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The Sea Breeze at and near Bombay

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ABSTRACT. The first portion of this paper deals with the theory of the sea breeze and also describes the work of Estoque.

The observational material collected by the sea breeze traverses of the U. S. Weather Bureau Research Flight Facility aircraft at Bombay is presented in the latter section of this paper.

1. Introduction

Before presenting some observational material on the sea breeze at Bombay as gathered by sea breeze traverses of the RFF aircraft, it is necessary to examine the theoretical model of the sea breeze circulation as built up in recent years — particularly so because one of the models as given by Estoque (1961, 1962) has partially been used as interpreting the observational material.

The older observational models that require special mention are those given by Van-Bemmelen (1922) in his study of the Jakarta sea breeze and the most modern model (observational) as given by Defant (1951) and Wexler (1946). Ramanathan (1931) also studied the landward extension of the sea breeze by planned pibal ascents.

The observed characteristics of the sea breeze are — (1) that the sea breeze starts within a small distance of the shoreline and then grows both horizontally (both ways) and vertically as time progresses; (2) that the flow shows a reversal with height (estimated at about 2 km in the tropics); (3) that the flow has a component parallel to the coast also — primarily brought about by a coriolis control — as a result of which the hodograph is more or less elliptical with definite sense of traverse; (4) that the sea breeze penetrates about 30 to 50 km inland in middle latitudes and 100 to 200 km in the tropics. Ramanathan (1931) even showed that the west coast sea breeze from the neighbourhood of Bombay penetrates substantially beyond Poona; and (5) that the corresponding land breeze is much less intense.

Unfortunately Van-Bemmelen's studies, based as they were on hourly pibal ascents, could not give a direct idea of vertical velocities — a situation which still obtains since aircraft instrumentation does not include any direct method of measuring vertical velocities on the meso-scale.

On the theoretical side, the sea breeze circulation may be regarded as a dynamical response to differential heating caused by 24-hr period oscillations of temperatures. This differential heating can be idealised as a single line singularity which separates two distinct oscillational regimes characterised by differences in amplitude and other significant characteristics of the temperature oscillation. Such a state of affairs obtains near extended coastlines — the coastline forming the required singularity for obvious and well known physical reasons. The most apt tool in the investigation of the sea breeze would hence be the circulation theorem as developed by Hoiland (1939) and Bjerknes (1934). This, in fact, was the earliest sound explanation of the sea breeze, as offered by the application of the idea that differential heating solenoids produced an appropriate horizontal component of vorticity resulting in the direct flow from sea to land during day time (afternoon) and reverse flow at some higher levels. Since, however, the solenoids give only the acceleration of the circulation, any developments whereby the motion alters the solenoidal field could be taken account of only with great difficulty. In particular, the theory did not directly provide for development of a component parallel to the shore.

In the subsequent development of the theory, these defects were corrected. Amongst several efforts a mention may be made of Pearce's (1955) work which helped explain the component parallel to the shore. But in all these attempts the basic set of equations had to be linearised and this involved assumptions somewhat open to question. In addition, the effect of turbulence in changing the solenoidal field with time had to be taken account of. The satisfactory treatment of this factor, by inclusion of appropriate terms in the equation of motion, had to await a clear atmosphere on the concept of turbulence. When this became available the next stage was set — but naturally, the equations remained non-linear and analytical solutions could be obtained only under very special conditions (which in effect reduced them to linear equations). Amongst the solutions of this type, we may specially mention Haurwitz (1947), Pierson (1950), Schmidt (1947) and Defant (1950). Haurwitz, in particular, was able to show the effect of coriolis control through the Elliptic Hodograph and also to explain the fact that the short time lag between the maximum temperature epoch was of the proper order. The tool used was, significantly enough, the circulation theorem.

Fresh ground could be broken in the field with the advent of computational procedures for the numerical solutions of differential equations and this in fact has been done by Fisher (1961) and Estoque (1961, 1962). Fisher's paper finally results in a reasonable enough $U\ (x,\ z,\ t)$ relationship. We shall, however, describe in some measure the work of Estoque as the model produced by him is being utilised in our studies. The first paper by Estoque (1961) dealt with the development of a sea breeze under "no synoptic wind" conditions. This was extended by him to specifically include "synoptic winds" on shore, off-shore, parallel to the coast in one sense and parallel to the coast in another sense etc (Estoque 1962). Obviously the latter step is absolutely necessary since the non-linearity of the basic equations means that the total wind cannot be computed by combining the sea breeze under "no synoptic wind" with a given "synoptic wind".

A brief summary of Estoque's procedure is as follows—

The basic set of equations consisted of the equation of motion, the hydrostatic equation and the equation of continuity. This set was augmented by the turbulent transport equation and a modelling assumption. The set was integrated over a grid extending 2 km in the vertical and 200 km in the horizontal with initial conditions requiring the perturbation to reach zero at boundaries of the grid. The lower layer of the grid (below 50 m) was characterized by a constant flux and the upper layer by a turbulence coefficient decreasing linearly with height (the solutions for the two layers being appropriately matched). The initial temperature distribution was characterised by constant surface temperature at sea, sinusoidal variation overland and a matching on the coastline, the initial lapse rates being 7°C/km. A case with an isothermal layer up to 1 km and a lapse rate of 7°C/km above was also included to study the role of thermal stability.

The basic set was split up by writing $\mathbf{V} = \mathbf{V}_L + \mathbf{V}'$; $\theta = \theta_L + \theta'$ etc where the dash represented the (finite) sea-breeze perturbation (L refers to the unperturbed synoptic wind). The final prediction equation set is hence

$$\frac{\partial \mathbf{V}'}{\partial t} = -\mathbf{V}'.\nabla\mathbf{V}_L - \mathbf{V}.\nabla\mathbf{V}' - w'\frac{\partial \mathbf{V}_L}{\partial z} - w\frac{\partial \mathbf{V}'}{\partial z} - \frac{RT}{p}\nabla p' - f\,\overline{\mathbf{k}\times\mathbf{V}'} + \frac{\partial}{\partial z}\left(K\cdot\frac{\partial \mathbf{V}}{\partial z}\right) \qquad (1)$$

$$\frac{\partial \theta'}{\partial t} = -\mathbf{V}'.\nabla\theta_L - \mathbf{V}.\nabla\theta' - w'\frac{\partial \theta_L}{\partial z} -$$

$$-w\frac{\partial \theta'}{\partial z} + \frac{\partial}{\partial z}\left(K\cdot \frac{\partial \theta'}{\partial z}\right) \qquad (2)$$

$$\frac{\partial p'}{\partial z} = -\frac{gp}{RT} + \frac{gp_L}{RT_L} \qquad (3)$$

Together with a modelling assumption

$$\frac{\partial}{\partial z}\left(\frac{1}{\rho}\frac{d\rho}{dt}\right) = 0 \qquad (4)$$

which ensured computational stability.

The diagrams in Estoque's papers clearly show the evolution of the sea breeze circulation; movement towards land and its decay. They also show the computed vertical velocities clearly as also the temperature changes at various heights. The history of the pressure profiles is also shown beautifully by the last few diagrams in his paper (Estoque 1962).

Summarizing, the main results from Estoque are—

(1) Strongest vertical circulations occur in the cases when the synoptic wind is zero, or when it is offshore or when it is parallel to the coast (with low pressure at sea). The vertical circulations are weaker in others.

(2) The onshore synoptic wind case shows only weak development while the offshore case shows strong development.

(3) The case with synoptic wind parallel to the coast (with low pressure at sea) shows stronger development than the case with the synoptic wind parallel to the coast (with low pressure over land). (Obviously, as one of the cases corresponds to an inflow component which is offshore and hence may be expected to partially exhibit the characteristic of the strong circulation resulting from offshore synoptic winds).

(4) The landward penetration is greatest with zero synoptic wind. Calculated in a certain way the penetration is about 32 km.

(5) There is a region of descending motion ahead of the leading edge of the sea breeze.

(6) As a result of descending motion there is adiabatic warming in a region close to the coast.

(7) The leading edge has many characteristics of a cold front.

2. Some applications of the sea breeze theory

The sea breeze concept may possibly be extended since it is only a dynamic response to a heat source of changing intensity. As such the differential heating on an extended scale, both in space and time, which the monsoon circulations imply can legitimately be dealt with by regarding monsoon circulations as extended sea breeze.

Estoque has also drawn attention to the fact that the generation of cyclones by travel over warm seas could fall within the field considered in the sea breeze theory.

3. Observational material

The specially instrumented aircraft of the U. S. Weather Bureau Research Flight Facility (RFF) made three sorties in May 1963, gathering data for a study of the sea breeze. On the 20th two aircraft, a W-26 and a DC-6 flew identical flight paths; on the 21st the W-26 alone gathered data. Since little difference was noted in the data for the two days, discussion refers only to the DC-6 flight on the 20th.

The flight plan is illustrated by Fig. 1. The point marked 0 km corresponds to Santacruz airport, the section extending

Fig. 1. Aircraft temperature observations (raw data) in degrees C.

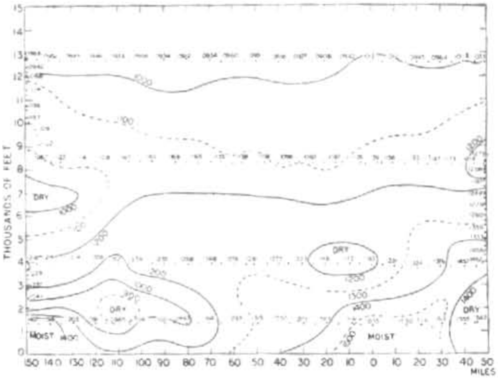

Fig. 2. Aircraft moisture observations made with infra-red hygrometer (raw data) in arbitrary units, data for same flight as temperature data of Fig. 1

Zero of horizontal scale refers to Bombay coast line, east to right and west to left of this point. Observations along vertical at end points made during ascents. Flight begun at 0·4 km altitude 92 km east of Bombay at 1012Z (1542 IST) and ended at 3·6 km 92 km east of Bombay at 1400Z (1930 IST) 20 May 1963.

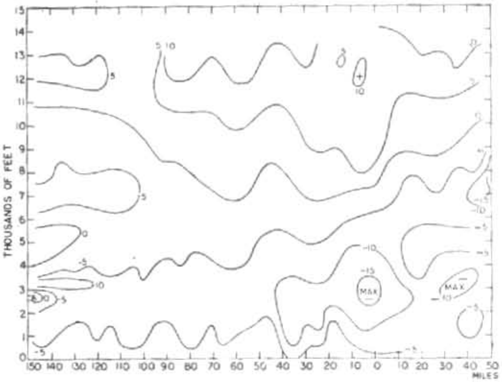

Fig. 3. Wind component parallel to coast line, in knots, from Doppler wind observations made during same flight referred to in Fig. 1

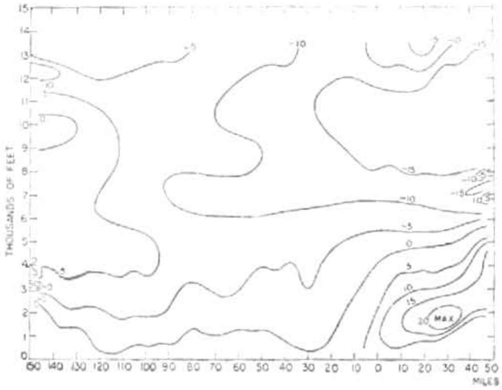

Fig. 4. Wind component perpendicular to coast line, in knots, from Doppler wind observations of flight referred to in Fig. 1

280 km west, or seaward, and nearly 100 km east, or landward. The aircraft flew 100 km inland at an altitude of about 0·4 km then turned and flew west at the same altitude until it reached a point 280 km west of Bombay. Thereupon, a vertical sounding was made during climb, to an altitude of 1·2 km. The aircraft returned on an easterly track until a point 92 km inland was reached whereupon it once again climbed making vertical soundings to an altitude of 2·4 km. The procedure followed for 0·4 km and 1·2 km was repeated at 2·4 and 3·6 km. Observations are available at roughly 1 km intervals.

Fig. 1 shows salient features of the temperature observations which include (1) a surface cold dome along the shore over the ocean and a surface warm dome 100 km inland, and (2) an inversion ranging from 0·4 km to over 0·6 km altitude, and a warm pocket at 0·6 km, 150 km west of Bombay.

This figure reproduces essentially the same features which appear in a diagram from Estoque's paper (1962) showing the theoretical sea breeze under conditions of a prevailing wind parallel to the coast with lower pressure over the coast. In Estoque's model maximum warming occurred at distances greater than 40 km inland, but with warming occurring from the sea coast inland; further, the warming tended to bulge upward and seaward and protrude over the sea coast at about 1 km. The RFF data suggest that the circulation extended much farther seaward, out to or beyond 160 km, since a maximum temperature core occurs at that point. One difference appears in the bulge of isotherms landward above 1·2 km, however this may be due to the lapse of 1½ hours between the observations at 0·4 km and those at 1·2 km.

Fig. 2 shows the moisture distribution. We see what we might expect, namely greater moisture in the inland branch, which extends to a tongue out to seaward at the upper levels where the moister air is probably carried by a sea breeze return current. Lastly, we note a small dry pocket about 160 km to seaward, and other larger pocket farther out.

Fig. 3 depicts the component of the wind parallel to the coastline which is oriented 348°—168°. The principal feature of interest is the maxima of northerly winds: one on either side of Bombay at 0·4 km and one over Bombay at and above 1·2 km. The synoptic situation that day was one in which the surface winds were northwesterly with backing aloft to become northerly at 850 mb and easterly at 700 mb. In Estoque's model the maximum northerly speed was found to begin at 0·4 km and slope slightly to the east. Our results suggest that the maximum may slope one way or the other.

Fig. 4 shows the component of the wind perpendicular to the coast. Here, as predicted by Estoque, we find the maximum onshore wind over land with the axis of the maximum sloping upward and inland. In part, this slope may be due to the time difference between observations made at 0·4 km and those made immediately above at 1·2 km, the winds at 1·2 km being somewhat stronger due to strengthening of the sea breeze, since both sets of observations were taken prior to the time of sea breeze maximum. The maximum offshore wind is found aloft; it reaches its lowest altitude some 120 to 150 km out to sea, a fact which, taken in concert with the temperature and moisture patterns, suggests that the circulation extends that far. Here the maximum is seen as an extension downward of the upper easterly winds associated with an anticyclone to the northeast of Bombay. Interestingly enough, the zero isopleth lies over Bombay at about 1·4 km. In the aerological observations made at Bombay, the 850-mb winds were due north from 1200 GMT on the 19th to 1200 GMT on the 21st; at 700 mb also no variation in speed regular enough to attribute to the sea breeze appeared. However, the sea breeze appeared to affect temperatures at 850 mb.

4. Summary

The observations and analyses illustrated here are in accord with the picture revealed by previous studies. Some uncertainties exist in the analyses due to lack of sufficient data to establish changes occurring in time.

We may again note that the data suggest a much greater seaward extension of the sea breeze circulation than shown in Estoque's theoretical circulation.

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