LAND BREEZES AND NOCTURNAL THUNDERSTORMS

By J. Neumann

Israel Meteorological Service

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ABSTRACT

After extension of the definition of land breeze and introductory discussion of the problem of nocturnal thunderstorms, tables are presented for Lydda Airport, Israel, showing the diurnal variation of thunderstorms and the associated surface wind-directions. There is a notable excess of nocturnal thunderstorms with wind directions in the quadrant from which the land breeze blows.

The fundamental fact is pointed out that, because of the curvature of the coast of the eastern Mediterranean (concave toward the sea), the fields of the land breezes and the diurnal winds in the friction layer constitute a convergent wind field, particularly pronounced in the winter. The type of low over the eastern Mediterranean in which land-breeze convergences make an important contribution toward the formation of nocturnal thunderstorms is discussed briefly. A diagram shows the divergent nature of the sea breezes in summer, again, first and foremost, because of the concave curvature of the coast.

A number of stations, located on or near notably convex coasts of the eastern Mediterranean, are shown to have daytime maxima of thunderstorm activity.

U. S. Weather Bureau data also show a diurnal variation of thunderstorms which varies fairly consistently with the curvature of the coast of the United States, notably concave sections of the coast showing either a majority of nocturnal thunderstorms or, at least, a sensibly higher percentage than at the nearest convex section of the coast.

1. Introduction

A recent article by Byers and Rodebush [1],[1] declaring the "double" sea breeze of Florida in summer responsible for the almost daily formation of thunderstorms over that peninsula, raises the following questions: What effect has the sea breeze in other parts of the world? Has the land breeze no consequences comparable to those of the sea breeze?

It is the aim of this paper to show that the great variation in percentage of nocturnal thunderstorms within coastal areas is connected, at least in part, with the convergent or divergent nature of the sea and land breezes involved; in turn, *the convergent or divergent nature of the field of sea and land breezes depends, first and foremost, on the curvature of the coast line.*

The high, or relatively high, percentage of daytime thunderstorms in some coastal areas and that of nighttime thunderstorms in others—*despite the persistence of the pressure systems day and night*—and the consistent pattern of distribution with the shape of the coastline in many cases, indicate that the contribution of land and sea breezes toward the formation or prevention of formation of thunderstorms is not at all negligible.

Throughout this paper, the term sea breeze is meant to include any anabatic winds which may develop in the vicinity of the coast, the two usually linking up sooner or later. Likewise, the land breeze is thought of as including any katabatic winds from mountains near the coast; further, the term should include *the difference wind between the daytime and nocturnal winds due to the diurnal change of friction at all heights within the friction layer.*

The present paper originated from an investigation of the causes of the high percentage of nocturnal thunderstorms along the eastern Mediterranean coast. Hence, the detailed discussions relate to that region.

2. The problem of nocturnal thunderstorms

Buchan (quoted in [4] and [14]), investigating the diurnal variation of thunderstorm frequency over Scotland, found that 58 per cent of the thunder or thunderstorms reported by lighthouses in northwest Scotland occurred at night. The data collected by the "Challenger" in the course of her cruise over the Indian Ocean (see [12, vol. 2, p. 29]) indicated that 93 per cent of the thunder or lightning observed occurred between 1800 and 0600 local standard time. Shaw's diagrams [12, vol. 2, p. 409] also bring out the existence of a maximum of thunderstorm activity at night in the Caribbean and the open ocean near the West Indies.

Some writers questioned the reliability of the above observations and the existence of a nocturnal maximum over the oceans. Thus Whipple [14], as late as 1929, though admitting the existence of a nocturnal maximum in coastal areas, doubted its existence over the oceans. His belief was based on the simple, synchronous diurnal oscillation of the (electrical) potential gradient over the oceans, discovered by Hoffman and confirmed by Mauchly (see, *e.g.* [14]). In Whipple's

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[1] See also subsequent correspondence: [11; 2].

opinion, the maximum of the potential gradient at 1800 GCT is connected with the maximum thunderstorm activity over the prominent thunderstorm areas of the continents (Central Africa, South America, *etc.*), where the storms occur fairly close to this time.

Today, the existence of a nocturnal maximum over most of the extensive water bodies, including large lakes and coastal *waters*, appears to be an established fact.

A maximum frequency of thunderstorms at night, especially during the second half, at coastal or near-the-coast *land* stations has been observed in a number of regions of the world, as, for example, at most stations of the Atlantic coast of the northeastern United States ([6][2] and [15, p. 270]), coastal Germany [9], and the eastern Mediterranean coast (see data presented below). A similar maximum is shown at near-the-coast stations of the Great Lakes in the United States, especially on their east coasts [6], and on the west and northwest coasts of Lake Victoria, East Africa [5].

Conventionally, the higher percentage of nocturnal thunderstorms in some coastal areas is attributed to the proximity of the sea, where instability is greatest at night. The climate of these areas is usually classed as of "maritime" or "oceanic" type. Some shortcomings of this explanation are as follows:

a. It fails to explain notable variations in the percentage of nocturnal thunderstorms between coastal or near-the-coast stations along the same littoral. These variations, as will be shown, show a fairly consistent relationship with the curvature of the coast.

b. It fails to render a unified picture in which the higher percentage of daytime thunderstorms on many islands, peninsulae, and some sections of the littorals appears consistent with the higher percentage of nocturnal thunderstorms in other areas.

TABLE 1. Frequency of daytime and nighttime periods with at least one thunderstorm, with or without rain, at Lydda Airport, Israel, October 1939–May 1949.

Month	Frequency		Percentage	
	0800–1959	2000–0759	0800–1959	2000–0759
October	5	10	33	67
November	11	17	39	61
December	13	23	36	64
January	13	17	43	57
February	12	14	46	54
March	12	16	43	57
April	5	12	30	70
May	4	5	45	55
Total	75	114	40	60

Note: The data for the first three years were taken from Ramleh Airport (31°55′N, 34°53′E, 257 ft m.s.l.), 10 km south of Lydda Airport. Through 1943–1944, the bulk of the observations was taken at 3-hr intervals. From 1944–1945 on, hourly observations were available. In the eastern Mediterranean, the rainy season begins in September or October and ends in May; the summer is dry.

To explain the time of occurrence of the maximum of thunderstorm activity at coastal land stations, a factor must be found which has a diurnal variation similar to the diurnal variation of thunderstorm frequency itself. This factor should be active in all coastal areas where there is a tendency toward a nocturnal maximum. Such a factor appears to be the land breeze, as defined *in the wider sense* above, where the coast is concave toward the sea.

Before a wider examination of the distribution of nocturnal thunderstorms, the case of the eastern Mediterranean will be considered.

3. Role of the land breeze in night thunderstorms along the eastern Mediterranean coast

Night thunderstorms along the Israel coast.—Table 1 summarizes the frequency of thunderstorms, with or without rain, observed during 10 years at Lydda Airport (31°59′N, 34°53′E, 132 ft m.s.l.), Israel, 16 km from the eastern coast of the Mediterranean. To show the diurnal variation, the frequencies are presented for two periods, 0800–2000 and 2000–0800.[3] When more than one thunderstorm was recorded during any period, only the first observation was counted. Of a total of 189 thundery periods, 114, or just over 60 per cent, occurred at night.

Another point emerging from the investigation of past records and from experience is the repeated occurrence of periods, lasting from two to as much as seven days in a row, of thunderstorms developing or at least lightning being reported during the night, with very little or no observed thunderstorm activity during the rest of the day. Most of the rain falls during the hours of darkness and early in the morning; some clearing takes place around midday and in the afternoon.

The occurrence of thunderstorms in the eastern Mediterranean is generally associated with lows or troughs, although the storms do not necessarily develop at the time when pressure is lowest. Lows or troughs with strong pressure-gradients or with clear-cut fronts do not particularly favor nocturnal thunderstorms. The situation most favorable for formation of night thunderstorms in this region is a low or trough extending to great heights *with a weak pressure-gradient in the lower layers*. Such a low acts merely as a "region of convergence." The weak pressure-gradient freely permits the generation of land breezes from the surrounding land areas, especially at night, when the thermal difference is amplified. At night, the inflow from inland regions to the coastal area is strengthened by the diurnal change in direction (and strength) of the winds, due to increased friction, up to 3000–4000 ft or more, the winds showing a notable component

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[2] Here Shands discusses in detail both the diurnal variation of thunderstorm frequency and the problem of nocturnal thunderstorms.

[3] These times and all future time citations refer to local standard time.

toward the sea, where pressure is low.[4] The change in wind direction from day to night is observed in the *diurnal backing* of the winds all along the coast.

In the months when the sea is relatively warm (see table 2) and pressure is low over it, the land breezes persist for the major part of the 24-hr day, and at times for the whole day for a few successive days, the winds at the surface and for some height above it acquiring the character of what may be termed a shallow "monsoon" (of short life-span) from a generally easterly direction. But even when the land breezes are active the greater part of the day, they can be expected to be better developed at night, and especially during its second half. *Thus, a pulsation, a diurnal rhythm is established.*

TABLE 2. Mean sea-surface temperatures 1–70 km off the central Israel coast and average mean temperatures and mean maximum temperatures at Lydda Airport, deg. C.

Month	A Sea mean temp.	B Lydda mean temp.	C A–B	D Lydda mean max. temp.	E D–A
Jan.	17	13	4	18	1
Feb.	16.5	13	3.5	18.5	2
March	17	14	3	20	3
April	18.5	17.5	1	24.5	6
May	22	21.5	0.5	29	7
June	25	23.5	1.5	30	5
July	26	25.5	0.5	31.5	5.5
Aug.	27	26	1	31.5	4.5
Sep.	27	25	2	31	4
Oct.	25	23	2	29.5	4.5
Nov.	23	18.5	4.5	24.5	1.5
Dec.	20	15	5	20.5	0.5

Note: The figures relating to sea temperatures can be found in Clerget [3]. Clerget's figure for April was corrected by Mr. E. Rosenau. The figure in the table is the corrected one.

This is particularly true for the months October through December; in these months the percentage of night thunderstorms can be expected to be large. In January and February, migratory cyclones with strong winds are frequent and there is less chance for the de-

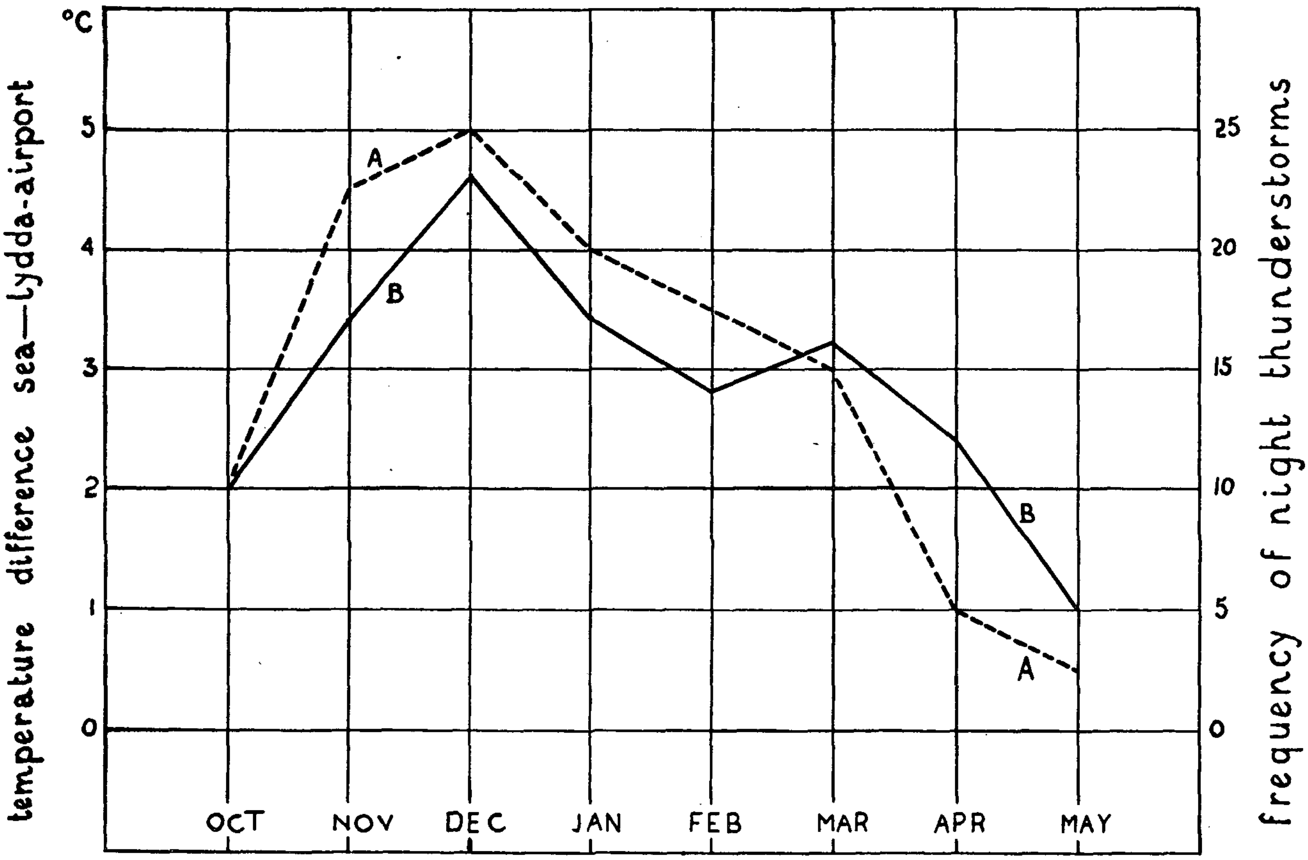

FIG. 1. Curve A: Difference between mean sea-temperature off central section of Israel coast and mean temperatures at Lydda Airport. Curve B: Frequency of nocturnal thunderstorms (10 years) at Lydda.

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[4] According to Means [10], the high percentage of night thunderstorms at Omaha and in the midwestern United States is related to warm-air advection at night in the layer from 2000 to 8000 ft, resulting in a steepening of the lapse rate in the lower atmosphere. The mechanism responsible for this warm-air advection is to be found *in the diurnal wind variations* described by Wagner [13]. Wagner's mechanism is essentially the same as that causing the sea and land breezes.

It is also to the point to quote Iyer [7]: ". . . Generally the probability (of rain at Bombay) seems to be greatest when the wind direction is nearly opposite the prevailing wind direction, and least when it approaches the prevailing direction. Hence the statement made by Blanford in the case of Calcutta that 'it is not when the monsoon current is blowing steadily that rain is most probable, but when it is deflected from its normal direction *by some local irregularity of pressure* (italics mine, J. N.), and rain is the more probable in proportion as this deflection is greater' seems to be equally applicable to Bombay."

velopment of land breezes. *These circumstances should tend to weaken the dominance of nocturnal thunderstorms.* So far, the expectations are well borne out by table 1. The high percentage of night thunderstorms in March, April and May, despite the relative coldness of the sea and insolational heating of the land, is due to the fact that the sea breeze, the frequency of incidence of which is on the increase now, is, as will be pointed out below, a highly divergent wind acting against the formation of thunderstorms by day.

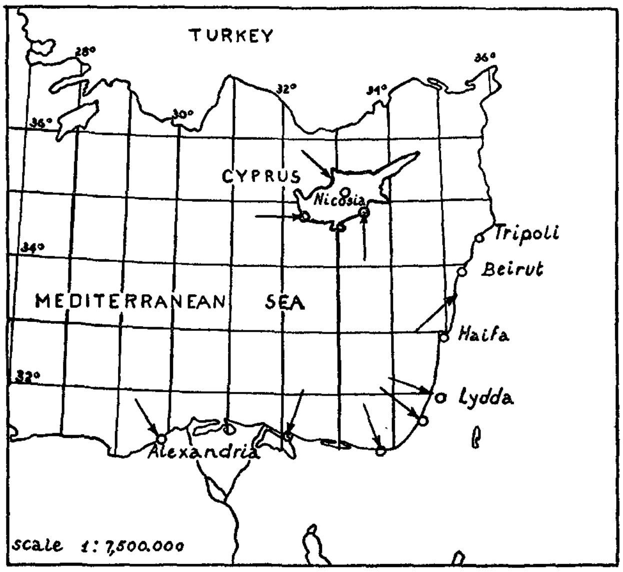

FIG. 2. Prevalent direction of sea breezes at selected points along eastern Mediterranean coast and Cyprus.

Fig. 1 shows the course of the difference between monthly mean sea-surface temperatures and monthly mean temperatures at Lydda Airport (column C, table 2) as well as the frequency of night thunderstorms during 10 years at the airport. Excepting March, there is good agreement in the trend of the curves.

Sea and land breezes in the eastern Mediterranean.—Fig. 2 shows the prevalent direction of the sea breeze at selected points along the coast. This is an eminently divergent wind-field! In summer, when the sea breeze is strongest, this divergent wind-field is responsible for the often complete dissipation by about 0900–1000 of the Scu and Fst which form in large amounts almost daily in the early-morning hours (cloudiness reaches its peak about 0500–0700). It is responsible for the almost complete absence of low clouds during the rest of the daylight hours.

As could be expected, the sea breezes are convergent over Cyprus.

The change in prevalent direction of the sea breeze from NNE in the southeast to SW in the north is explained, at least partially, through the curvature of the coastline, which is concave toward the sea, thus creating a divergent wind-field by day. The directional divergence is so strong that it is not compensated at all by frictional retardation of the current over the land.

Sea breezes, however, are absent in the colder months of the year. The land breeze, on the other hand, is evident in varying strength and steadiness most of the year, depending on the season, and is quite marked in the cold months which comprise the rain (and thunderstorm) season in the eastern Mediterranean. Roughly speaking, the land breeze is opposite in direction to the sea breeze. Thus, because of the particular curvature of the coastline, the land breezes constitute a convergent wind-field. The diurnal change in direction of the winds in the friction layer, as a factor extending the depth of the convergent fields at night, has already been discussed. Lastly, the "return current" of the land breeze appears in the layer between 1 or 1.5 km and 2.5 km over the surface. As shown by Mané in an unpublished investigation of sea- and land-breeze circulation over the Israel coast, the return current manifests itself in strengthening of the on-shore component of the winds during the night in the layer involved. This local acceleration is an additional factor conducive to increased convergence over the coast, although it is accompanied by directional divergence.

The proportion of land breezes (winds between S and E; usually the land breeze at Lydda is SSE) at and near times of thunderstorms at Lydda may be seen in table 3.

TABLE 3. Frequency of direction of surface winds at and near times of occurrence of thunderstorms at Lydda Airport; 10 years, see also table 1; D = 0800–1959; N = 2000–0759; S–(E) = wind direction between S and E, *including* S and *excluding* E, *etc.*

	S–(E)		E–(N)		N–(W)		W–(S)		Calm		Unknown		Total	
Months	D	N	D	N	D	N	D	N	D	N	D	N	D	N
Oct.	—	6	—	1	2	—	3	3	—	—	—	—	5	10
Nov.	4	10	—	1	2	2	5	2	—	2	—	—	11	17
Dec.	3	10	1	3	1	—	8	10	—	—	—	—	13	23
Jan.	—	6	—	1	5	1	8	9	—	—	—	—	13	17
Feb.	—	5	1	—	1	1	10	8	—	—	—	—	12	14
March	4	6	1	—	2	1	5	9	—	—	—	—	12	16
April	1	1	—	1	1	2	3	5	—	1	—	2	5	12
May	1	2	—	1	1	—	2	—	—	—	—	2	4	5
Total	13	46	3	8	15	7	44	46	—	3	—	4	75	114

TABLE 4. Diurnal variation of thunderstorm frequency; D = 0800–1959, N = 2000–0759.

Station	Latitude N	Longitude E	Elevation ft	Years of record	Frequency D	Frequency N
Nicosia	35° 09′	33° 17′	716	5	48	31
Beirut	33° 52′	35° 27′	230	5	52	67
Alexandria	31° 18′	30° 06′	40	5	7	10
Benina	32° 05′	20° 16′	400	4	16	10

In table 3, the following points are of special interest: (a) the relatively small number of storms with winds from the NE and NW quadrants; (b) *the nearly equal distribution over day and night of storms with winds from the SW quadrant* (*the latter winds are usually fresh and do not permit the generation of land breezes, with the consequent absence of a high percentage of night thunderstorms*); (c) *the high percentage of nocturnal storms with winds from the SE quadrant, from which Lydda Airport's land breezes blow;* (d) the notable disparity between daytime and nighttime storms with winds from the NE quadrant (some of these winds are suspected to be land breezes in actual fact); (e) the greatest day-night disparity of thunderstorm frequency with SE winds occurs in the months October-February, just when the land breeze is best developed.

Diurnal variation of thunderstorm frequency at other eastern Mediterranean stations.—Table 4 presents figures on the diurnal variation of thunderstorm frequency at a number of stations in the eastern and central Mediterranean. The basic data (3-hr synoptic reports as received by wireless) from which the information was extracted cover only 4 to 5 years, admittedly a short period. Despite the fact that the figures cannot be considered as reliable means, synoptic experience and knowledge of the region both confirm the correctness of the *type* of diurnal variation shown.

Nicosia, Cyprus, is an island station (area of island: 9300 km^2) about 20 km aerial distance from the coast. The coastline of Cyprus may be considered as convex in the main. Benina, an airfield near Benghazi, is situated near a notably convex section of the North African coast (see fig. 3). At both Nicosia and Benina one would expect the land breezes to be of divergent character and, as far as the contribution of the land breeze is concerned, it should decrease the number of nocturnal thunderstorms. Both stations do indeed have a majority of daytime thunderstorms.

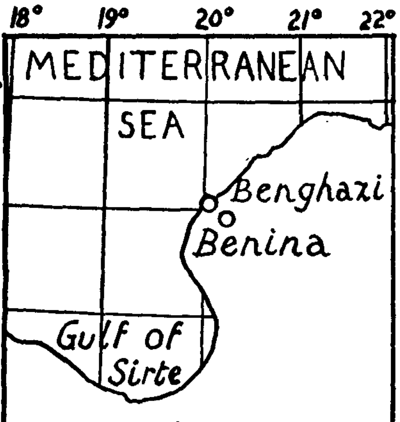

FIG. 3. Convex coast of Benghazi-Benina.

Beirut and Alexandria are located along the concave coast of the eastern Mediterranean.

4. Some generalizations

The idea that the land breeze may be a factor favoring the formation of nocturnal thunderstorms has been mentioned in the literature. The tendency toward maximum thunderstorm activity between 0600 and 0900 over coastal Germany was attributed to the instability of maritime air at that time and to the cold-front-like action of the land breeze [6, p. 212]. Similarly, the high percentage of night thunderstorms at the west and northwest coast of Lake Victoria is ascribed by Henderson [5] to the land breeze, which would "assist the maintenance and development of any cumulonimbus that came within its range and may be, at least partially, the reason for the severity of thunderstorms in the northwest Lake (Victoria)."

The emphasis in the present paper is on the divergent or convergent nature of the breezes. Their nature will depend on a number of factors, such as the curvature of the coastline, orography and sea temperatures. In addition, attention is directed to the fact that, because of the generally low mean temperatures of land bodies, *the incidence of land breezes should be far higher than that of sea breezes.* It is unlikely that the same factor or factors would cause a nocturnal or daytime majority of thunderstorms in all coastal areas of the world, wherever the storms occur, but it appears plausible that the land and sea breezes should make a contribution, often a decisive one, toward determining the type of diurnal variation of the storms. With this in mind, an attempt can be made to generalize the results obtained for the eastern Mediterranean. The following relationships are suggested as valid:

a. Where the coastline is concave toward the sea, the percentage frequency of nocturnal thunderstorms should be higher than that of daytime thunderstorms over the coastal area of the land, or at least sensibly higher than the percentage frequency of nocturnal storms at stations situated on the nearest non-concave section of the coast. This will not be valid in summer, when insolational and, therefore, daytime thunderstorms will be predominant over land areas, whatever the curvature of the coast line.

b. In regions where the incidence of sea breezes is large and is not confined in the main to a "dry season," the percentage of daytime thunderstorms should be large in areas bounded by a coastline that is convex toward the sea.

The validity of (a) should be particularly prominent along coasts where the regional circulation is on-shore. Here the frictional retardation of the landward current, as well as the direction of the land breeze, nearly diametrically opposed to the on-shore wind, both are conducive to an increased convergence over the area.

The validity of (b) may be impaired in coastal areas of very large land-bodies where the coast is but slightly convex, if the landward penetration of the sea air is accompanied by a downward motion of the air as the penetration increases during daylight hours. There does not seem to be a factor of similar nature weakening the validity of (a) on concave coasts.

Since the frequency of days with sea breeze increases with decreasing latitude, (b) will be better realized in low latitudes. But it will be noted that small islands cannot establish a sea-breeze circulation,[5] particularly not in higher latitudes. Thus Block Island, Rhode Island, for example, cannot be expected to have a large percentage of daytime thunderstorms merely because of its convex coast.

5. Diurnal variation of thunderstorm frequency along the United States coast

The largest single region for which detailed data are available is the United States. Data were published by the U. S. Weather Bureau [6] for 192 stations, based on 20 years of record (for most stations) between the years 1906 and 1925, and broken down to show the frequency of thunderstorm occurrence (the hour in which thunder is first heard) for four periods of the day: 0000–0600, 0600–1200, 1200–1800 and 1800–2400.

Table 5 was prepared from [6] by combining the data for 0600–1200 and 1200–1800 under the designation D and those for 1800–2400 and 0000–0600 under the designation N *for the three seasons: winter* (December-February), *spring* (March-May) and *autumn* (September-November).

The first column of the table lists the coastal or near-the-coast stations, beginning at Eastport, Maine, and proceeding around the coast in a clockwise fashion. The character of the curvature of the coast in the

TABLE 5. Thunderstorm occurrences at coastal stations of the United States. For explanation of notation, see text.

	Frequency		Percentage		
Station	D	N	D	N	Measure of agreement
Eastport, Me.*	56	49	*53*	47	Good
Portland, Me.	45	52	46	*54*	Good
Boston, Mass.	64	83	43	*57*	Good
Nantucket, Mass.*	96	104	48	*52*	Small island; not expected to agree
Providence, R. I.**	59	106	36	*64*	
Block Is., R. I.*	78	96	45	*55*	Small island; not expected to agree
New Haven, Conn.	104	106	49	*51*	Fair
New York, N. Y.	125	145	46	*54*	Good
Sandy Hook, N. J.*	80	60	*57*	43	Agreement not considered significant
Atlantic City, N. J.*	101	139	42	*58*	Bad
Norfolk, Va.*	182	155	*54*	46	Good; station located on peninsula
Cape Henry, Va.*	197	166	*54*	46	Good
Hatteras, Va.*	150	196	43	*57*	Bad; narrow island
Wilmington, N. C.*	233	197	*54*	46	Good; station located somewhat inland
Charleston, S. C.*	277	176	*61*	39	Good
Savannah, Ga.	305	168	*65*	35	Bad
Jacksonville, Fla.*	532	177	*75*	25	Good
Miami, Fla.*	365	163	*70*	30	Good
Key West, Fla.*	394	246	*62*	38	Small island; agreement probably not insignificant
Tampa, Fla.*	528	202	*73*	27	Good
Pensacola, Fla.	500	306	*62*	38	Tendency good; highest percentage night thunderstorms in Florida (except Key West)
New Orleans, La.*	469	227	*67*	33	Good; station located on peninsula
Port Arthur, Tex.**	204	117	*64*	36	Doubtful
Galveston, Tex.	324	269	*55*	45	Tendency good; *e.g.*, percentage night thunderstorms much higher than any Florida stations
Corpus Christi, Tex.	231	222	*51*	49	Tendency very good; highest percentage night thunderstorms of all Gulf stations considered
San Diego, Calif.*	21	19	*53*	47	Good
Los Angeles, Calif.*	41	28	*61*	39	Good
San Luis Obispo, Calif.*	28	24	*54*	46	Good; station located about 25 km east of Pt. Buchon
Eureka, Calif.**	39	35	*53*	47	Doubtful; probably bad

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[5] According to Kimble and collaborators [8], sea and land breezes are inappreciable over islands less than approximately 10 miles across. The exceptional cases are quite mountainous islands where the prevailing wind is so light "that the heated air is able to accumulate *in situ*."

vicinity of the station is indicated by appending an asterisk when the curvature is convex. Absence of an asterisk indicates concave curvature. Double asterisks indicate that the station is discussed in the text. The character was decided by consulting a 1:5,000,000 map, this scale being considered, somewhat arbitrarily, sufficiently small to suppress undulations of the coastline which might be too "small" to be significant. Where a station is situated between a cape and the center point of the coast of a bay, the principle was to classify the character according to whether the station was nearer to the cape or the center point of the bay coast. Thus, the curvature of the coast at Wilmington, N. C., was taken as convex because the station is closer to Cape Fear than to the center of Onslow Bay's coast.

The central columns of the table give the frequency and percentage of daytime and nocturnal thunderstorms. The data are for 20 years at all stations except Miami, Fla., which is 14 years.

The final column states the measure of agreement of the character of the curvature of the coast with the type of percentage distribution. To decide the measure of agreement of the observed with the expected (mainly qualitatively) distribution, the following procedure was adopted: If the coast is concave (convex) and the station shows 53 per cent or more nocturnal (daytime) thunderstorms, the agreement was considered "good"; if the percentage is 52 or 51, the agreement was considered "fair." If the percentage is 50 or less, the tendency in the sense of generalization (a), above, was examined and, if found satisfactory, the distribution was classified "tendency good." If the tendency was not of the type expected, the agreement was considered "bad."

It is somewhat difficult to characterize the coastline at Providence, R. I. Though it lies on the shore of a bay-like water-body, that body is studded with islands. The proximity of these islands is, without doubt, unfavorable to the development of land breezes from the mainland. The fact should, however, not be overlooked that east of Westerly, R. I., and west of New Bedford, Mass., the coast is by and large concave and, since most of the area of the northeastern United States shows a tendency towards a high percentage of nocturnal thunderstorms, the mainly concave character of the coast in the Providence region should tend to increase that percentage. In fact, Providence has the highest percentage of night storms of all stations in table 5.

Atlantic City, N. J., is one of the few stations which do not obey the suggested relationships at all. But it may be noted here that any station located on a convex coast is more likely to observe the night thunderstorms over the ocean.

It would appear that from Wilmington, N. C., southward the effects of insolation are overwhelming in both spring and autumn, producing a large percentage of daytime thunderstorms. Thus Savannah, Ga., despite the concave coast, has a high daytime percentage for the *combined period* of autumn, winter and spring. But when only the winter season is considered, Savannah shows the highest percentage of nocturnal thunderstorms of all stations as far north as Norfolk, Va. Of 54 thunderstorm beginnings in 20 winters, 34, or 63 per cent, occurred between 1800 and 0600 (cf. [6, table 21]).

Mobile, Ala., has been omitted from table 5. The bay extending from the Gulf of Mexico is narrow, and the station itself is about 50 km from the Gulf. In passing, it will also be noted that the Gulf coast is convex between Pensacola to west of Moss Point.

Port Arthur, Tex., is another difficult case. In the fact that the lands bordering the outlet of Sabine Lake protrude toward the Gulf, some justification can be found for considering Port Arthur's coast as convex.

Galveston, Tex., has a fairly high percentage of nocturnal storms as compared, for example, to New Orleans, La. (45 per cent against 33), so that the "tendency" is very good. In turn, Corpus Christi, Tex., shows a still higher nocturnal percentage amounting to 49 per cent (54 per cent in winter and 57 in spring). It will be noted that the Gulf coast is markedly concave in the vicinity of Corpus Christi.

As pointed out by Prof. H. R. Byers, in correspondence with the writer, the case of Corpus Christi warrants further attention. This station lies on the seaboard fringes of an extensive continental area, reaching across the midwestern states as far north as the Canadian provinces, where nocturnal thunderstorms predominate. Del Rio, Tex., and San Antonio, Tex., the nearest inland stations for which data are available, have, relatively speaking, more night storms than Corpus Christi in the three seasons, winter, spring, and autumn. However, examination of the figures of thunderstorm occurrences [6, table 21] for the periods 1800–2400 and 0000–0600 *separately* shows that the type of variation at Corpus Christi is different from that at Del Rio and San Antonio. Corpus Christi has relatively more storms between 0000 and 0600 than Del Rio and San Antonio and, in fact, more than any other Texas station (Abilene, Dallas, Ft. Worth, Groesbeck, Houston, Palestine and Taylor). Since one can expect that night thunderstorms formed through a contribution of the sea breeze should be most frequent in the second part of the night, it appears likely that the high percentage of nocturnal storms and especially their distribution through the night are connected with land-breeze convergence and are not simply due to the fact that the station is in an area where night thunderstorms are in the majority. As a counterpart, it may be mentioned that New Orleans, located near a strongly convex section of the Gulf coast, has relatively fewer thunderstorms between

0000 and 0600 than the continental stations Shreveport, La., Meridian, Miss., and Vicksburg, Miss.

On the Pacific coast the agreement is good, though its value is somewhat open to question due to the small number of thunderstorms. Stations such as San Francisco, Calif., Point Reyes, Calif., and Port Angeles, Wash., are not included in the table at all because of the very small number of storms.

Some words need be said on the islands. As was stressed in a previous section, small islands and narrow peninsulae cannot be expected to satisfy the suggested relationships because such islands would not establish a circulation of their own except, perhaps, in low latitudes. Thus the agreement in the case of Sandy Hook, N. J., is not considered significant. On the other hand, the agreement in the case of Key West, Fla., may not be insignificant. This island is located at a fairly low latitude, 24 deg.

Although table 5 indicates that at most stations the diurnal distribution of thunderstorm frequencies varies consistently with the curvature of the coastline when the frequencies of autumn, winter and spring are combined, a further examination of the figures in relation to wind directions associated with the thunderstorm beginnings, as well as to sea-land temperature contrasts and to other causes that might be responsible for increased nocturnal thunderstorm activity, would be desirable before the validity of the relationship set forth in this paper can be considered as established in a satisfactory manner. Also, since the causes bringing about the nocturnal maximum should be most active in the second part of the night, and particularly about the end of the night, a breakdown of the thunderstorm-frequency data for the periods 0200–0800, 0800–1400, *etc.* would be more appropriate for the purposes at hand.

6. Conclusion

From the factual material presented, including data from such diverse littorals as the eastern Mediterranean and the coasts of the United States, it is concluded that the curvature of the coastline in the vicinity of a station is an important factor in the diurnal variation of the frequency of thunderstorms. In some parts of the world this factor is only of a secondary (though not negligible) importance, imposing a variation (according to the curvature of the coastline) on the type of diurnal variation characteristic for the wider region in which the station is located.

The nature of the coastline determines to some extent whether the sea and land breezes are convergent or divergent, and it is this convergence or divergence which is actually responsible for the variation described.

In the picture here created, the high percentage of daylight thunderstorms in some areas, such as the Florida peninsula, appears to be natural and consistent with the high or relatively high percentage of nocturnal thunderstorms in other areas as, for example, at Corpus Christi, itself on the Gulf of Mexico coast. Similarly consistent variations were shown to exist in some other littorals of the world.

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[6] Prof. Byers has pointed out, *inter alia*, the need for a further critical examination of thunderstorm occurrences along the Atlantic seaboard of the United States, where a maximum number of thunderstorms appears to occur around 1800. Hourly reports covering a period of at least ten years would be required for such an investigation, but do not seem to be available.

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