# Sea breezes over north-west Arabia

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ABSTRACT

Using surface and upper wind observations on three days at each of three sites in north-western Saudi Arabia it was found that the sea breeze could extend at least 225 km inland at an average speed of 6.7 m sec$^{-1}$ between 1445 and 2300. At 25 km inland both the on-shore component and the off-shore return flow above it were about 1.2 km deep. At this site two increases in dew point, separated by about two hours, followed the arrival of the sea breeze and may have represented the arrival of air with a mostly land track followed by air with a mostly sea track. An unexplained fall in dew point immediately preceded the arrival of the sea breeze on six out of 11 days.

## Introduction

This note presents an analysis of 12 days' meteorological observations taken during late spring 1972 in north-west Arabia as part of a study to examine the possibility of downwind movement by swarms of the Desert Locust, *Schistocerca gregaria* (Forskål), from Arabia across the Red Sea. The observations illustrate some properties of the sea breeze in a region where little has been written about the weather.

There is much evidence for downwind movement by Desert Locust swarms in many parts of its invasion area (northern and eastern Africa and south-west Asia). This evidence is both direct, from the tracking of individual swarms, and indirect, from the displacement of whole populations (see, e.g., Rainey, 1963). Although spring-time crossings of the Red Sea have not been directly observed they are likely to occur in spells of easterly winds accompanying synoptic-scale disturbances moving eastwards across the Near East (Steedman, in prep). Such winds flow over the north-westerlies that are dominant near the sea surface (K.N.M.I., 1949).

An additional wind flow within which coastal swarms might be carried over the sea is the return current above the sea breeze. Although the sea breeze is known to occur frequently along the Red Sea coasts (Pedgley, 1966), its vertical structure and its inland penetration are unknown. To examine these properties of the sea breeze, a mobile team worked near Al Madinah (Fig. 1) during late June and early July 1972.

## Observations

Because less than two weeks could be spent in the field, the mobile team used only three sites. They were on a line approximately at right angles to the coast, and for convenience they were on the only metalled road that runs inland. The sites were chosen to be representative of the three topographic regions: coastal plain, mountains and interior plain.

1. Coastal plain site. This was 0.5 km west of the village of Badr Hunayn, at an altitude of 90 m and 25 km from the sea. The coastal plain is 30–50 km wide, slopes very gently towards the sea, and has a sparse cover of *Acacia* trees and a few small cereal cultivations in wadi beds.
2. Mountain site. This was 15 km north-east of the city of Al Madinah, at 570 m among barren lava hills 150 km from the sea.
3. Interior plain site. This was 1.0 km west of the village of Al Hanakiyah, at 825 m on a barren, sandy and stony, south-eastward sloping plain 225 km from the sea.

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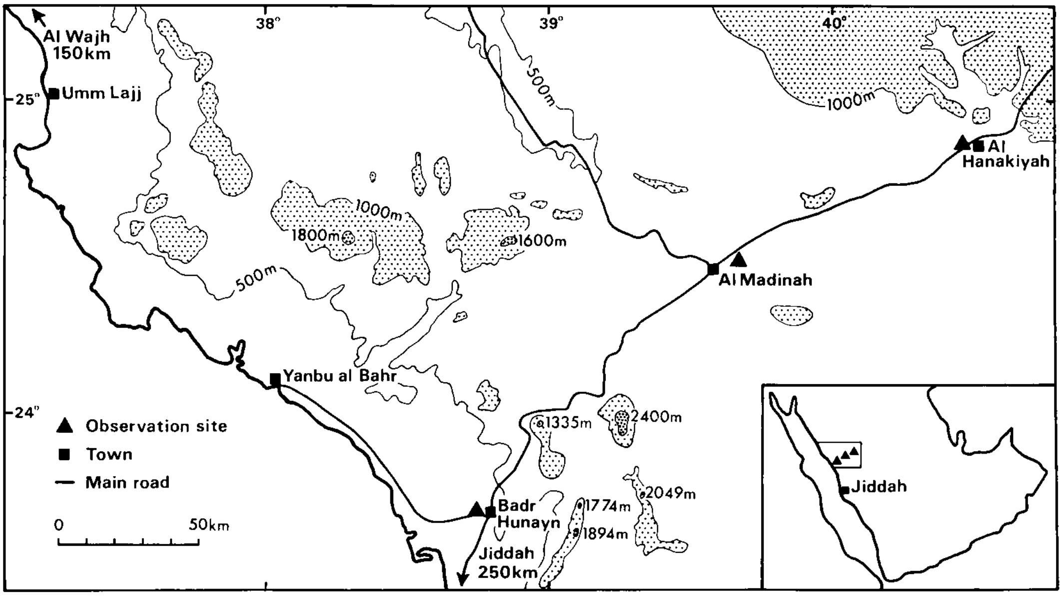


*Fig. 1.* Map showing topography of the study area and places mentioned in the text.

Three days were spent at each site: 22–24 June at Al Hanakiyah, 26–28 June at Al Madinah, and 30 June – 2 July at Badr Hunayn.

To examine the inland penetration of the sea breeze, wind speeds and directions were measured at 20 min intervals from 0600 to 1900 local time (and later on some evenings) using a hand-held anemometer and a portable vane on a 2 m mast. In addition, thermohygrographs were placed in Stevenson screens at all three sites from 22 June to 3 July. Their records were used to find the arrival times of moist air; as shown by many other studies, such times can be taken to be the times of onset of the sea breeze. The instruments were calibrated with an Assmann psychrometer during the three days spent at each site.

To find the vertical structure of the sea breeze, wind speed and direction were measured to an altitude of about 3 km at hourly intervals from 0600 to 1900 (and at 2130 on most evenings). A single theodolite was used to track pilot balloons. There was insufficient hydrogen for hourly soundings throughout the day, so soundings at 1300 and 1400 were omitted. Temperature soundings were available at 1500 on six days from the Al Wajh radiosonde station operated by the Saudi Meteorological Department.

It is helpful when examining sea breeze structure to choose days with little interdiurnal variation of wind; otherwise the sea breeze can be obscured. Interdiurnal changes were examined by preparing the following weather maps, using data provided by the Saudi Meteorological Department and from routine daily broadcasts on file at the Centre for Overseas Pest Research:

1. surface—0900, 1500 and 2100 local time (GMT + 3 h);
2. 700 mb at 1500. This level was chosen as being near the maximum height likely to be reached by flying locusts.

Some interdiurnal changes are now discussed, before consideration is given to the sea breeze.

### *Interdiurnal changes*

Synoptic charts showed little variation from the seasonal pattern and from day to day. The variation is also illustrated by Fig. 2, a vertical time section of daily wind soundings at 0800 and 1500 LT. It shows the dominant north-westerly winds at all levels up to 3 km with little interdiurnal change except that on 22 June winds were south-westerly at Al Hanakiyah and on 26 and 27 June they were north-easterly during the morning at Al Madinah.

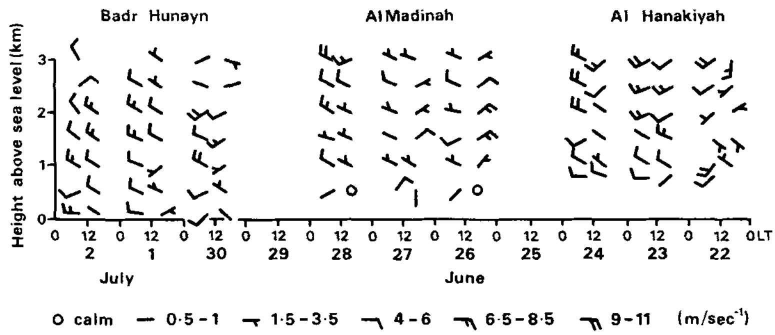


*Fig. 2.* Vertical time sections showing a morning and an afternoon sounding for each day spent in the field. The wind arrows point downwind.

Generally, winds during the morning were lighter (3–6 m sec$^{-1}$) than during the afternoon (5–7 m sec$^{-1}$) except on the two days with north-easterlies when morning winds were stronger than those in the afternoon. These north-easterlies at Al Madinah are discussed further as they were the only breaks in the dominant wind flow during the study period.

On 26 June at Al Madinah between 0600 and 1000, winds below 1 km and above 3 km (to at least 3.5 km) were light, but with a westerly component; between these levels a north-easterly wind with a maximum speed of 9 m sec$^{-1}$ was recorded. By 1100 speeds did not exceed 2.5 m sec$^{-1}$ and remained low during the 1200 sounding, when the north-easterly had backed to north-north-east above 2.4 km and was westerly at 3 km. At 1500, and throughout the afternoon, winds below 3 km were north-westerly. Surface winds were calm during the morning but during the afternoon there was a north-westerly with a maximum speed of 5 m sec$^{-1}$.

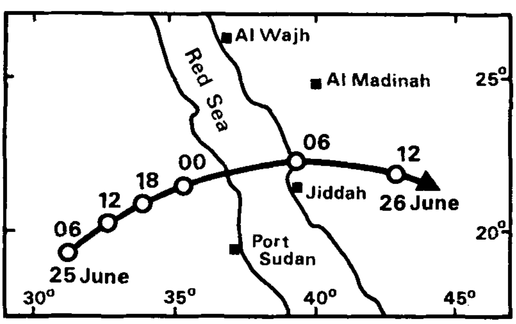


*Fig. 3.* Track of the centre of an eastward-moving disturbance, June 1972.

The strength and organisation of the north-easterlies suggest that they were caused by the passage of a synoptic-scale disturbance. A study of the surface, 850 mb, and 700 mb synoptic charts based on data from Sudan, the Arab Republic of Egypt and Saudi Arabia, showed that a small cyclonic disturbance developed over northern Sudan north of the ITCZ on 25 June, the day before the onset of north-easterlies at Al Madinah. Fig. 3 shows the track of this disturbance at 850 mb. Changes in the wind soundings at Al Madinah on the 26th were consistent with the passage of such a disturbance. Temperatures (1500 LT) were higher at Jiddah (by 3°C) and at Al Madinah (by 2°C) than on the previous day; of the six days during the study period when temperatures aloft at Jiddah were available, on only one was it as high as on the 26th. These high temperatures are consistent with the northward advection of warm air ahead of the disturbance.

## The sea breeze

Fig. 2 shows that 2 July was a day with only small diurnal changes. This was a day when the sea breeze seemed to be well developed at all three sites. Fig. 4 gives the thermohygrograph records. At Badr Hunayn there was an abrupt fall of temperature from 41°C to 38°C at 1500, followed by a rise of dew point from 3°C at 1500 to 17°C by 1600. (Dew points have been calculated from the calibrated records; times have been read to the nearest quarter hour.) Surface winds were light mainly northerly during the early morning, becoming north-westerly,

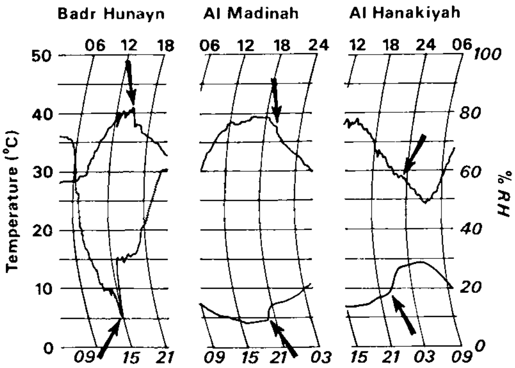


*Fig. 4.* Thermohygrograph traces for 2 July 1972 showing sudden changes (arrowed) in temperature and relative humidity thought to be a result of the arrival of the sea breeze.

Corrections to be made to the records:

| | Relative humidity | Temperature | Time of arrival of the sea breeze |
|---|---|---|---|
| Al Hanakiyah | − 6 % | 0 | 2 330–2 430 LT |
| Al Madinah | + 6 % | + 2°C | 1 930 LT |
| Badr Hunayn | 0 | + 0.5°C | 1 500 LT |

and then freshening to 8 m sec$^{-1}$ during the afternoon backing to westerly at 1400 and persisting until 1500. Upper winds were north-westerly above 600 m all day, except above 2.5 km where they were north-easterly. Near the ground, winds were west-south-westerly from 1000 until 1900 (perhaps an effect of surface friction although this direction is not consistent with that at the surface, which may be due to a site effect), but were light and variable again by 2110.

These changes in temperature, dew point and surface wind indicate the sudden arrival at about 1500 of cooler and moister air from the west, almost certainly the sea breeze. Such sudden changes are characteristic of the passage of a sea breeze front. It is very unlikely that these changes were caused by the passage of a synoptic-scale front (none was detected on the synoptic charts) or the leading edge of a downdraught squall from a shower (there were no shower clouds seen around Badr Hunayn, nor was the synoptic pattern favourable to the development of showers).

Fig. 4 also shows that the sea breeze continued to spread inland, reaching Al Madinah at 1930 and Al Hanakiyah at 2330.

Diurnal variations of upper winds on this day were not obvious from the pilot balloon soundings at Badr Hunayn, presumably because the sea breeze direction was similar to the broad-scale wind direction. However, to clarify the variations, wind vectors for each of the afternoon soundings were compared level for level with the mean vectors based on the morning soundings. Differences are assumed to be caused by a 'local wind' circulation such as

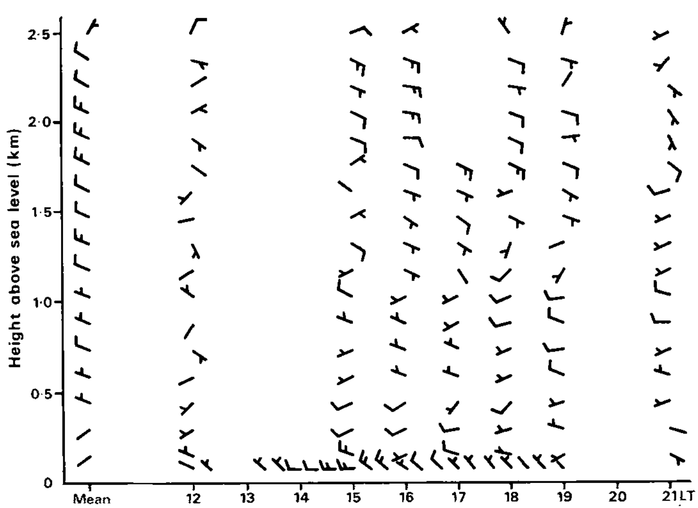


*Fig. 5.* Vector differences between afternoon balloon soundings and the mean of soundings from 0600 to 1100 at Badr Hunayn, 2 July 1972, showing the sea breeze and its return flow aloft. The wind arrows are defined in Fig. 2.

Table 1. *Estimated arrival times (to nearest quarter hour) of the sea breeze, based on thermohygrograph records*

| | Badr Hunayn | Al Madinah | Al Hanakiyah |
|---|---|---|---|
| June 1972 | | | |
| 22 | 1415 | 1945 | No record |
| 23 | 1445 | Not detected | 2200 |
| 24 | 1400 | 2200 | 0045 |
| 25 | 1600 | 1815 | Not detected |
| 26 | 1400 | 1845 | 2400 |
| 27 | Trace obscure | 1830 | 2300 |
| 28 | Trace obscure | 1900 | 2045 |
| 29 | 1400 | Not detected | 2345 |
| 30 | 1530 | 2100 | 2315 |
| July 1972 | | | |
| 1 | 1500 | Not detected | Not detected |
| 2 | 1500 | 1930 | 2330 |
| Average time of arrival | 1445 | 1930 | 2300 |
| Average time of travel between sites (h) | 5 | 3.5 | |
| Distance between sites (km) | 125 | 75 | |
| Mean speed of sea breeze front (m $sec^{-1}$) | 7.2 | 5.8 | |
| Total | 200 km in 8.25 h, i.e. 6.7 m $sec^{-1}$ | | |

might be expected on days when there is little interdiurnal variation of wind. Differences on 2 July at Badr Hunayn (Fig. 5) were small at 1200 in contrast with those of the later afternoon when the sea breeze was well established. There were on-shore winds up to about 1200 m during the afternoon, reaching a maximum of 5 m $sec^{-1}$ at 1000 m at 1800. The return current above was well-defined and reached 7 m $sec^{-1}$ at 2300 m at 1600, but both on- and off-shore flows had become weaker by 1900. Upper wind observations at Badr Hunayn on 30 June and 1 July were analysed in the same way as those made on 2 July but they did not show the sea breeze so well, possibly because the broad-scale wind was stronger and changing speed somewhat from day to day. However, the arrival was clearly shown on the thermohygrograph record.

Because there was good agreement between independent estimates of arrival times of the sea breeze on the three days at Badr Hunayn, using both wind and thermohygrograph records, the latter were used to estimate arrival times when no winds were measured, especially for the later arrivals at Al Madinah and Al Hanakiyah (Table 1). At Al Madinah changes in dew point and temperature were not as great as at Badr Hunayn but were often as abrupt, while at Al Hanakiyah changes were much smaller and more gradual, perhaps because the sea breeze air had mixed with dry desert air as it spread inland. For example, on 26 June at Al Madinah (Fig. 6) the temperature fell from 40°C to 37°C between 1845 and 1900

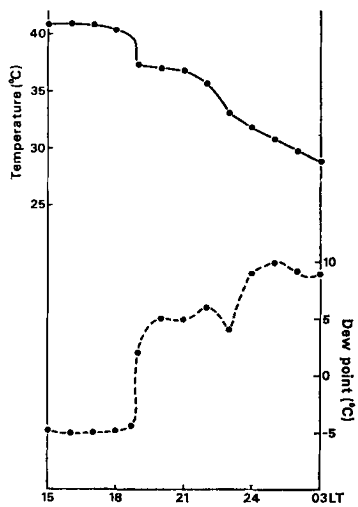


*Fig. 6.* Arrival of the sea breeze at Al Madinah, 1845, 26 June 1972.

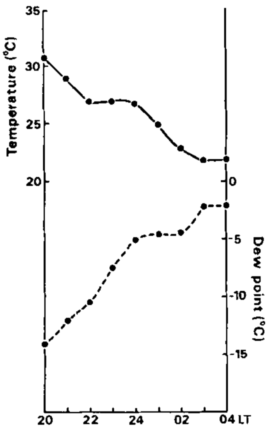


*Fig. 7.* Arrival of the sea breeze at Al Hanakiyah, 2200, 23 June 1972.

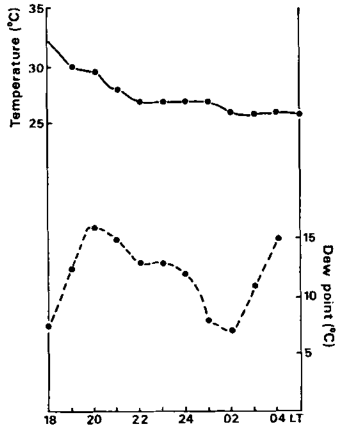


*Fig. 9.* Replacement of sea air by land air during the night, Badr Hunayn, 22–23 June 1972.

while the dew point rose from $-5$°C to 4°C. The vector difference between the upper winds at 1900 and the mean of soundings between 1500 and 1800 was on-shore up to 0.5 km with a return current extending to 2 km. As a further example, at Al Hanakiyah on 23 June (Fig. 7) the steady decline of temperature during the night was interrupted between 2200 and 2400 by a small increase (0.5°C); during the same period the steady increase in dew point was broken by a more rapid change from $-10$°C to $-5$°C.

At Badr Hanayn two abrupt increases in dew point occurred on each of three afternoons, 23 and 24 June and 1 July. The changes were at 1515 and 1830 on both 23 June and 1 July,

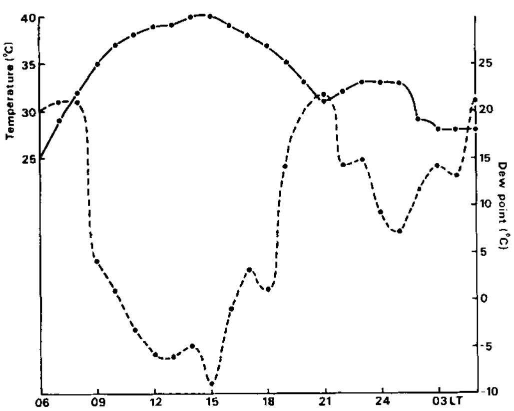


*Fig. 8.* Arrival of the sea breeze at Badr Hunayn, 1500, 1 July 1972.

and at 1400 and 1600 on 24 June. These double increases were most marked on 1 July (Fig. 8) when at 1500 the surface winds suggested the arrival of the sea breeze but the dew point rose only to 3°C from $-9$°C. However, there had been a large and rapid fall in dew point by mid morning, possibly a result of replacement of a shallow layer of moist air near the ground with dry air aloft. From 0600 to 0900 surface winds were either calm or light north-easterly; aloft, the wind at 150 m (and up to 450 m at 0900) was also a light north-easterly while at higher levels the winds were north-westerly. Such a situation would be consistent with the low dew point at the time of arrival of the sea breeze at 1500, for the first air to be brought inland is likely to have had a mostly land track in the previous 24 hours. Three hours later, when presumably marine air with a mostly sea track arrived, the dew point rose very rapidly to a level close to that of the air in the early morning and close to the average dew point of air over the sea (K.N.M.I., 1949). The pattern of changes of temperature and dew point on 23 and 24 June were similar but the changes in humidity were smaller.

A feature of the second rapid increase in the dew point on all three evenings, and of the first increase on six of the 11 afternoons, was an abrupt fall, of up to 5°C, in dew point within the hour preceding the increase. These falls occurred only at Badr Hunayn; an example is shown in Fig. 8 where the dew point fell rapidly between 1400 and 1500.

On three of the eleven nights moist air at Badr Hunayn was replaced by dry air. Thus, on 22 June (Fig. 9) between 2000 and 2400 the dew point fell from 16°C to 12°C before a sharper fall to 7°C at 0200; it rose again to 15°C at 0400. The temperature fell 1°C between 2200 and 0400. Similar changes occurred on 23 June when the minimum dew point (12°C) was at 0200. Such changes are consistent with the retreat of sea air after the development of a land breeze or katabatic wind, but this cannot be confirmed because no wind observations were made at night.

On the night of 1–2 July there was an incursion of dry warm air over a longer period (Fig. 8) than on 22 and 23 June; between 2100 and 0100 there was a fall in dew point from 22°C to 7°C. Temperature rose by 2°C between 2100 and 2300 but remained constant until 0100 when it fell 4°C by 0200. This 'step' pattern in the dew point curve may indicate that the sea breeze front retreated and advanced—a suggestion consistent with the light north-easterly wind recorded at 150 m at 2145, and with the sea breeze not being detected at Al Madinah.

## Discussion

From these few observations, it seems that the sea breeze over north-west Arabia has a vertical structure very similar to that of sea breezes elsewhere (Hsu, 1969) in the tropics. At a place 25 km from the coast, an onshore component was present to an altitude of about 1 km, with a return current above to about 2.5 km. These depths are likely to be typical of days when the cross-coast component of the broad-scale wind is small. On days with easterly winds, the sea breeze may well be both weaker and shallower. The shallow depth shown by the one sounding at Al Madinah may have been because the sea breeze arrived shortly before the balloon was released.

Thermohygrograph records have given good evidence for the sea breeze front reaching 225 km inland by about 2300 local time. On some nights, however, the breeze failed to reach Al Madinah, and on other nights there was evidence for the front returning intermittently at Badr Hunayn. From Table 1, the mean speed of the front between Badr Hunayn and Al Hanakiyah, during late afternoon and the evening, was found to be 6.7 m sec$^{-1}$, agreeing well with observations in other tropical countries, e.g. Australia (Clarke, 1955) and Texas (Hsu, 1969). The records also give evidence for considerably gradients in the moisture field of the sea breeze air. These gradients may well indicate the presence of air with various land and sea trajectories in the previous 24 hours. Such trajectories have been demonstrated for the California sea breeze (e.g. Kauper, 1960; Angell et al., 1966).

Another feature of the records was the temporary fall in humidity on several days before the arrival of moist air. No mention has been found in the literature of similar falls elsewhere, but there is some indication in the humidity records used to illustrate the arrival of the sea breeze at Madras (Ramakrishnan & Jambunathan, 1958) and over southern England (Wallington, 1959). The origin of this dry air is unknown; it is perhaps related to the subsidence just ahead of the sea breeze front that has been derived from some numerical studies (e.g. Estoque, 1962).

## Conclusions

There is reasonable evidence from these few observations that the sea breeze front can penetrate inland more than 200 km over north-western Saudi Arabia, at speeds of about 7 m sec$^{-1}$ in the late afternoon and evening. In other ways the sea breeze is similar to that in many tropical countries. At 25 km from the coast, the breeze is about 1 km deep with a return current above of similar depth. Two features not so far widely recognised are:

(*a*) the possible presence of sea breeze air with a variety of recent histories;

(*b*) the possible presence of subsidence just ahead of the front.

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## МОРСКИЕ БРИЗЫ НАД СЕВЕРО-ЗАПАДНОЙ АРАВИЕЙ

Путем использования наблюдений над ветром у поверхности и на высотах в течение трех дней на каждой из трех площадок на северо-западе Саудовской Аравии найдено, что морской бриз может распространяться по крайней мере на 225 *км* вглубь суши со средней скоростью 6,7 *м/с* в период времени от 14.45 до 23.00. На расстоянии 25 *км* от берега обе компоненты — направленная к берегу и обратный поток над нею распространялись до высоты 1,2 *км*. На этой площадке были зафиксированы два повышения точки росы с интервалом в 2 часа, последовавшие за приходом морского бриза и отражающие последовательный приход воздуха, который в основном находился над сушей, и воздуха, в основном находившегося над морем. Необъяснимое падение точки росы непосредственно предшествовало приходу морского бриза в 6 из 11 дней.