values and statistical values for the selected data did not differ significantlyfrom the valuespresented in Table 1.

Figure 8 presents the relationship between the LW radiation and the radiosonde-derived PWV for both the Riyadh and Adelaide sites. It can be seen thatthe relationship between the LW radiation and the atmospheric water contents, as represented by PWV, issignificantly improved when compared with usingthe screen level water vapour (Figures 5 and 6). The correlation coefficient and RMSE were0.71 and 26.02 Wm^{-2}respectively for Adelaideand 0.48 and 38Wm^{-2} for Adelaide.

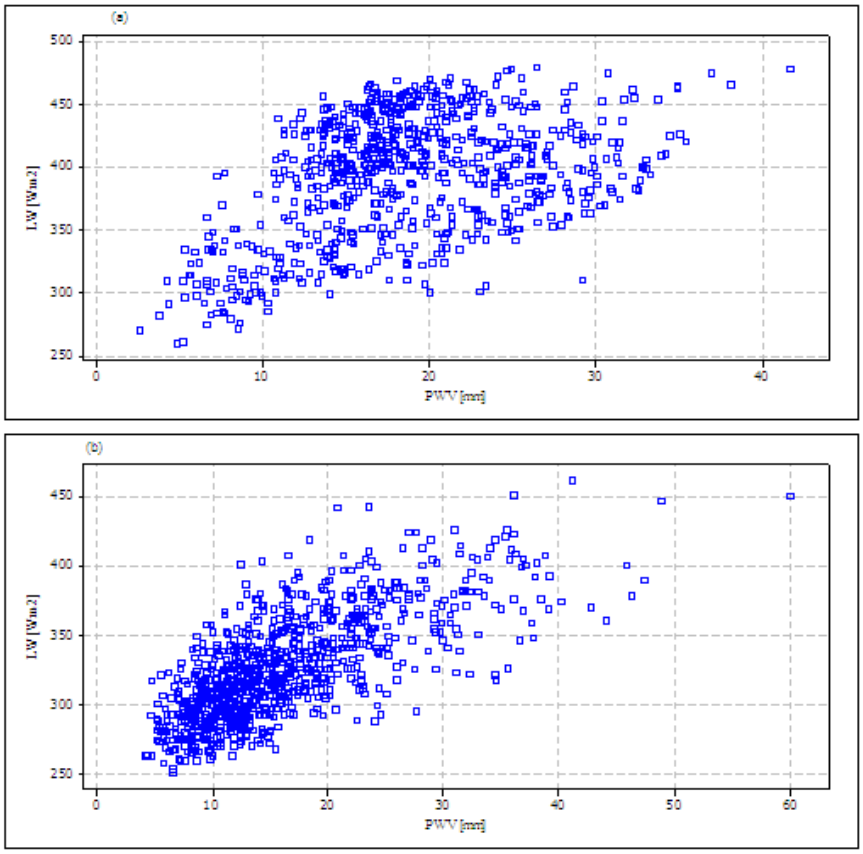

Fig. 8 Scatter plot ofLW radiation and precipitablewater vapour (PWV) data for (a) Adelaide and (b) Riyadh .

Multiple regression analyses between the LW radiation and both the screen temperature and PWV for the three groups of data give the following equations:

$$LW\ (T, PWV) = 222.51\ + 4.51\ T + 1.93\ PWV \qquad \text{(Riyadh) (5)}$$

$$LW\ (T, PWV) = 239.68 + 2.99\ T + 1.86\ PWV \quad \text{(Adelaide) (6)}$$

$$LW\ (T, PWV) = 222.43 + 4.48\ T + 1.57\ P \qquad \text{(Both Sites) (7)}$$

Thestatistical results of these equations are presented in Table 3. It is noticeable that the use of PWV, as a representative of atmospheric water, improves the prediction of the LW radiation significantly. For

instance, the RMSE values have been reduced by 16% for Adelaide, 34% for Riyadh, and 14% for the combined data when the PWV is used rather than the screen level vapour pressure. The slopes of the regressions between the measured and the predicted data are 0.9 for Riyadh, 0.82 for Adelaide and 0.89 for the combined data. The MPE for all three datasets was less than 1%, and the t-values were less than the critical values at a 95% level of significance.

Table 3. Statistical results forregression analyses (Eqs. 5–7) between the hourly LW radiation and the screen level temperature and PWV for the three datasets

	Riyadh	Adelaide	Combined
MBE	0.0006	0.0003	0.0005
MPE	-0.14	-0.28	-0.27
RMSE	14.79	17.10	19.54
R	0.87	0.95	0.93
Slope	0.90	0.82	0.89
t-stat	0.0011	0.0005	0.0011
n−1	755	940	1696

Figure9 shows the relationship between the measured and the calculated LW radiation from the three parameterizations (Eqs. 5−7). It is clear that all the models predict the measured data with good accuracy. The data fallentirely or closeto the 95 % confidence line for allthree models.

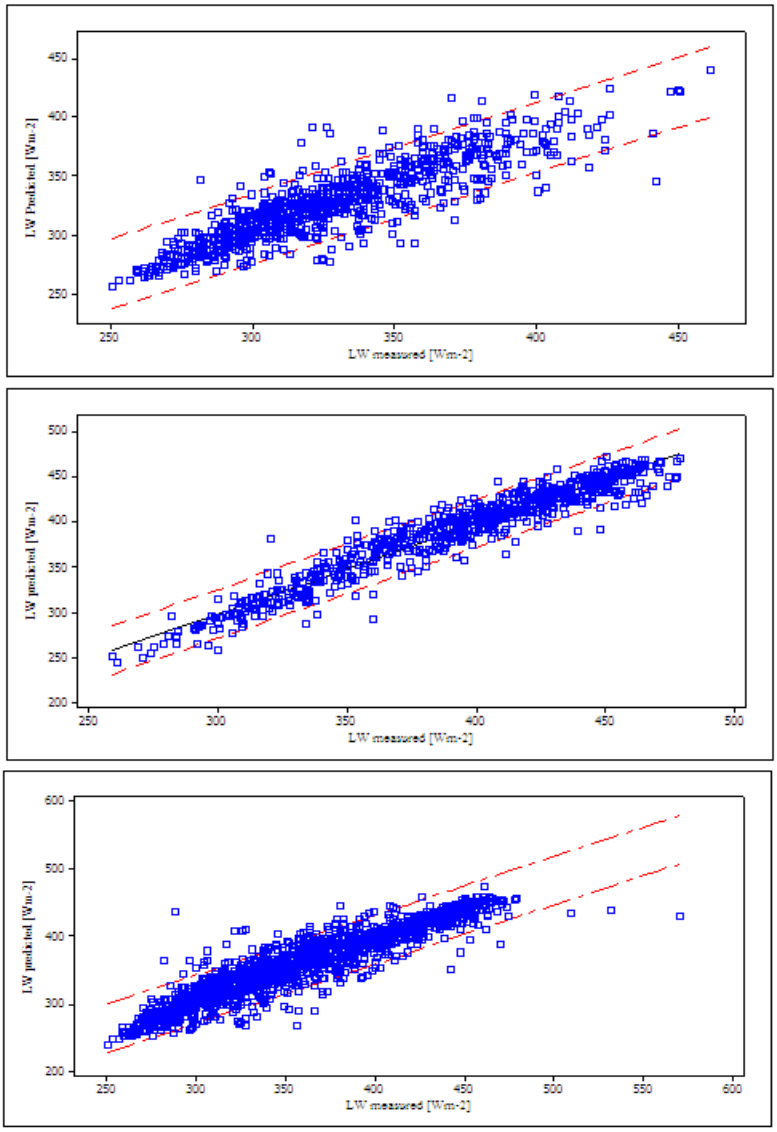

Figure 9. Scatter plot ofthe measured LW radiation and values predictedusing Equation (5-7).The dashed red lines representthe 95% confidence interval.

3.5 Comparisons with Some ExistingParameterizations

Several empirical modelsfrom geographical locations around the world have been developed to estimate the LW based oneasy-to-measure meteorological variables. These schemes differ from each other in terms of the variables they use, their functional form, and the atmospheric conditions where they were developed.

In this section,19clear sky models will be used to evaluate predictionsofLW radiation data in Riyadh, Adelaide, and the combined data from both sites. The selected models were chosen forthe differences in the variables being used and their functional forms.

Table 4 presents the selected models, their function forms, and thecalculated statistical indicators for the three datasets. It can be seen that the predictions of these models differ from one site to another. While some models give adequate predictionsforone site, they fail in others. However, some models present reasonable estimates when the measured data are combinedfrom both sites.

For the Riyadhsite, the RMSE, MBE and MPE were between 60.65 Wm^{-2} and21.5 Wm^{-2}, 56 Wm^{-2}and7.7 Wm^{-2}, and 13%and1.7% respectively. Based on their statistical indicators, models 1, 4,10,12, and 15 gavesatisfactory predictions for the measured LW radiation data in Riyadh. However, models 2, 5, 11, and 17 showed poorer predictions according to their statistical values.

The overall predictions of the selected models for the measured data are better forAdelaide than for Riyadh. The RMSE ranges between 35.93 Wm^{-2}and21.46 Wm^{-2}, MBE varies between -1.33 $Wm^{-2}$and 28.3 Wm^{-2}, and MPE remainsbetween 8.66% and−0.63. Models 1,3,4,6, 10, and 15havebetter statistical indicatorsforpredicting the measured data in comparison with models 2,5,7,10,11, and 17.

Whenpredicting the measured LW radiationusingdata from both sites are combined, the best estimate was achieved by model 1 (MBE = −2.57 Wm^{-2}, MPE=−1.21%, and RMSE 22.55 Wm^{-2}) followed by model 4 (MBE = −3.06 Wm^{-2}, MPE= −1.33%, and RMSE 22.76 Wm^{-2}), model 10 (MBE = 3.89 Wm^{-2}, MPE= 2.55%, and RMSE 26.83 Wm^{-2}), model 12 (MBE = −2.57 Wm^{-2}, MPE= −1.86%, and RMSE 22.41 Wm^{-2}) , and model 15 (MBE = 4.54 Wm^{-2}, MPE= 0.87%, and RMSE 24.07 Wm^{-2}).

The rest of the models under- or overestimated the measured values to variousextents.

Table 4.Author(s) and functional forms ofthe selected models. MBE, MPE, RMSE values are given for the three datasets.

No	Name	Equation	Riyadh			Adelaide			Both sites		
			MBE	MPE	RMSE	MBE	MPE	RMSE	MBE	MPE	RMSE
1	Angstrom (1915)	$\varepsilon_{sky} = 0.82 - 0.25 \times 10^{(-0.168 \times e)}$	7.74	1.78	21.98	-7.76	-2.72	22.83	-2.57	-1.21	22.55
2	Brunt (1932)	$\varepsilon_{sky} = 0.52 + 0.065 \times \sqrt{e}$	56.98	14.30	60.65	26.75	8.08	34.41	36.88	10.16	44.94
3	FAO (1990)*	$\varepsilon_{sky} = 0.64 + 0.044 \times \sqrt{e}$	27.10	6.70	33.37	4.88	1.28	21.46	12.33	3.10	26.06
4	Efmova(1961)	$\varepsilon_{sky} = 0.746 + 0.0066 \times e$	9.58	2.24	21.72	-9.43	-3.13	23.26	-3.06	-1.33	22.76
5	Garratt (1992)	$\varepsilon_{sky} = 0.79 - 0.17 \times e^{-0.96e}$	53.19	13.34	56.80	27.89	8.35	34.66	36.37	10.02	43.36
6	Swinbank(1963)	$\varepsilon_{sky} = 9.365 \times 10^{-6} \times T^2$	-24.02	-5.61	45.55	-3.55	-0.97	30.43	-10.41	-2.52	36.20
7	Idso& Jackson (1969)	$\varepsilon_{sky} = 1 - 0.261 \times exp[-0.000777(273 - T)]^2$	44.14	10.99	49.35	24.98	7.32	33.36	31.39	8.55	39.44
8	Ohmura (1981)	$\varepsilon_{sky} = 8.733 \times 10^{-3} \times T^{0.788}$	13.08	3.39	28.38	10.66	3.12	25.97	13.54	4.15	25.69
9	Brutsaert(1975)	$\varepsilon_{sky} = 1.24 \times \left(\frac{e}{T}\right)^{1/7}$	42.20	10.50	47.35	11.23	3.26	24.85	21.61	13.65	34.09
10	Jin (2006) (Brutsaert)**	$c = 0.0003 \times (T - 273.16)^2 - 0.0079 \times (T - 273.16) + 1.2983$	6.38	2.00	30.03	2.64	0.81	25.06	3.89	2.55	26.83
11	Kruk (2010)	$\varepsilon_{sky} = 0.576 \times \left(\frac{e}{T}\right)^{0.202}$	61.05	15.28	66.07	22.34	6.73	33.37	35.31	22.45	46.93

12	Satterlund(1979)	$\varepsilon_{sky} = 1.08 \times [1 - \exp(-e^{T/2016})]$	8.35	1.98	21.55	-8.07	-2.72	22.83	-2.57	-1.86	22.41
13	Clark & Allen(1978)	$\varepsilon_{sky} = 0.787 + 0.764ln\left(\frac{T_{dp}+273}{273}\right)$	10.62	2.51	22.51	-5.68	-2.03	21.82	23.08	-0.53	23.08
14	Berdhal& Martin (1984)	$\varepsilon_{sky} = 0.711 + 0.56 \times \left(\frac{T_{dp}}{100}\right) + 0.73 \times \left(\frac{T_{dp}}{100}\right)^2$	41.42	10.34	46.32	15.40	4.57	26.44	23.92	6.46	35.60
15	Berger 1984	$\varepsilon_{sky} = 0.77 + 0.0038 \times T_{dp}$	17.19	4.18	26.01	-1.64	-0.76	20.97	4.54	0.87	24.07
16	Herrero 2012	$\varepsilon_{sky} = -1.17 + 0.16 \times RH + 0.0062T$	7.94	2.57	22.18	28.35	8.66	35.93	28.88	8.51	41.05
17	Dilley& O'Brien (1998)	$L_{clr} = 59.38 + 113.7 \times \left(\frac{T}{273.16}\right)^6 + 96.96 \times \sqrt{\frac{PWV}{25}}$	52.27	13.00	56.31	18.84	5.45	28.27	30.04	7.98	39.92
18	Prata(1996)***	$\varepsilon_{sky} = 1 - (1 + IWV) \times exp[-(1.2 + 3 \times IWV)^{0.5}]$	36.88	7.73	36.88	6.33	1.72	21.88	14.68	3.73	27.83
19	Dupont et al. (2008)	$\varepsilon_{sky} = \left[\frac{1.2 \times \left(\frac{e}{T}\right)^{1/7}}{0.0492 \times log\left(\frac{(e/T)^2}{IWV} \times 10^4\right) + 0.88}\right.$	25.43	6.24	32.53	-1.33	-0.63	21.73	7.64	1.67	25.85

*This is a modified version of Brunt's model, as adopted by FAO (REF)

**This model is a modified version of Brutsaert's (1975) model. Jin et al. (2006) have suggested an empirical formula to calculate the constant c, which was taken as 1.24 in the original Brutsaert (1975) model

*** This is the total atmospheric content calculated from $IWV = 0.465 \times (\frac{e}{T})$ cm,as proposed by the author of the model

The inaccuratepredictions made by some of the selected models highlights that they were developedfor sites with atmospheric conditions different from those found in the two considered sites. Likewise, the good performance of some of the models showsthat these models were developed under similar atmospheric conditions to those found at theindividual sites or both sites.

Furthermore, it is obvious that some of the selected models yield great diversity in their predictions, although they contain the same variable with different forms. For instance, the Swinbank (1963) model (which uses the screen level temperature) and Berdhal and Martin's (1984) formula (which uses the dew point temperature) failed topredict the measured LW radiation accuratelyfor the three datasets, whereas the Satterlund (1979) and Berger (1984) schemes, which have the same variables,gavebetter predictions.

IV. Conclusions

In this study of longwave radiation,measurements of the temperature, water vapour pressure, and precipitablewater vapour attwo sites (Adelaide, South Australia, and Riyadh,Central Saudi Arabia) with different atmospheric conditions were used to characterize themonthly and daily variations and to investigate the relationship between LW radiation and these three meteorological variables.

Several conclusions may be drawn from this study:

1- LW radiation at both sitesfollows the trend in temperature,which reaches amaximum in summer andaminimum in winter. The monthly variations inLW radiation, temperature, vapour pressure andPWV, were36%, 24%and 146% respectively; these values were 78% in Riyadh and 22%, 158%, 59%, and 45% in Adelaide.

2- While the amount of LW radiation is confined to asmall range (2%–4%) during winter and summer, it varies considerably (8%–12%) during the transition seasons (spring and autumn) atboth sites.

3- For both sites, the maximum LW radiation values were reached ataround midday and the minimum values occurred in theearly morning. The daily variations inthe LW radiation were13.5% in Riyadh and 10% in Adelaide.

4- For both sites, the screen temperature showsbetter correlation with LW radiation than the screen level water vapour pressure. The latter parameter may not be a suitable measure ofthe atmospheric water content atall times due to the night/day variations inthe height of the atmospheric boundary layer. The relationship between the LW radiation and water contentis improved when the precipitable(total, integrated across the whole atmospheric profile) water vapourwasused instead.
5- Two types of multivariable models have been suggested forpredicting the LW radiation, for each site individually and for the combined data from both sites. The first type includesmodels that use temperature and water vapour pressure at screen level (T, e); the second type usesscreen temperature and PWV (T, PWV). Both categories makegood predictionsofthe measured data, although the type which uses(T, PWV) gives better predictions for the three datasetsthan the model that uses (T, e).
6- Nineteen models are selected frompreviously developed approachesfound in the literature,with different functional forms and different meteorological variables; these were used to calculate the measured data for the three datasets (Adelaide, Riyadh, and the combined data from both sites). We find that the predictability of these models variesbetweendataset andanother. Although some models give adequate predictionsforone site, they fail forthe other. However, some models givereasonable estimates when the measured data from both sitesare combined.

Acknowledgements

We would like to thank King Abdulaziz City for Science and Technology (KACST) for supporting this work.

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Maghrabi A.H. " Monthly and Daily Variations Indownward Longwave Radiation and Its Relationship with Atmospheric Temperature and Water Content Indesert and Mediterranean Climates." IOSR Journal of Environmental Science, Toxicology and Food Technology (IOSR-JESTFT) 13.1 (2019): 44-56.