

University of Nebraska - Lincoln

DigitalCommons@University of Nebraska - Lincoln

Papers in the Earth and Atmospheric Sciences

Earth and Atmospheric Sciences, Department
of

2019

Effects of the Sea Breeze Circulation on Soil Temperature Over Kuwait Using in Situ Observations and the ECMWF Model

Hussain Alsarraf

Matthew V.D. Broeke

Hala Aljassar

Follow this and additional works at: <https://digitalcommons.unl.edu/geosciencefacpub>



Part of the [Earth Sciences Commons](#)

This Article is brought to you for free and open access by the Earth and Atmospheric Sciences, Department of at DigitalCommons@University of Nebraska - Lincoln. It has been accepted for inclusion in Papers in the Earth and Atmospheric Sciences by an authorized administrator of DigitalCommons@University of Nebraska - Lincoln.



The Open Atmospheric Science Journal

Content list available at: <https://openatmosphericssciencejournal.com>



RESEARCH ARTICLE

Effects of the Sea Breeze Circulation on Soil Temperature Over Kuwait Using *in Situ* Observations and the ECMWF Model

Hussain Alsarraf^{1,*}, Matthew V.D. Broeke² and Hala Aljassar³

¹Department of Mathematics and Natural Sciences, American University of Kuwait, Salmiya, Kuwait

²Department of Earth and Atmospheric Sciences, University of Nebraska-Lincoln, Lincoln, NE 68588, USA

³Department of Physics, Kuwait University, Kuwait City, Kuwait

Abstract:

Background:

The mesoscale circulation over Kuwait is an important influence on changes in surface temperatures and soil temperatures.

Introduction:

This paper presents two common summertime atmospheric features over Kuwait linking wind circulation to soil temperatures.

Methods:

In this study, we use the European Centre for Medium-range Weather Forecasts ECMWF reanalysis ERA-Interim dataset to investigate effects of the synoptic scale and mesoscale circulations.

Results:

The results show that a large-scale pressure gradient in summer typically leads to northerly winds over Kuwait, while a weak synoptic-scale pressure gradient leads to light easterly humid winds from the Persian Gulf, consistent with a mesoscale circulation.

Conclusions:

The results demonstrate the significance of wind circulations in driving the Soil Temperature (SOILT). Using the Era-Interim/Land reanalysis dataset for August 2015 over Kuwait, the average SOILT on days of sea breeze is higher than the average SOILT on days dominated by a synoptic-scale pressure gradient.

Keywords: Synoptic scale forcing, Mesoscale circulation, Kuwait, Arabian Peninsula, Soil temperature, Shamal, ECWMF, AWOS, ERA-Interim.

Article History

Received: March 15, 2019

Revised: July 08, 2019

Accepted: July 19, 2019

1. INTRODUCTION

Atmosphere-land interactions control the soil thermodynamic properties, including interactions between soil temperature (SOILT), skin temperature, and air temperature. The SOILT in the region is affected by various factors including global and regional weather patterns, soil type, and topography. Normally, precipitation frequency plays a large role in controlling soil water in terms of infiltration and percolation processes [1]. In this study, we will address the

changes in summertime SOILT over Kuwait as influenced by variations in the regional mesoscale circulation. Fig. (1) is provided to familiarize the reader with the topography of the region and the locations of cities in Kuwait referenced throughout this paper.

The land-sea temperature contrast is one of the most important factors allowing development of the sea breeze. Greater magnitude of daytime heating of the land surface will result in strengthening sea breeze propagation inland [2]. The sea breeze relies on a surface temperature difference, topography, wave propagation, stability, and the background synopticscale wind [3]. The summer season in the Arabian Peninsula is defined by many factors such as high diurnal

* Address correspondence to this author at the Department of Mathematics and Natural Sciences American University of Kuwait Salmiya, Kuwait; Tel:+996 99663313; E-mails: dr.hussain.alsarraf@gmail.com and halsarraf@auk.edu.kw



Fig. (1). Kuwait map, (a) Abraque Alhabari (29.3703, 46.9686), (b) Jal Aliyaah (29.6124, 47.5767), (c) Managish (29.0670, 47.539), (d) Wafra (28.5930, 48.1049), (e) Abdaly (30.0235, 47.7046), (f) Rabyah (29.295, 47.9331), (g) Sulaibiya (29.2856, 47.8180).

temperature variation and hazy weather. The development of a local thermal low pressure system over southern Iran depends on the increase in solar heating during summer, resulting in northwesterly winds across Kuwait and the Arabian Gulf. These hot and dusty winds, which prevail through most of June and July, are known as Shamal winds. These winds can persist for 2-5 consecutive days at a speed of $10\text{-}15\text{ m s}^{-1}$ [4].

The strong pressure gradient in the region normally causes the Shamal wind over the Arabian Peninsula, which results in a temperature reduction. The strong pressure gradient across the Arabian Peninsula sometimes weakens during the summertime resulting in a mesoscale circulation near the coast. Normally, this will cause a shift in the wind to become easterly or southeasterly during midday due to a sea breeze near the Kuwait coast which allows moister air to propagate inland, as this depends on the strength of the sea breeze during the daytime [5]. The sea breeze can penetrate several kilometers inland with average velocities between $2\text{ and }5\text{ m s}^{-1}$ and can develop a vertical structure of up to 2 km in depth [6].

Monsoon rainfall over the Indian subcontinent is initiated by thermal lows starting in May. When the Indian monsoon is at its peak intensity during mid-summer it extends to the Mediterranean Sea, resulting in blocking of frontal systems. The reduced large-scale pressure gradient associated with the monsoon trough favors the formation of mesoscale low pressure during the last part of summer, also increasing humidity along the Kuwait coast. Regions far away from the coast will experience low humidity.

Evaluation of the Reanalysis ECMWF (ERA-40) and ECMWF Interim Re-Analysis (ERA-Interim) from ECMWF

for temperature, wind speed, precipitation, downward shortwave radiation, net surface radiation, and latent and sensible heat fluxes has been done in multiple prior studies [7]. Several studies have evaluated and compared the reanalysis from different regions [8 - 10].

The Shamal wind is supported by the presence of a large-scale pressure gradient [11]. The occasional breakdown of this pressure distribution results in a sea breeze circulation formed near the coast and extending inland. In this study, two case studies will be investigated to illustrate the character of the mesoscale circulation in the region under these distinct synoptic regimes. Effects on SOILT over Kuwait by weakening of the large-scale pressure gradient resulting in a sea breeze will be investigated by comparing days during August 2015 dominated by a mesoscale circulation with days dominated by a large-scale pressure gradient over Kuwait using the ECWMF ERA-Interim/Land reanalysis dataset.

Soil temperature is an important variable for atmospheric and land emissions, surface radiative emissions, evaporation fluxes, soil water phase change, and ecosystem exchange. The SOILT forecasts from ECMWF are also used in Numerical Weather Prediction (NWP), regional climate modeling, the SMOS level2 iterative optimization scheme, and the Soil Moisture Active Passive (SMAP) L-band [12]. A comparing study has been done comparing nearly 700 stations in different environments in the U.S. and Europe with ECMWF forecasts of SOILT during 2012. The results indicate that ECMWF is able to predict soil temperature with reasonable accuracy [13, 14]. The ECWMF reanalysis model for SOILT will provide an illustration of the relationship between the mesoscale circulation and soil temperature in the Kuwait desert.

Table 1. 'Automatic Weather Observing System (AWOS) stations in Kuwait.'

WMO NO.	Station Name	Height (above mean sea level)	Longitude	Latitude	Type	
1	40550	ABDALY	23 m	47° 41'26.747"E	30° 3' 57.467" N	Synoptic, Agricultural
2	40573	ABRAQUE AL HABARI	236 m	46° 58' 7.315" E	29° 22'13.735"N	Climatic
3	40552	JAL ALIYAH	119 m	47° 34'36.341"E	29° 36'34.561"N	Synoptic
4	40580	RABYAH	21 m	46° 58' 7.315" E	29° 22'13.735"N	Climatic
5	40587	SULAIBIYA	55 m	47° 43'16.914"E	29° 15'34.856"N	Agricultural
6	40592	WAFRA	105 m	48° 3' 35.789" E	28° 33' 23.09" N	Synoptic, Agricultural
7	40590	MANAGISH	189 m	47.5333°E	29.0667°N	Synoptic

Table 2. Variables measured by the agricultural and synoptic AWOS stations.

Agricultural AWOS variables																			
Wind Spd 2M (m/s)	Evap Pan (mm)	Evap Pen (mm)	LW In (KJ/cm2)	LW Out (KJ/cm2)	SW In (KJ/cm2)	SW Out (KJ/cm2)	Net Rad (KJ/cm2)	Net UV-B (KJ/m2)	Leaf Wet (%)	Soil T 5 (°C)	Soil T 10 (°C)	Soil T 20 (°C)	Soil T 50 (°C)	Soil T 100 (°C)	Soil Wet 10 (g/cm2)	Soil Wet 20 (g/cm2)	Soil Wet 30 (g/cm2)	Soil Wet 50 (°C)	Heat Flux (W/m2)
Synoptic and Climatic AWOS variables																			
T (°C)	RH (%)	Td (°C)	T Grass (°C)	Wind Speed (m/sec)	Wind Dir (Deg)	Wind Gust (m/sec)	QNH (hPa)	QFF (hPa)	QFE (hPa)	Vis (km)	Rain (mm)	Sun (hr)	Cloud (oct)						

2. MATERIALS AND METHODS

2.1. Reanalysis ECWMF ERA-Interim

In this study a reanalysis ECWMF model the ERA-Interim is used to investigate two common atmospheric scenarios in the summer by averaging surface temperature and relative humidity on 17 days with a large-scale pressure gradient and 11 days dominated by a mesoscale circulation in August 2015. The reanalysis ECMWF model is a forecast model and data assimilation system to reanalyze archived data for the atmosphere and land surface. The data assimilation system used to produce ERA-Interim started in 1979 and is continuously updated. The system includes a 4-dimensional vibrational analysis with a 6-hour analysis window. The spatial resolution of the data set is approximately 80 km (T255 spectral) on 60 vertical levels from the surface up to 0.1 hPa. The ERA-Interim is simulated daily and monthly to include the Mean Sea Level Pressure (MSLP), surface temperature, relative humidity, and SOILT at 5 cm depth [15].

2.2. In Situ Observations

The *in situ* observations in this study originate from Automatic Weather Observation System (AWOS) stations operated by the Kuwait Meteorological Center to investigate the mesoscale circulation of the sea breeze. Six AWOS stations were selected from over Kuwait (Abraque Alhabari, Jal Aliyaah, Managish, Abdaly Wafra, Rabyah, Sulaibiya. The description regarding the AWOS are showing on Table 1, the variables are indicated on Table 2, and their location are shown in Fig. (1).

2.3. ECWMF Reanalysis ERA-Interim/Land

The ECWMF reanalysis ERA-Interim/Land, near-surface

data were used to force the latest version of the Hydrology-Tiled ECMWF Scheme for Surface Exchanges over Land (HTESSEL) land-surface model. HTESSEL includes improved soil hydrology [16], a new snow scheme [17, 18], a multi-year satellite-based vegetation climatology [19, 20], and revised bare-soil evaporation [13]. The HTESSEL used SOILT at 5 cm depth on days with a sea breeze and days dominated by a large scale pressure gradient during August 2015 over Kuwait.

The temperature of the topmost layer of soil is examined using a point-wise one-dimensional optimum interpolation (1-D OI) method as explained in Douville [21]. The examination increments from the screen-level temperature examination are used to generate increments for the first layer of soil and snow temperature (equation 1).

$$\Delta T = c (T_a - T_b) \tag{1}$$

T_a and T_b are examined and model first-guess temperatures, correspondingly. The coefficient c (equation 2) given the enquiry increment depends on two experimental functions that account for (F₁, equation 3) the cosine of the mean solar zenith angle (μ_M) and (F₃, equation 4) the model orography (to reduce the increments over mountainous areas where observations are considered less reliable).

$$C = (1 - F_1)F_3 \tag{2}$$

$$F_1 = \frac{1}{2} \{1 + \tanh [\lambda (M_\mu - 0.5)]\} \quad \lambda = 7 \tag{3}$$

$$F_3 = \begin{cases} 0 & \text{if } Z > Z_{max} \\ \left(\frac{Z - Z_{max}}{Z_{min} - Z_{max}}\right)^2 & \text{if } Z_{min} < Z < Z_{max} \\ 1 & \text{if } Z < Z_{min} \end{cases} \tag{4}$$

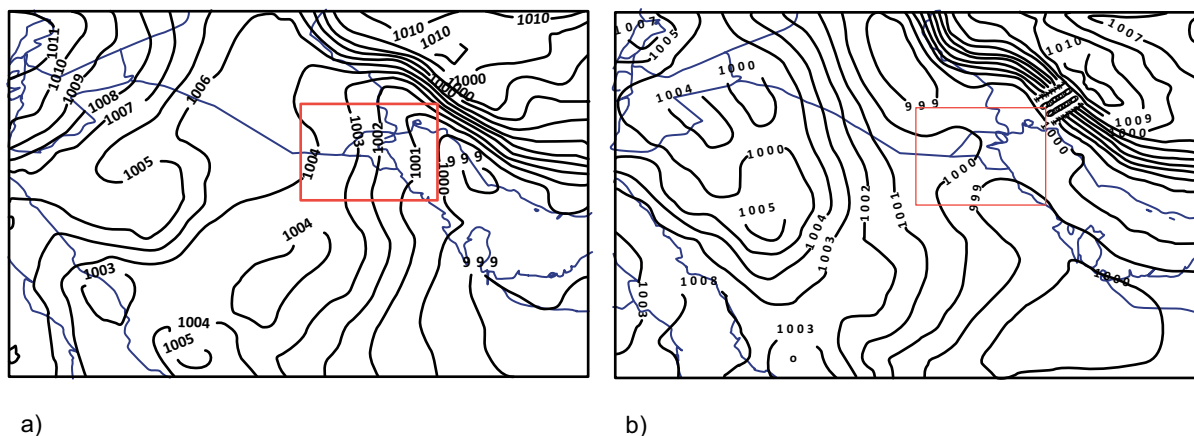


Fig. (2). Mean sea level pressure **a)** 28 August 2015 at 1200 UTC, showing a pressure gradient over the northeastern Arabian Peninsula with pressure increasing toward the northwest. **b)** 4 August 2015 at 1200 UTC, showing a weak pressure gradient over the northeastern Arabian Peninsula.

The Z is the model orography, $Z_{min} = 500$ m and $Z_{max} = 3000$ m. The coefficient c is modelled such that soil temperatures examination is greater productive throughout the night and in winter when the temperature inaccuracies are less possible to be connected to soil moisture [13].

3. SOILT OVER KUWAIT DURING AUGUST 2015

In August 2015 there were 11 days on which a weak pressure gradient across Kuwait resulted in development of a sea breeze (Fig. 2b) and 17 days with a large-scale pressure gradient (Fig. 2a). The reanalysis ECMWF model was used to generate the mean surface temperature during these sets of days in August 2015 (Fig. 6a). While there is a strong SOILT contrast over Kuwait on sea breeze days, there was little difference in SOILT across Kuwait on days with a strong pressure gradient (Fig. 6b). A calculation of the average RH from the reanalysis ECMWF during the 11 sea breeze days (Fig. 9a) indicates high-RH air extending farther inland than on 17 days dominated by a weak pressure gradient (Fig. 9b). The model indicates higher SOILT associated with sea breeze days versus days when there is northerly to northwesterly wind caused by the large scale pressure gradient over the region (Fig. 11) as was observed by the agricultural AWOS stations over Kuwait (Fig. 10). Normally a sea breeze affects the air temperature and RH. This study has also shown a link between sea breeze days and an increase in SOILT over Kuwait during the month of August. Two case studies were selected carefully to ensure no cloud cover on both days, on 4 August 2015 a sea breeze day observed a greater SOILT than on 28 August 2015 the large-scale pressure gradient day.

4. CASE STUDY OVERVIEW

Two case studies were investigated to illustrate the difference between common summertime weather patterns. In the first case, on 28 August 2015, the eastern Mediterranean Sea high pressure system intensified and a thermal low developed over Iran. These resulted in a strong pressure gradient across the Arabian Peninsula leading to dry sustained northwesterly wind (Fig. 2a). Such a pressure gradient is often sustained for a few days to a week in the afternoon [22]. More closely-spaced isobars correspond to a greater pressure

gradient force and therefore to a stronger wind.

The second case is 4 August 2015, when weak synoptic forcing was present in the local area. On 4 August a thermal low developed in northern Kuwait near Iraq, produced by local surface heating (Fig. 2b). This pressure distribution intensified the temperature difference between the land and the Persian Gulf [5, 23]. Thus, temperature advection from the northwest is suppressed. The contrast in the land and water temperature creates a mesoscale circulation near the Kuwait coast. In the daytime the wind shifts from a northerly direction to an easterly or southeasterly direction due to the sea breeze, and then it shifts back to northerly due to the land breeze overnight [5]. Normally the southeasterly and easterly wind from the Persian Gulf causes moisture advection. The advection of water vapor plays a large role in increasing soil moisture over the coastal areas and affects the soil moisture in desert areas in Kuwait. The advection of relative humidity can be used to represent moisture advection, which will affect the upper SOILT especially near the coastal area [24].

Due to Kuwait's geographic location, the wind direction plays a major role for increasing the surface relative humidity near the coastal area or farther inland depending on the strength of the sea breeze and attendant moisture advection. The main objective is to study the impact on SOILT by wind direction, in this case the southeasterly and easterly wind dominating on 4 August 2015.

The wind speed observations on 4 August 2015 over Jal Aliyaah show a northwesterly wind during the morning and a wind shift to southeasterly at 11:00 local time due to a sea breeze passage. This is in contrast to the 28th of August, when a northwesterly wind was sustained throughout the day (Fig. 3a). A similar pattern was present on these two days at Managish (Fig. 3b). The Abraque Alhabari station indicates on 4 August 2015 a similar shift in the winds from northwesterly to southeasterly at 17:00 local time (Fig. 3c).

The Reanalysis ECMWF streamline simulations demonstrate the wind direction during the sea breeze day compared with the large-scale pressure gradient day (Fig. 4). The model captured the Sea Breeze Convergence Zone (SBCZ) propagating toward the land and moving inland (Fig. 4c). The

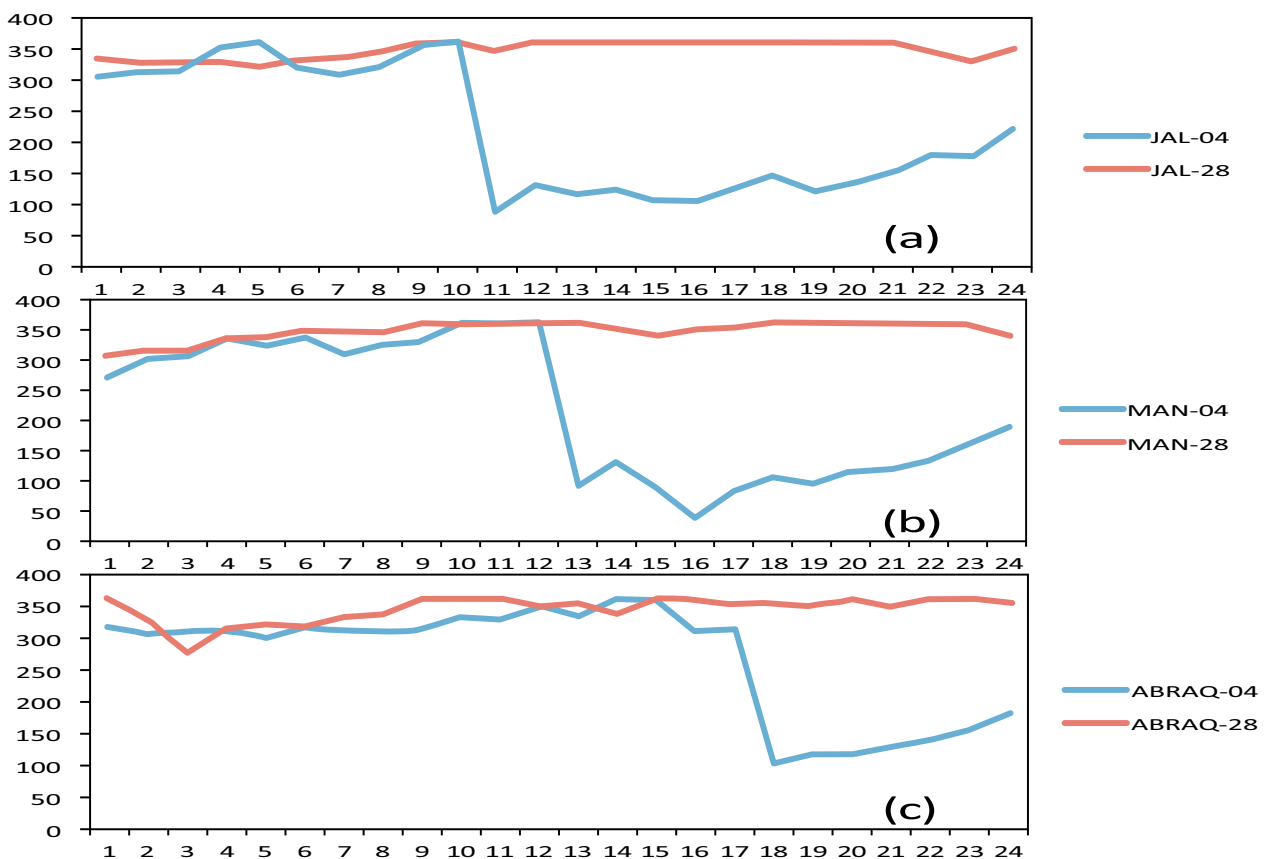


Fig. (3). Wind direction for 04 August 2015 (blue) and 28 August 2015 (red) at (a) Jal Aliyaah, (b) Managish, and (c) Abraq Alhabari. A wind direction of 360° is defined as north.

ECMWF wind barb cross section (Fig. 5) illustrates the wind direction up to 1400 meters height over Kuwait.

The weak pressure gradient over Kuwait generated a mesoscale circulation that enhanced the 2-meter temperature difference between the land and the Persian Gulf.

Between the two case studies that were selected for this study, on 4 August 2015 (Fig. 6) the weak synoptic forcing over Kuwait generated a sea breeze circulation which led to a thermal gradient during the daytime, where on 28 August 2015 the strong pressure gradient is associated with a homogeneous temperature distribution during the daytime over Kuwait (Fig. 6d)

The temperature vertical cross section shows the east-west temperature contrast on 4 August 2015 during a sea breeze event (Fig. 7d). Strong thermal contrast is evident at 12 and 18 UTC on 4 August (Fig. 7c, 7d), with cooler air over the Persian Gulf. In contrast, on 28 August 2015 the temperature was more uniform east-west throughout the day, with some cooling still evident over the Persian Gulf (Fig. 7e-7h).

The diurnal cycle of the Relative Humidity (RH) is important to illustrate the interaction and soil temperature. The

mesoscale circulation can affect the diurnal cycle of RH [25]. The strong synoptic forcing on 28 August 2015 resulted in a nearly constant RH at all stations due to the dry northwesterly wind over Kuwait (Fig. 8). The comparison between the dry day and days where the sea breeze extends inland indicates higher RH values in the afternoon on 4 August 2015 for the three locations (ABRAGQ-04, LAJ-04, MAN-04) shown by the black circle on (Fig. 8). The RH in Jal Aliyaah (JAL-04) increased to 40% by 19:00 LT, then declined at night. Mangish (MAN-04) reached 25% at 18:00 LT and Abraq Alhabari (ABRAG-04) reached 30% at 17:00 LT, but the same location during the northwesterly wind on 28 August 2015 decreased to 5% at MAN-28, and 10% at JAL-28 and ABRAQ-28. The RH shows a strong signal of a sea breeze that propagated inland between 100-150 km over the desert of Kuwait, which has not yet been reported in the literature. The effect of the sea breeze is well represented on the diurnal cycle of RH, which will be shown to influence the SOILT over the desert in summertime.

The two case study days on 4 August 2015 (Fig. 9) show higher RH extended in land than 28 August 2015 (Fig. 9d). A very similar pattern in the RH average calculated over the 11 days of sea breeze and 17 days of large-scale pressure gradient.

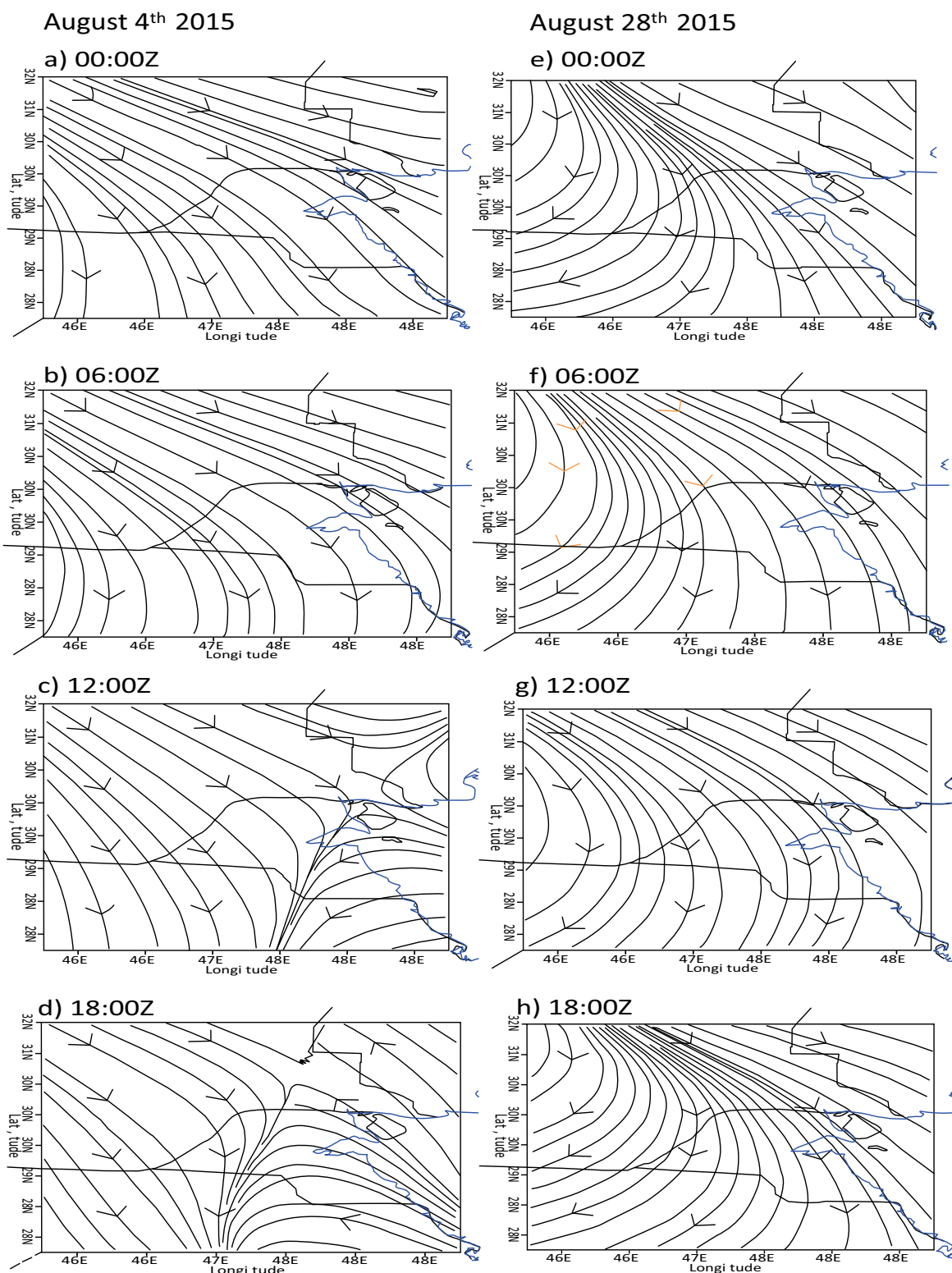


Fig. (4). Reanalysis ECMWF streamlines **a)** 4 August 2015 at 00 UTC **b)** 4 August 2015 at 06 UTC, **c)** 4 August 2015 at 12 UTC, **d)** 4 August 2015 at 18 UTC, **e)** 28 August 2015 at 00 UTC, **f)** 28 August 2015 at 06 UTC, **g)** 28 August 2015 at 12 UTC, and **h)** 28 August 2015 at 18 UTC. Sea breeze convergence is visible in panels c and d.

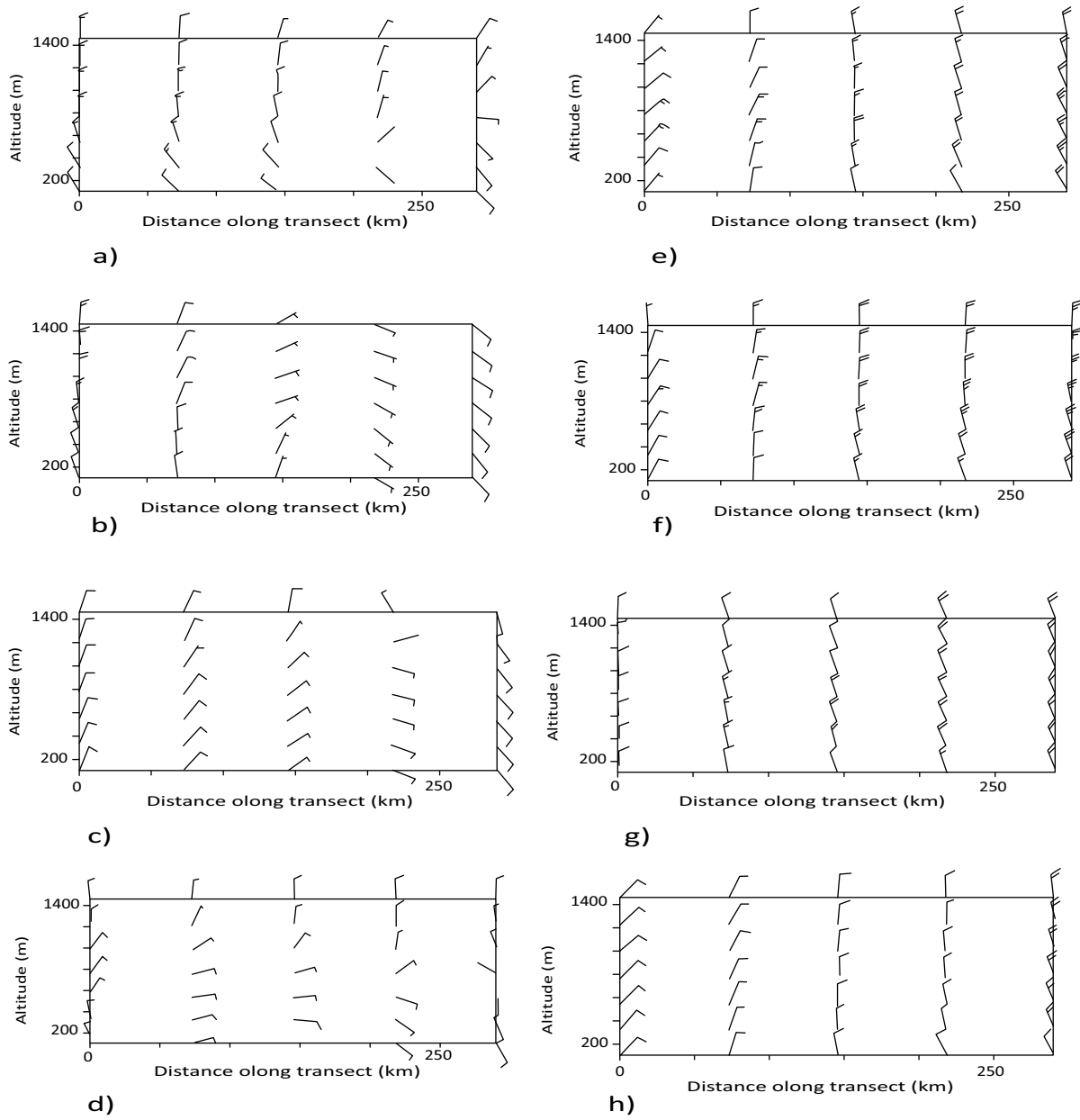


Fig. (5). Wind barb cross section Location (Lat 29.6, Lon 45.8) to (Lat 29.6, Lon 48.8). **a)** 4 August 2015 at 00 UTC **b)** 4 August 2015 at 06 UTC, **c)** 4 August 2015 at 12 UTC, **d)** 4 August 2015 at 18 UTC, **e)** 28 August 2015 at 00 UTC, **f)** 28 August 2015 at 06 UTC, **g)** 28 August 2015 at 12 UTC, and **h)** 28 August 2015 at 18 UTC.

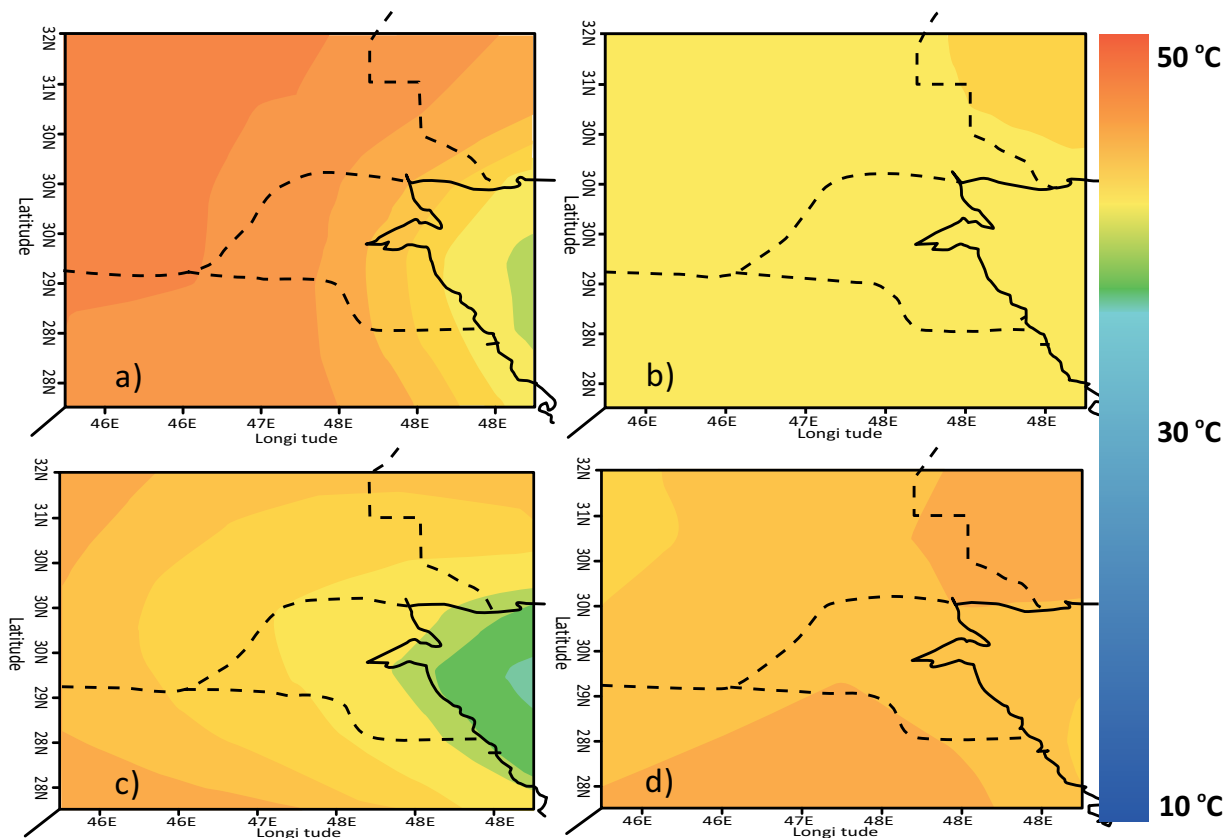


Fig. (6). Reanalysis ECMWF. **a)** The average of surface temperatures during the 11 sea breeze days in August 2015. **b)** The average of 17 days surface temperatures during strong pressure gradient in August 2015. **c)** Surface temperatures on August 4th 2015, **d)** Surface temperatures on August 28th 2015.

Table 3. Maximum and minimum SOILT at 4 Kuwait AWOS stations: Abdaly, Wafra, Sulaibiya, and 438 Rabyah.

Date	Maximum SOILT		Minimum SOILT	
	04/08/2015	28/08/2015	04/08/2015	28/08/2015
Abdaly	54.3	52.2	36.3	34.9
Wafra	54.9	53.3	34.2	33.3
Sulaibiya	56.8	53.3	34.1	33.8
Rabyah	56.1	56	36.9	34.9

5. SOIL TEMPERATURE

We investigate the SOILT from AWOS agricultural stations: ABDALY which is located in northern Kuwait by the Iraqi border, WAFRA which is located in southern Kuwait close to the border of Saudi Arabia, SULAIBIYA which is located west of Kuwait City, and RABYAH which is near Kuwait City (Fig. 1).

The observational data indicate that SOILT recorded higher max and min values on sea breeze days than days with a large scale pressure gradient over Kuwait (Fig. 10). These AWOS stations show that the soil temperature at 5- cm depth recorded higher SOILT (max, min) over all agricultural stations in Kuwait on the sea breeze day (4 Aug 2015), and on the day dominated by a large-scale pressure gradient (28 Aug

2015) cooler SOILT (max, min) was observed (Table 3).

The ECMWF indicates that SOILT on 4 August 2015 had a stronger gradient across Kuwait and higher SOILT (Fig. 11c). On 28 August 2015 both models show a weaker temperature gradient and lower maximum SOILT (Fig. 11d), in agreement with the SOILT observation stations over Kuwait (Fig. 10).

The reanalysis ECMWF averaging the 11 sea breeze days during August 2015 shows higher SOILT with a stronger gradient (Fig. 11a) than 17 days with a large-scale pressure gradient over Kuwait. The case study days (Fig. 11c, 11d) are analogous to the average pattern observed when many such days are averaged (e.g., compare (Fig. 11a, 11c) and (11b), (Fig. 11d).

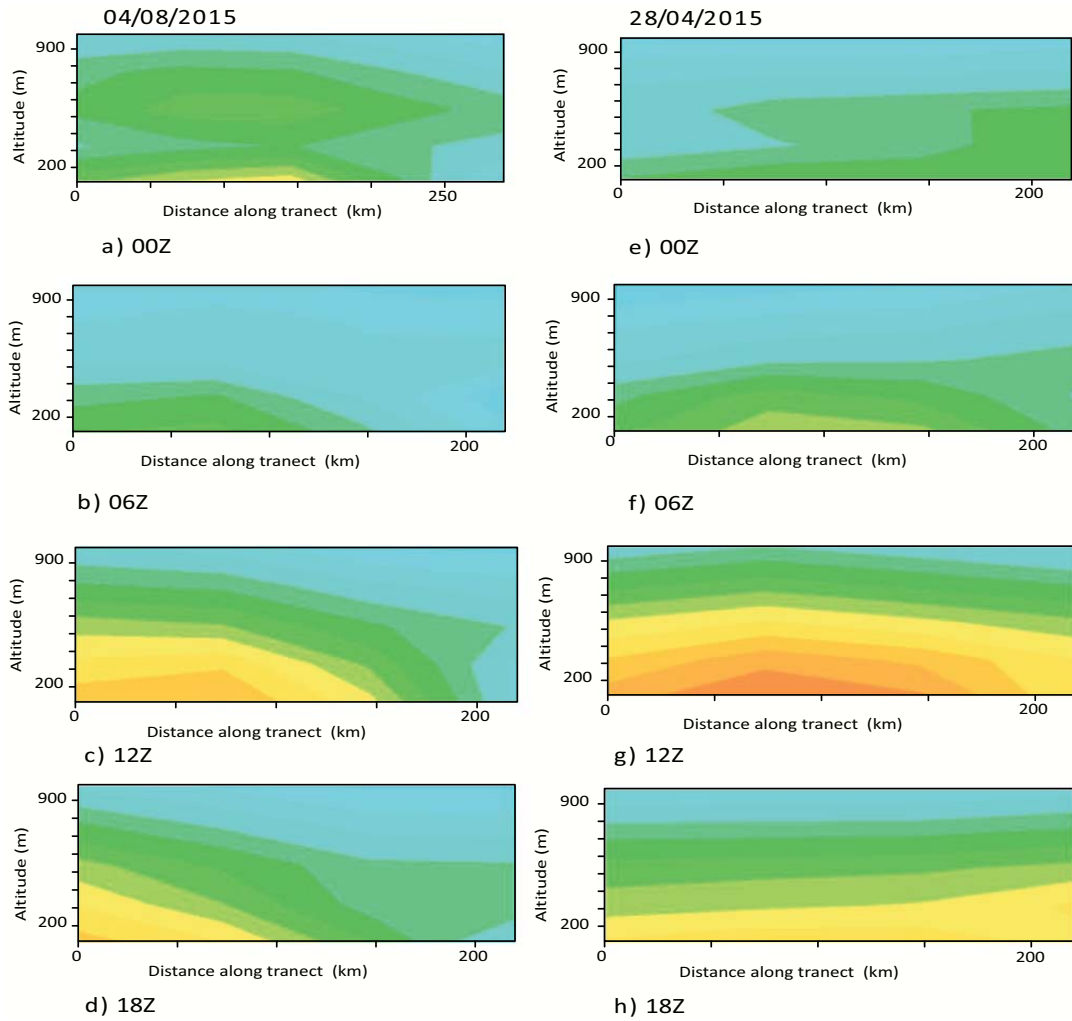


Fig. (7). Vertical cross section of temperature from the reanalysis ECMWF for 4 August 2015 (left column) and 28 August 2015 (right column). Location (Lat 29.6, Lon 45.8) to (Lat 29.6, Lon 48.8).

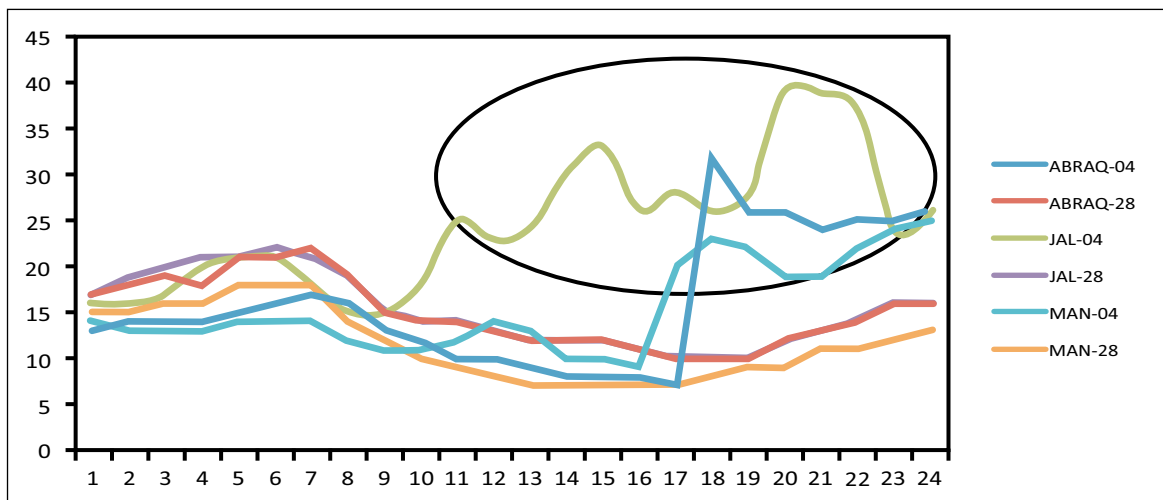


Fig. (8). Relative humidity (%) for 4 and 28 August 2015. The x-axis is time (hours, local time) and the y-axis is the RH %, for the 4th of August 2015 (ABRAQ-04) Abraque Alhabari. (JAL-04) Jal Aliyaah. (MAN-04) Managish, The black circle indicates the increase in RH in the afternoon due to a sea breeze.

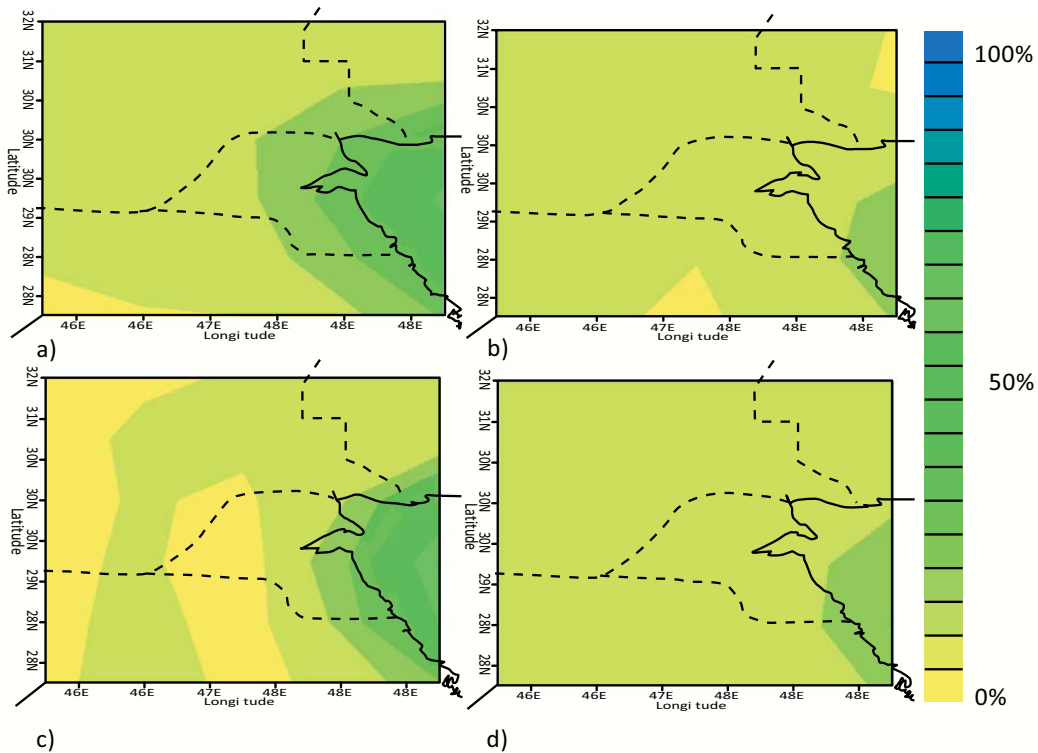


Fig. (9). Reanalysis ECMWF. **a)** The mean surface relative humidity (RH) during the 11 sea breeze days in August 2015. **b)** The mean surface relative humidity (RH) during the 17 large-scale pressure gradient days in August 2015. **c)** Surface RH on 4 August 2015 at 1200 UTC, and **d)** Surface RH on 28 August 2015 at 1200 UTC.

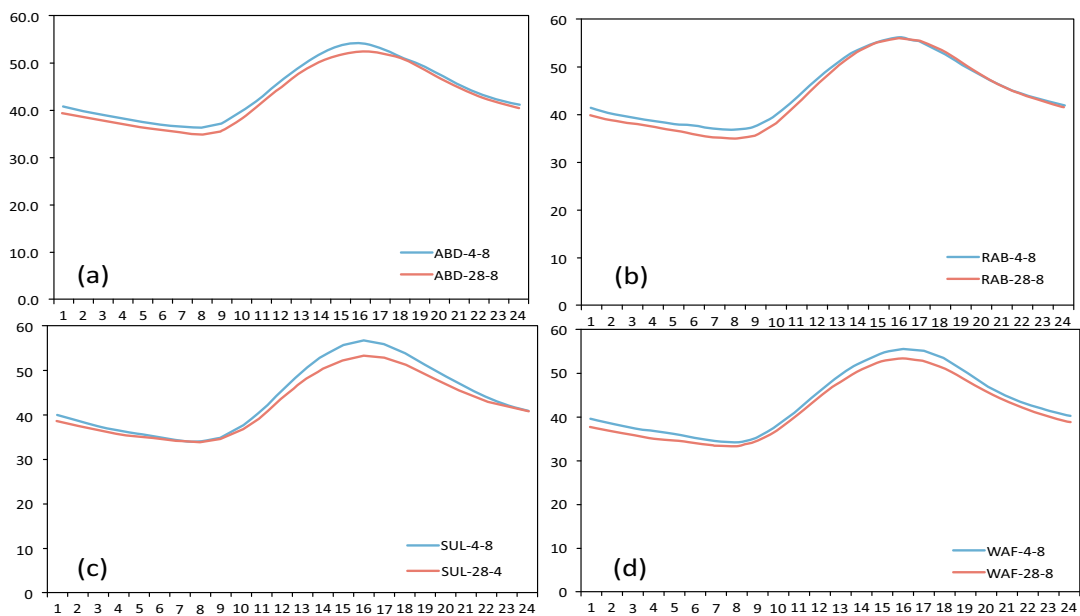


Fig. (10). Agro AWOS soil temperatures at 5 cm depth for 4 August 2015 (blue lines) and 28 August 2015 (red lines) at **(a)** Abdaly (30.0235, 47.7046), **(b)** Rabyah (29.295, 47.9331), **(c)** Sulaibiya (29.2856, 47.8180), and **(d)** Wafra (28.5930, 48.1049).

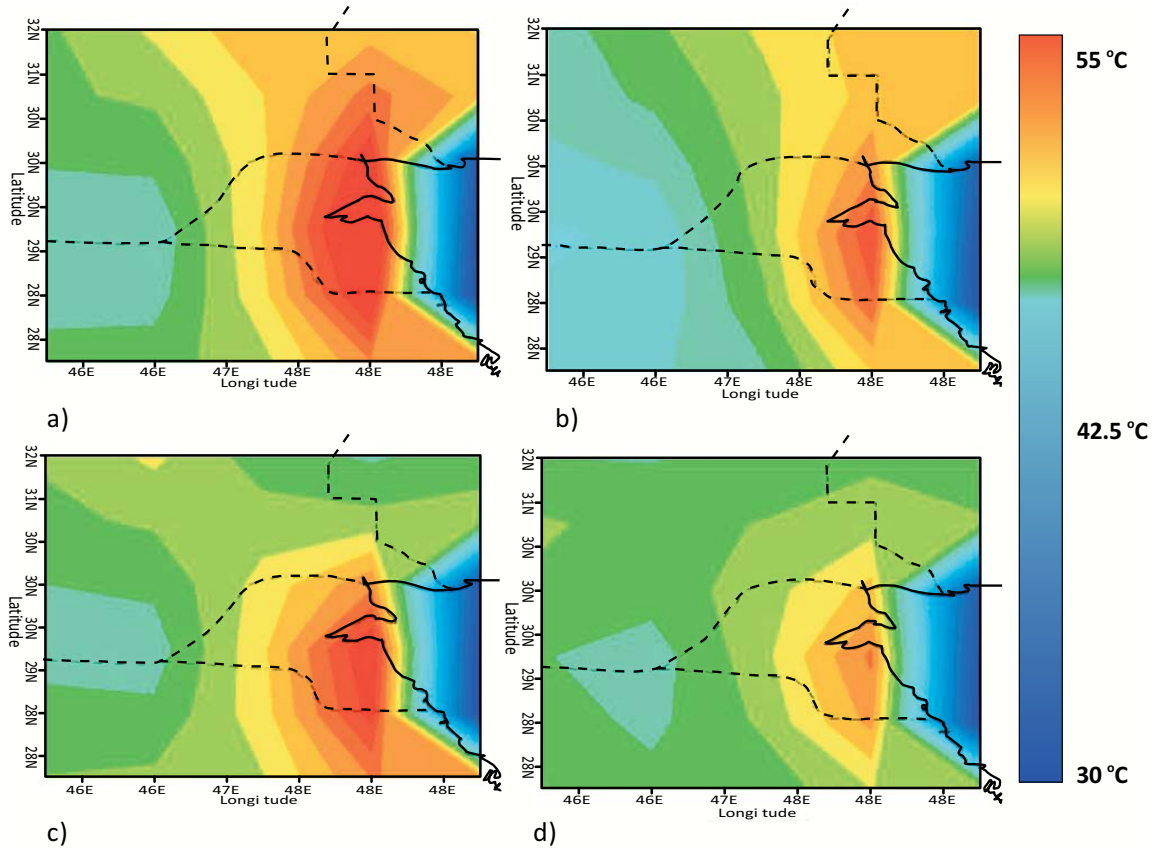


Fig. (11). Reanalysis ECMWF soil temperature at 5 cm depth (SOILT; Celsius) **a)** The average SOILT during the 11 sea breeze days in August 2015. **b)** The average of SOILT during 17 strong pressure gradient days in August 2015. **c)** SOILT on 4 August 2015, and **d)** SOILT on 28 August 2015 12UTC.

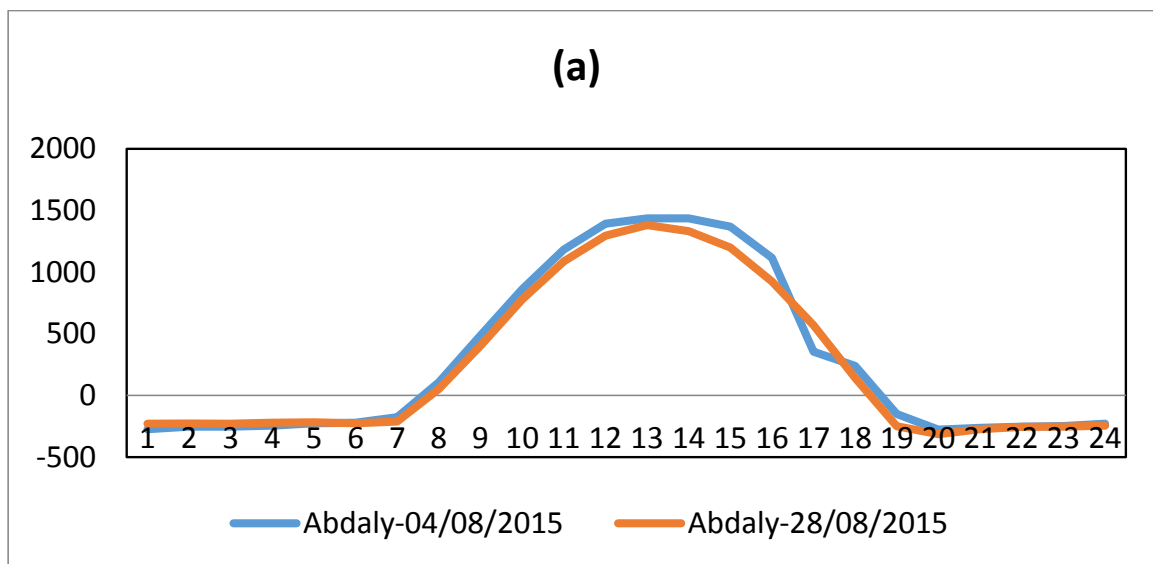


Fig. 12 cont.....

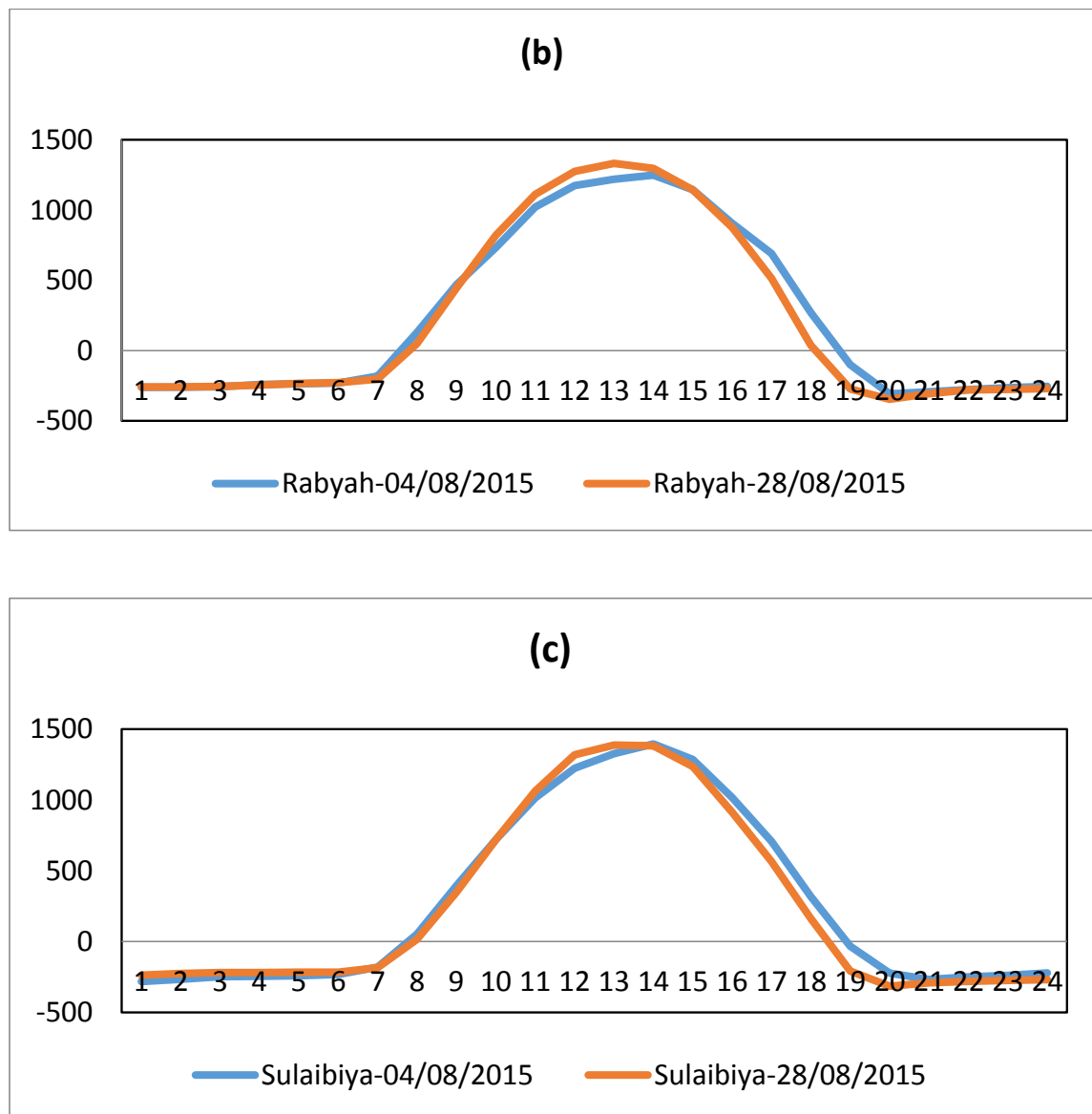


Fig. (12). AWOS Net Radiation (W m^{-2}) at (a) Abdaly, (b) Rabyah, and (c) Sulabiya. Blue lines indicate the sea breeze day (4 August 2015), and orange lines indicate the day dominated by a large-scale pressure gradient (28 August 2015).

Fig. (12) shows net radiation from several AWOS sites around Kuwait on the sea breeze case study day (blue lines) and Shamal wind day (orange lines). Note that the sea breeze day (4 August) is expected, all else equal, to have greater net radiation than the Shamal day (28 August) because of sun angle considerations. This was only clearly the case at Abdaly (Fig. 12a). At Rabyah (Fig. 12b) and Sulabiya (Fig. 12c), midday net radiation was similar to slightly lower on the sea breeze day. Thus, warmer temperatures might be expected at Abdaly due to greater solar radiation on the sea breeze day, while similar to cooler temperatures might be expected at Rabyah and Sulabiya. Why it was instead warmer on the sea breeze day at Rabyah and Sulabiya has not been determined, but this discrepancy may be related to characteristics of the air mass brought in by the sea breeze, or to the lower wind speeds experienced once the sea breeze has passed a point (*e.g.*, Fig.

5). Future studies should investigate whether aerosol loading should influence insolation, and therefore SOILT.

CONCLUSION

In this paper, two case studies were investigated by using AWOS observations, and the reanalysis ECMWF (ERA-Interim), to evaluate the impact of the mesoscale wind circulation on SOILT over Kuwait. The two case studies were selected to coincide with clear sky days over Kuwait.

The first case, on 4 August 2015, was characterized by weak synoptic forcing that led to a mesoscale circulation near the Kuwait coast. The combination of a weak pressure gradient and strong solar heating caused large temperature variation between the land and the Persian Gulf, leading to sea breeze development and a change of wind direction near the coast. In

the second case on 28 August 2015, conditions were associated with a strong pressure gradient across the Arabian Peninsula, which overcame the mesoscale circulation.

1- This study indicates that the sea breeze extended 100-150 km inland over the desert of Kuwait, reaching desert areas like Abraque Alhabari (29.3703, 46.9686), Jal Aliyaah (29.6124, 47.5767), and Managish (29.0670, 47.539). This is the first time of which we are aware that a sea breeze has been documented this far inland in this region.

2- There are indications that summertime SOILT changes are linked to the mesoscale sea breeze circulation leading to higher max SOILT than on days where a large-scale pressure gradient was observed by the agricultural AWOS stations Abdaly (30.0235, 47.7046), Rabyah (29.295, 47.9331), Sulaibiya (29.2856, 47.8180), and Wafra (28.5930, 48.1049).

3- Results suggest that the ECMWF is able to accurately forecast wind, surface temperatures, and RH in a very dry region and can capture the mesoscale sea breeze circulation and the sea breeze convergence zone (SBCZ) during summertime.

4- The ECWMF reanalysis ERA-Interim/Land indicates that during the 11 August days with a sea breeze circulation have higher mean SOILT with an increase of SOILT gradient versus the 17 days dominated by a large-scale pressure gradient. The increased SOILT is not clearly linked to variations in net surface radiation.

AUTHORS' CONTRIBUTIONS

1. **Hussain Alsarraf:** Conceived of the presented idea, designed the model and the computational framework and analysed the data. Derived the models and analysed the data. Worked out almost all of the technical details, and performed the numerical calculations. Drafted the manuscript and designed the figures. Took the lead in writing the manuscript.

2. **Matthew Van Den Broeke:** Helped supervise the project, helped shape the research, interpreting the results, contributed to the final version of the manuscript.

3. **Hala Aljassar:** Contributed to the final version of the manuscript

CONSENT FOR PUBLICATION

Not applicable.

AVAILABILITY OF DATA AND MATERIALS

The weather station datasets (AWOS) generated and analysed during the current study are available from the corresponding author on reasonable request.

Reanalysis ECMWF data generated and analysed during this study can be found online at (<https://www.ecmwf.int/en/forecasts/datasets/archive-datasets/browse-reanalysis-datasets>).

FUNDING

I would like to express my sincere gratitude to Kuwait Foundation for the Advancement for sciences and Kuwait Meteorological Department for supporting this project.

CONFLICT OF INTEREST

The authors declare no conflict of interest, financial or otherwise.

ACKNOWLEDGEMENTS

I would also like to extend my appreciation to Derare Alali and Salah Alansari from the Kuwait meteorological Department for their support.

DISCLAIMER

Capsule: The purpose of this paper is to examine the influence of synoptic-scale forcing and the mesoscale circulation on soil temperature over Kuwait.

REFERENCES

- [1] Lee KS, Kim JM, Lee DR, Kim Y, Lee D. Analysis of water movement through an unsaturated soil zone in Jeju Island, Korea using stable oxygen and hydrogen isotopes. *J Hydrol (Amst)* 2007; 345: 199-211. [<http://dx.doi.org/10.1016/j.jhydrol.2007.08.006>]
- [2] Jin MS, Mullens T. A study of the relations between soil moisture, soil temperatures and surface temperatures using ARM observations and offline CLM4 simulations. *Climate (Basel)* 2014; 2: 279-95. [<http://dx.doi.org/10.3390/cli2040279>]
- [3] Miller STK, Keim BD, Talbot RW, Mao H. Sea breeze: Structure, forecasting, and impacts. *Rev Geophys* 2003; 41: 1011. [<http://dx.doi.org/10.1029/2003RG000124>]
- [4] Hamidi M, Kavianpour MR, Shao Y. Synoptic analysis of dust storms in the Middle East, Asia-Pacific. *J Atmos Sci* 2013; 49(3): 279-86.
- [5] Alsarraf H, Van Den Broeke M. Using high-resolution WRF model simulations to investigate the relationship between mesoscale circulations and aerosol transport over Kuwait. *J Climatol. Weather Forecast* 2015; 3: 3-126.
- [6] Lopes A, Lopes S, Matzarakis A, Alcoforado MJ. Summer sea breeze influence on human comfort during hot periods in Funchal (Madeira Island). *Meteorol Z (Berl)* 2011; 20: 553-64. [<http://dx.doi.org/10.1127/0941-2948/2011/0248>]
- [7] Bao X, Zhang F. Evaluation of NCEP/CFSR, NCEP/NCAR, ERA-Interim, and ERA-40 reanalysis datasets against independent sounding observations over the Tibetan Plateau. *J Clim* 2012; 26: 206-14. [<http://dx.doi.org/10.1175/JCLI-D-12-00056.1>]
- [8] Beljaars A, Viterbo P. 1998. The role of the boundary layer in a numerical weather prediction model in: 307 Clear and cloudy boundary layers, A.A.M. Holtslag and P. Duynkerke (eds.), Royal Netherlands Academy of Arts 308 and Sciences, p. 287-304, Amsterdam, North Holland Publishers.
- [9] Fan X, Walsh JE, Krieger JR. A one-year experimental Arctic reanalysis and comparisons with ERA-40 and NCEP/NCAR reanalyses. *Geophys Res Lett* 2008; 35L19811 [<http://dx.doi.org/10.1029/2008GL035110>]
- [10] Wang A, Zeng X. Evaluation of multireanalysis products with in situ observations over the Tibetan Plateau. *J Geophys Res* 2012; 117D05102 [<http://dx.doi.org/10.1029/2011JD016553>]
- [11] Aurelius L. The impact of Shamal winds on tall building design in the Gulf Dubai Building. Government of Dubai 2008.
- [12] Entekhabi D, Njoku eg, *et al.* The Soil Moisture Active Passive (SMAP) mission. *Proc IEEE* 2010; 98(5): 704-16. [<http://dx.doi.org/10.1109/JPROC.2010.2043918>]
- [13] Albergel C, de Rosnay P, Balsamo G, Isaksen L, Muñoz Sabater J. Soil moisture analyses at 319 ECMWF: evaluation using global ground-based in-situ observations *J Hydrometeor* (in press), also as ECMWF 320 Tech Memo, 2012b; *J Hydrometeor*. (in press), also as ECMWF. 320 Tech. Memo.
- [14] Albergel C, Dutra E, Munoz-Sabater J, *et al.* Soil temperature at ECMWF: An assessment using ground-based observations. *J Geophys Res* 2015; 120: 1361-73.
- [15] Kaiser-Weiss AK, Kaspar F, Heene V, *et al.* Comparison of regional and global reanalysis near-surface winds with station observations over Germany. *Adv Sci Res* 2015; 12: 187-98.

- [16] [http://dx.doi.org/10.5194/asr-12-187-2015]
Balsamo G, Viterbo P, Beljaars A, *et al.* A revised hydrology for the ECMWF model: Verification from field site to terrestrial water storage and impact in the Integrated Forecast System. *J Hydrometeorol* 2009; 10: 623-43.
[http://dx.doi.org/10.1175/2008JHM1068.1]
- [17] de Rosnay P, Balsamo G. C. Albergel J. Muñoz-Sabater and L. Isaksen (2014): Initialisation of land surface variables for Numerical Weather Prediction. *Surv Geophys* 2014.
[http://dx.doi.org/10.1007/s10712-012-9207-x]
- [18] Dutra E, Balsamo G, Viterbo P, *et al.* An improved snow 334 scheme for the ECMWF land surface model: description and offline validation *J Hydrometeorol* 2010; 11 899-916, also 335 as ECMWF Tech. Memo. No. 607.
[http://dx.doi.org/10.1016/j.atmosres.2007.03.010]
- [20] Boussetta S, Balsamo G, Beljaars A, Jarlan J. Impact of a satellite-derived Leaf Area Index 339 monthly climatology in a global Numerical Weather Prediction model *Int J Remote Sensing* 2015. also as ECMWF 340 Tech. Memo. No. 640.
- [21] Douville H, Viterbo P, Mahfouf J-F, Beljaars ACM. Evaluation of the optimum interpolation and nudging techniques for soil moisture analysis using FIFE data. *Mon Weather Rev* 2001; 128: 1733-56.
[http://dx.doi.org/10.1175/1520-0493(2000)128<1733:EOTOIA>2.0.CO;2]
- [22] Alsarraff H, Van Den Broeke M. Using the WRF Regional Climate Model to Simulate Future Summertime Wind Speed Changes over the Arabian Peninsula. *J Climatol. Weather Forecast* 2015; 3: 144.
- [23] Kawai Y, Wada A. Diurnal sea surface temperature variation and its impact on the atmosphere and ocean: A review. *J Oceanogr* 2007; 63: 721-44.
[http://dx.doi.org/10.1007/s10872-007-0063-0]
- [24] Tsang YK, Vanneste J. The effect of coherent stirring on the advection–condensation of water vapour. *Proceedings of the Royal Society A* 473.
[http://dx.doi.org/10.1098/rspa.2017.0196]
- [25] Haugland MJ, Crawford KC. The diurnal cycle of dewpoint across Oklahoma’s winter wheat belt.

© 2019 Alsarraff *et al.*

This is an open access article distributed under the terms of the Creative Commons Attribution 4.0 International Public License (CC-BY 4.0), a copy of which is available at: <https://creativecommons.org/licenses/by/4.0/legalcode>. This license permits unrestricted use, distribution, and reproduction in any medium, provided the original author and source are credited.