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STRESS — DIFFERENTIAL INDUCED DIVERGENCE WITH APPLICATION TO LITTORAL PRECIPITATION

Reid A. Bryson and Peter M. Kuhn

with 11 Figures and 1 Table

Durch Beanspruchungsdifferenzial hervorgerufene Divergenz in ihrer Anwendung auf Niederschläge an Küsten.

Zusammenfassung: Die Arbeit weist auf den Zusammenhang hin, der zwischen dem Land-Meer-Beanspruchungsdifferenzial, der dadurch hervorgerufenen Divergenz an der Küste und absinkender Luft, und der Trockenheit solcher Küsten besteht, bei denen das Land an der Tiefdruckseite des Windes liegt. Dieser Zusammenhang würde jedoch ein rein zufälliger zu sein scheinen, wenn nicht auch gezeigt werden könnte, daß diese trockenen Küsten mehr als nur die Linien sind, entlang welcher die Land-Meer-Grenze eine große Wüstenzone kreuzt, die durch eine ausgedehnte absinkende Luftbewegung im Zusammenhang mit dem planetarischen Windsystem hervorgerufen wird. Diese Frage wurde durch Lydolph (11) angeschnitten, der in seiner in diesem Bericht diskutierten Untersuchung fand, daß sie in der Tat trockener als ihr Hinterland sind. Dies weist darauf hin, daß ein Lokalfaktor der Küstenzone selbst in Rechnung gesetzt werden muß. Er weist auch auf ein Beispiel hin, das zeigt, daß Konvergenz in einem Gebiet , in dem das Land auf der Hochdruckseite des Windes gelegen ist, mit Küstenfeuchte zusammenfällt. Einem Klimatologen wird es klar sein, daß zahlreiche andere Gebiete in dieses allgemeine Schema hineinpassen. So ist z. B. im Falle der pazifischen Küste Amerikas die Grenze zwischen der Feucht- und der Trockenküste ebenfalls auch nahezu die Trennungslinie zwischen dem Landgebiet, das zur Rechten und dem Landgebiet, das zur Linken des Windes gelegen ist.

Eine kurze Überlegung zeigt auch, daß derselbe Wind, der das Oberflächenwasser von der Küste wegtreibt, auch

Aufsteigen des Tiefenwassers hervorrufen muß. Umgekehrt muß Konvergenz der Luft auch mit Konvergenz des Wassers gegen die Küste hin zusammenfallen. Daraus ergibt sich, daß der klassische Faktor aufsteigenden kalten Wassers zur Erklärung trockener Küsten von derselben Ursache herrührt, als die absinkende Luftbewegung. Diese gemeinsame Ursache ist die relative Orientierung des Küstenverlaufs zur Strömungsrichtung der Luft.

Obwohl sich die vorliegende Diskussion auf diese klimatische Erscheinung an Küsten konzentriert, so besteht kein Grund, warum ähnliche Kontraste des Oberflächenreliefs auf dem Festland nicht ähnliche Divergenzen hervorrufen sollten. Obwohl es mangels erforderlicher Unterlagen über das Verhältnis zwischen Bremsfaktor und Oberflächenform nicht möglich ist, dieses Prinzip quantitativ anzuwenden, die qualitativen Folgerungen sind evident. So müßte z. B. ein Südwind über dem unteren Mississippi-Tal an den Steilabfällen entlang der östlichen Talflanke konvergent und über der westlichen Talflanke divergent sein. Dies müßte seinerseits die östlichen Talhänge als eine für die Bildung von Gewittern bevorzugte Lage charakterisieren. Es ist Aufgabe weiterer Forschung, diese Frage zu beantworten.

Abstract. An expression for the computation of low level divergence from the curl and divergence of the wind stress is derived for practical application to coastal areas. With this basis, a dynamical explanation is given for the rainfall climate of dry, wet, and alternating dry and wet coastal regions in terms of low-level divergence. Several examples applying these expressions with seasonal resultant winds are given.

Introduction

Various factors have been suggested as possible controls of the littoral rainfall regime. It is evident from these studies that no single factor is solely operative in producing the observed conditions. This study deals with one factor, that of frictional drag variation across the coastline. Dines (1) first suggested qualitatively that when the wind blows along or across a coastline, some vertical motion would result from the greater frictional resistance of the land compared to the sea. We will attempt in the following paragraphs to make rough estimates of the magnitude of the divergence resulting from this land-sea differential as compared with the rainfall in seven coastal areas, principally chosen because of the availability of resultant wind data. When available, pilot balloon data are also used, but in some cases only surface resultants are obtainable and are used as an only alternative.

Relation between differential wind stress and the low-level divergence

It has been shown by Hidaka (2) that the horizontal divergence of the volume transport within the friction layer is proportional to the sum of the curl of the wind stress vector and the divergence of the wind stress vector,

$$\nabla_H \cdot V = 1/\rho f \, [\mathrm{curl}\, \tau_0 + \mathrm{div}\, \tau_0] \qquad (1)$$

While this result was obtained for the frictional layer in the sea, the same considerations hold for the friction layer in the atmosphere. In this expression $\nabla_H \cdot V$ indicates the horizontal divergence of the volume transport within the friction layer, ρ is the air density, f the coriolis parameter, and τ_0 the wind stress.

Qualitatively this result may be obtained rather readily by considering the well-known result that volume transport across the isobars within the friction layer is proportional to the wind stress and in turn therefore to the surface roughness. It is common knowledge that the surface wind nearly parallels the isobars at sea, while it may blow nearly perpendicular to the isobars in very rough country. If, then, the isobars parallel a coast, the mass transport across the isobars will vary in a direction perpendicular to the coast, yielding horizontal divergence if the land is towards low pressure, and convergence if the land is on the high pressure side. This relation is contained in the curl τ_0 portion of equation (1).

Now, if the the wind blows with a component towards the land, air must slow down and "pile up" upon reaching the rougher land surface. This is the significance of the div τ_0 term in equation (1).

Evaluation of land-sea stress differential

Reid (3), Munk (4), and Neumann (5) modified Ekman's (6) expression for the evaluation of the wind stress at a point over the sea surface and agree upon the following expression for stress evaluation over water, derived from Prandtl's (7) mixing length hypothesis,

$$\tau_0 = \rho \, C_D V^2 \qquad (2)$$

where v is the wind speed near the surface, and where C_D, the drag coefficient, ranges in values from .0026 to .008. The value of the drag coefficient used by Neumann, .004, gives consistently better results for wind speeds under 8 meters per second. Ekman's value of .0026 appears to be too small at low wind speeds as others have pointed out, and Munk's .008 appears to be too large for low wind speeds when compared with results obtained for C_D over land surfaces.

It seems obvious that the drag coefficient over the land will generally be greater than over the sea, but the magnitude of the difference must be determined for land of a given roughness. Upon examining the literature, it was found that pending further research on the magnitude of the drag coefficient over various types of terrain, we could only assume a reasonable drag coefficient differential between land and sea. As a first approximation, allowing for the range of C_D mentioned above, we shall use a differential of 10^{-3}. This assumes NEUMANN's C_D of .004 for the sea surface and an average C_D of .005 for land surfaces as computed by LETTAU's (8) method.

Practical Evaluation of Divergence of the Wind Field

Employing right handed cartesian co-ordinates in which the axes in the "x" and "y" directions are taken, along the coast, and seaward, we may evaluate equation (1). In finite difference notation, after simplification, we obtain from equations (1) and (2)

$$\nabla_H \cdot V = (\Delta C_D / f \Delta y)\,[(v \sin \beta)^2 - (v \cos \beta)^2] \quad (3)$$

where β is the angle between wind and coast. It is assumed here that there is no difference in stress parallel to the coast. In this notation ΔC_D is the land-sea drag coefficient difference across the coast. Thus in the northern hemisphere a gradient level flow parallel to the coast will be associated with divergence within the friction layer, if the land is to the left of the wind (i. e. toward low pressure) and convergent if the land is to the right of the wind (i. e. toward high pressure). The converse holds in the southern hemisphere. As might be expected onshore winds are convergent and offshore divergent. The signs of $\cos \beta$ and $\sin \beta$ are determined by the usual conventions of mathematics. The graph of Fig. 1 was prepared from equation (3) for a drag coefficient difference of 10^{-3}, while the height of the friction layer is assumed to be 500 meters and Δy is set at 21 km across the coastal strip, to spread out the divergent area in agreement with the proposal of DINES. Thus from (3) we obtain,

$$\nabla_H \cdot V = (10^{-13}/10.5f)[(v \sin \beta)^2 - (v \cos \beta)^2] \quad (4)$$

The values of divergence appearing in Figs. 2 through 11 for the various coastal areas were evaluated by entering Fig. 1 with the appropriate component of the wind speed and the latitude.

For rougher coastal areas it will be necessary to multiply the divergences of Fig. 1 by an appropriate factor as additional investigations concerning values for C_D over land areas reveal the actual values to be used for the terrain in question.

Dynamic Climatology of Certain dry and wet littorals

Several examples applying the hypothesis developed in the preceding paragraphs will now be considered from the point of view of regional climatology. The focus in the following paragraphs will be on dry littorals, but equally valuable applications to wet littorals are evident. It should be noted that the magnitudes of the divergence values are in accord with those obtained in many other investigations, such as those of KUHN (9) and COLLINS and KUHN (10). Table I contains a summary of precipitation and divergence data for all stations by seasons together with source information.

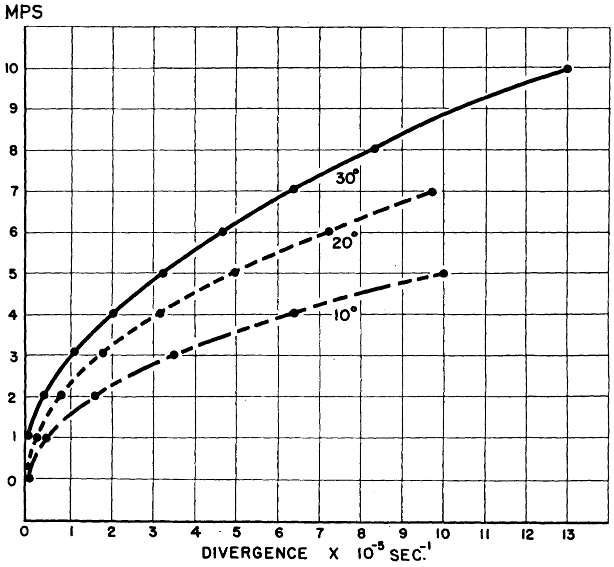

Fig. 1: Nomogram for computation of Divergence from equation (4). Enter with the components parallel and perpendicular to the coast and the latitude, and read the corresponding Divergence components on the abscissa in units of 10^{-5} sec.$^{-1}$. These components are then added.

Northwest Africa

From Dakar to Cape Juby, in a coastal strip from 25 to 150 miles wide, the terrain slopes, on the average, inland to 500 feet elevation but is punctuated by numerous ridges, presenting a relief certainly more rugged than the land over which C_D, the drag coefficient, has been measured. The persistent coastal divergence computed from surface resultant winds is evident both in the winter and the summer in Figs. 2 and 3. Except for Dakar, it is stronger in summer reaching a maximum at Port Etienne where the annual rainfall is less than two inches. The weakest divergence, at Dakar, is coincident with the wettest season, and here the rainfall exceeds 8 inches annually.

Southwest Africa

The largest values of positive divergence from Mossamedes to Luderitz Bay in Fig. 2 occur during a minimum of rainfall in July. This coast is a relatively narrow strip which may be des-

Table I

Precipitation data for all Stations

	June—July—Aug. Inches of Rain	(x 10^{-5} sec.$^{-1}$) Divergence	Dec.—Jan.—Feb. Inches of Rain	(x 10^{-5} sec.$^{-1}$) Divergence	Source
AFRICA					
Cape Juby	0	2.5	2.2	0.2	1
Port Etienne	0.1	3.3	0.1	2.2	2
Dakar	13.5	0.2	0	3.6	3
Loanda	0	1.2	3.6	0.6	3
Mossamedes	0	6.0	0.8	2.5	4
Walvis Bay	0	6.5	0	2.2	2
Luderitz Bay	0.3	2.2	0.1	2.6	2
Port Nolloth	1.0	0.4	0.3	2.3	2
SOUTH AMERICA					
Lima	0.3	0.2	0.1	3.6	2
Antofagasta	0	—0.1	0	—0.1	
Talara	0.2	7.2	0.3	10.1	5
Vallenar	3.1	0	0.1	—0.2	
AUSTRALIA					
Broome	1.3	0.1	15.4	—1.4	2
Port Hedland	2.1	0.4	4.8	2.0	2
Geraldton	11.3	0.4	0.7	4.7	2
Perth	19.8	—0.4	1.3	4.7	2
HONDURAS					
North Coastal Strip	0.5	1.6	2.0	0.6	7
NEW GUINEA					
Hollandia	18.3	—1.3	31.3	—2.7	6
Marauke	4.3	10.0	26.7	—0.2	6

Sources:

1. U. S. Navy Hydrographic Office, Pub. No. 260, Supplement B.
2. Lydolph, Paul E., A Comparative Analysis of the Dry Western Littorals, Ph. D. Thesis, University of Wisconsin, 1955.
3. U. S. Navy Hydrographic Office, Pub. No. 261, Supplement C.
4. U. S. Navy Hydrographic Office, Pub. No. 264.
5. Monthly Weather Review, Sup. No. 32, Climatological for Southern South America.
6. U. S. Navy Hydrographic Office, Pub. No. 276.
7. Sapper, K., Handbuch der Klimatologie, Band II, Teil H.

cribed as moderate in relief, similar to the California Coast. In places it rises rather abruptly to three thousand feet or more. The region of weakest positive divergence in January coincides with the area of maximum mean annual precipitation along the Loanda coastal strip. Seasonally the strongest divergence, assuming a constant coastal drag coefficient differential, coincides with the driest period, June, July, and August. Port Nolloth has a July maximum of precipitation and corresponding weak convergence.

West coast of South America

The entire west coast of South America from Talara to Vallenar is rugged, with many abrupt prominences rising three thousand feet or more directly at the sea coast. Hence the standard value of the land-sea drag coefficient differential, used throughout this work, could certainly be increased, resulting in an increase in the value of the strong positive divergence along the coast. The coastel area from Lima to Vallenar has a mean annual precipitation of less than 4 inches, but, in agreement with the lower divergence values in June, July, and August (Fig. 4) than in December, January and February, (Fig. 5) receives what little rain it does in these months. One reversal in divergence occurs at Antofagasta where weak convergence occurs, as is evident in Fig. 4. Talara does not quite follow the normal pattern since the summer divergence, with slightly more rain, exceeds the winter divergence. The variability, giving short periods of convergence and rain, may be greater in summer however, or the precipitable water and/or local convective conditions more favorable.

West coast of Australia

The coast from Perth to Geraldton is fairly rugged with many ranges close to the coast.

Fig. 2: Resultant Winds and Divergence, Africa, June—August. Winds in meters/second, Divergence given by bracketed values in units of 10^{-5} sec.$^{-1}$. Negative values indicate convergence.

Fig. 3: Resultant Winds and Divergence, Africa, December—February. Conventions as in Fig. 2.

Fig. 4: Resultant Winds and Divergence, West Coast of South America, June—August. Conventions as in Fig. 2.

Fig. 5: Resultant Winds and Divergence, West Coast of South America, December—February. Conventions as in Fig. 2.

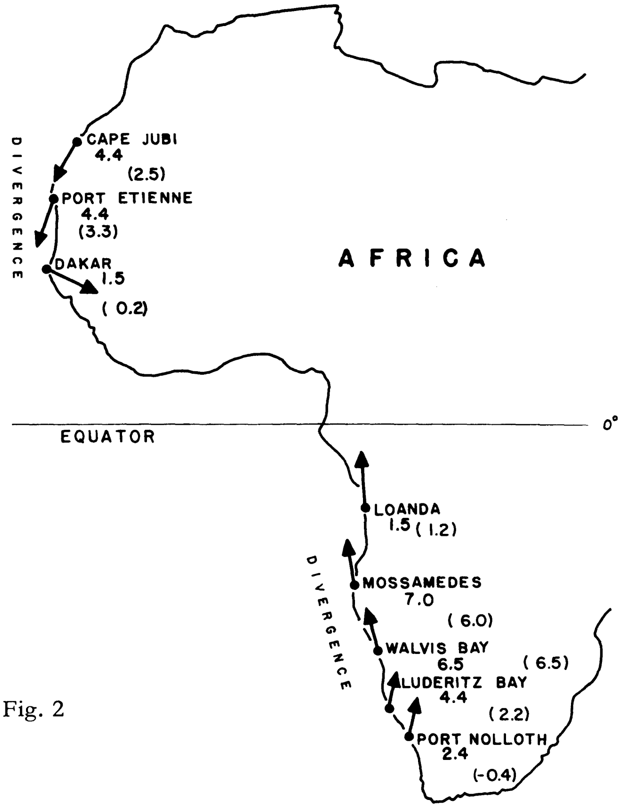

Fig. 2

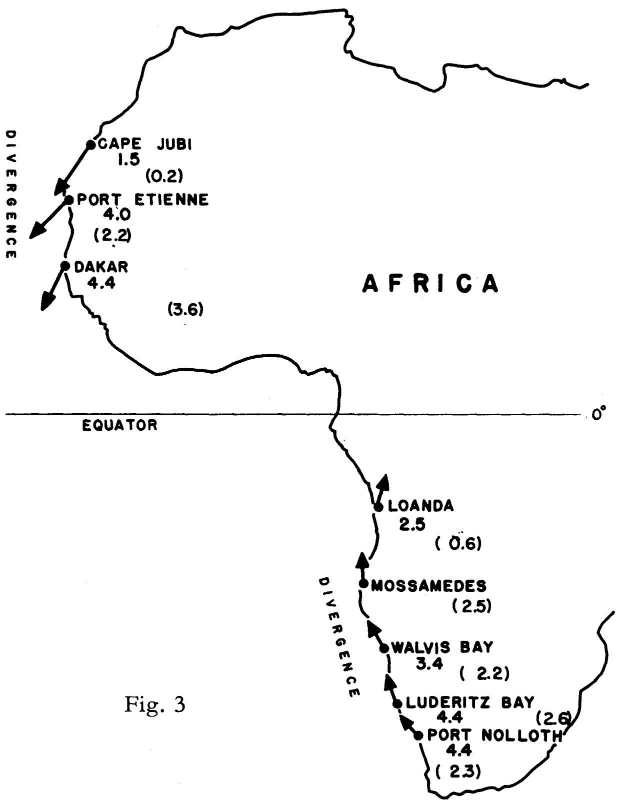

Fig. 3

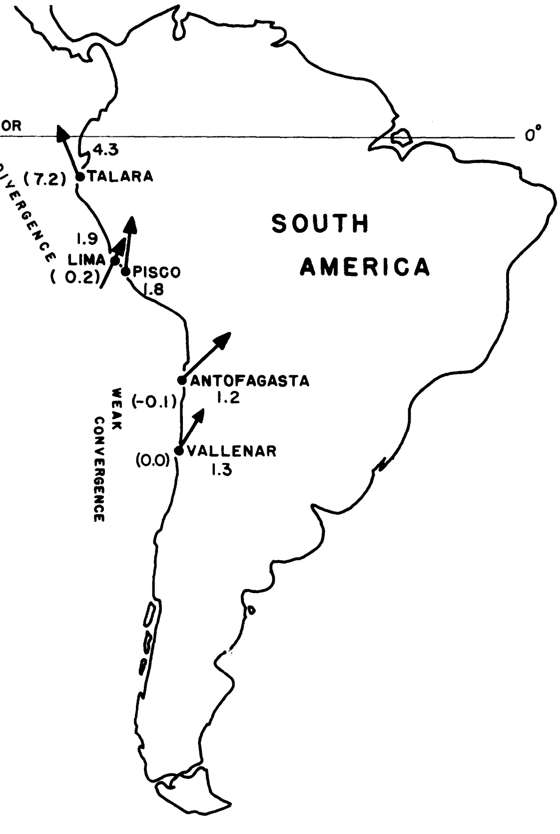

Fig. 4

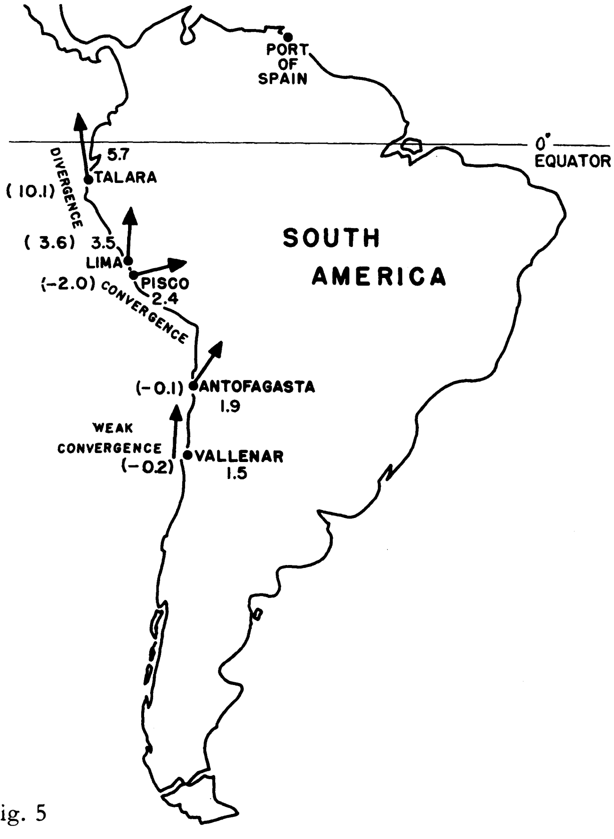

Fig. 5

The maximum of positive divergence in December, January and February (Fig. 6) results from the southerly winds along this coast. The coastal area from Port Hedland to Broome is a narrow, relatively smooth strip receiving more rainfall in December, January and February than in June, July and August. Nevertheless, it is still a dry coast. The rainfall pattern reverses, however, from Perth to Geraldton with more rain in the winter season than in summer. Weak convergence and weak divergence in Fig. 7 at Perth and Geraldton couple to aid in explaining the winter rainfall maximum. Summer in this region, shown in Fig. 6, has stronger divergence and less than ten percent of the precipitation. Port Hedland does not follow the hypothesis and no explanation other than short period resultants answers the apparent incongruity of heavier precipitation with stronger divergence in summer than in winter.

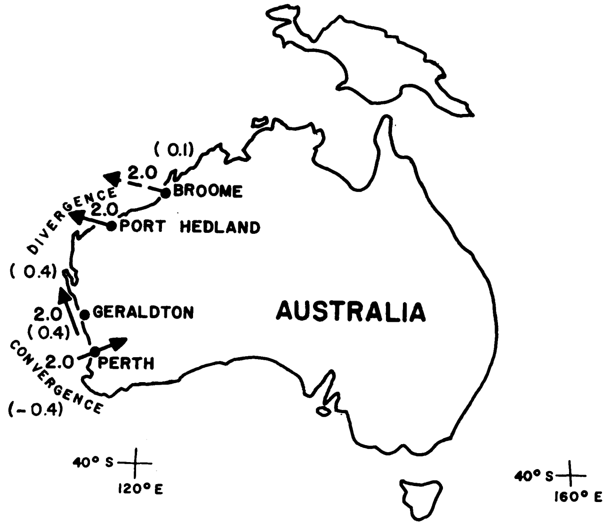

Fig. 6: Resultant Winds and Divergence, West Coast of Australia, December—February. Conventions as in Fig. 2.

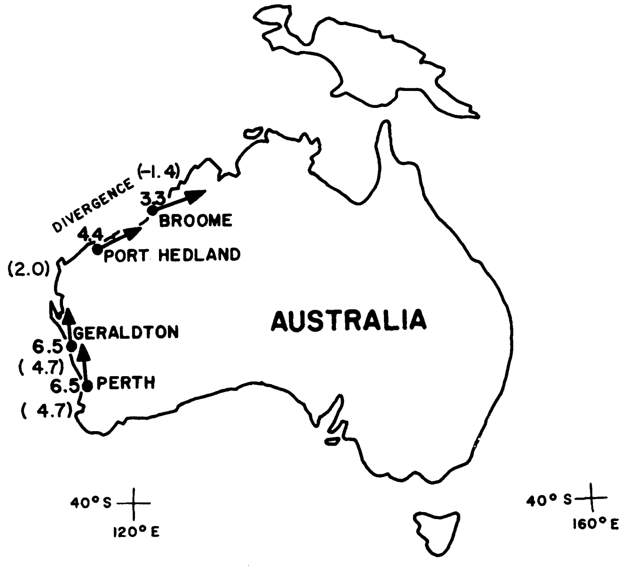

Fig. 7: Resultant Winds and Divergence, West Coast of Australia, June—August. Conventions as in Fig. 2.

New Guinea

The south shore of western New Guinea, fringing the Gulf of Papua, is a broad relatively flat coastal plain that actually covers nearly half of the central portion of the island to the base of the Orange Range. The north shore, however, offers a more rugged relief and would certainly present a greater drag on the winds than the south shore. Assuming, nevertheless, a constant drag coefficient differential from land to sea of — 10^{-3}, the coincidence of New Guinea's seasonal coastal precipitation with the patterns of stress-differential induced divergence is quite clear.

During the period June—August (Fig. 8) the resultant south-easterlies in the Hollandia area produce weak convergence associated with 18 inches of rain. During December—February, Fig. 9, the convergence is stronger largely due to the onshore component and the rain is proportionately heavier, amounting to 31 inches. On the south shore at Merauke the June—August season with south-easterlies has strong divergence and but 4 inches of rain, while the December—February season with weak convergence brings almost 27 inches.

Honduras

Along the Coast of most of eastern Honduras, the plains are wide and rise gradually inland. This topography exerts a pronounced influence on the rainfall regine of the North Honduras coast and it is through the resulting changes in the stress coefficient that we find a reason for the difference in the seasonal rainfall patterns. Western Honduras from Trujillo Bay to the Mouth of Rio Ulua is considerably more precipitous with high plateaus footing the mountains and dropping off to a narrow coastal plain.

Prevailing northeasterlies in the winter season contribute downstream convergence ("stowing effect") to partially counteract the crosswind divergence. The resulting weak divergence is associated with about 2 inches of rain along the coast. During summer the winds are nearly parallel to the coast, the crosswind divergence dominates and the rainfall amounts to only a half inch.

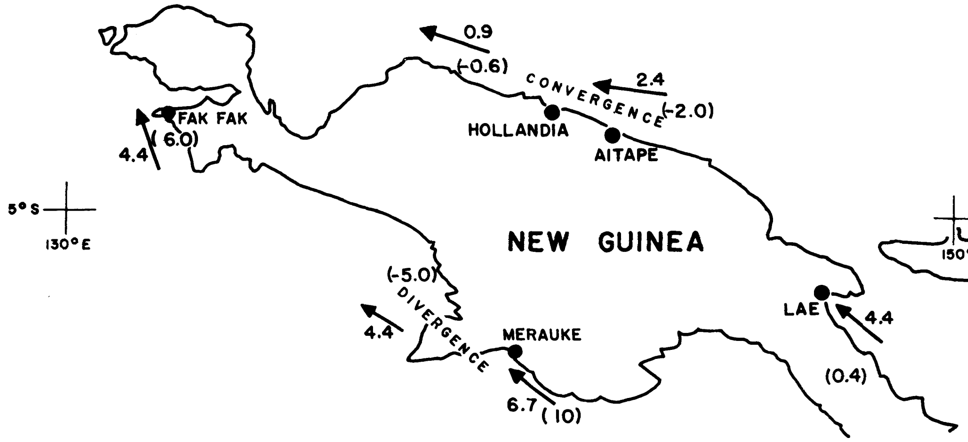

Fig. 8: Resultant Winds and Divergence, New Guinea, June—August. Conventions as in Fig. 2.

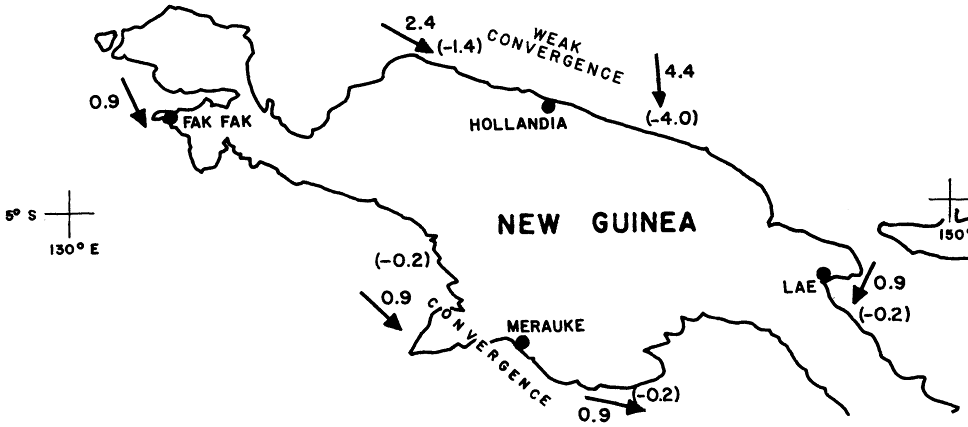

Fig. 9: Resultant Winds and Divergence, New Guinea, December—February. Conventions as in Fig. 2.

Fig. 10: Resultant Winds and Divergence, Honduras Coast, December—February. Conventions as in Fig. 2.

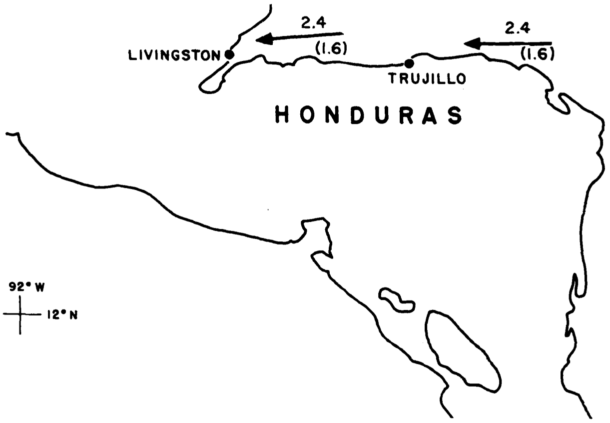

Fig. 11: Resultant Winds and Divergence, Honduras Coast, Summer Season, June—August. Conventions as in Fig. 2.

Conclusions

The preceding paragraphs suggest a relationship between the land-sea stress differential, the resulting coastal divergence and subsidence, and the dryness of those coasts where the land is on the low pressure side of the wind. This relation would seem to be fortuitous, however, unless it could also be shown that those dry coasts are more than just the line along which the sea-land boundary crosses an extensive desert whose cause is widespread subsidence related to the general circulation of the atmosphere. This question has been considered by LYDOLPH (11) who found in his study of the dry coasts discussed in this report, that they were indeed drier than their hinterland. Thus a local factor related to the littoral zone itself must be considered. One case was also discussed showing that the convergence in a region where the land is on the high pressure side of the wind is associated with coastal wetness. It will be clear to the student of climate that many other areas fit the general pattern. In the case of the Pacific coast of both Americas, for example, the boundary between wet coast and dry coast is nearly the dividing point between land to the right of the wind and land to the left.

Brief consideration also reveals that the same wind that produces coastal subsidence of the air also has the proper orientation to drive the surface water offshore and produce upwelling. Conversely, convergence in the air must be associated with convergence of the water against the shore. Hence, the classical factor of cold upwelling water as an explanation of dry coasts is seen to be dependent on the same cause as the subsidence. The basic cause, thus, becomes the relative orientation of coast line and stream line.

While the preceding discussion has been focused on coasts, there is no reason why similar roughness contrasts over land might not produce similar divergences. While we do not have the necessary data on the relationship of drag coefficient and topography to approach this application quantitatively, the qualitative implications are evident. For example, a south wind over the lower Mississippi Valley should be convergent over the bluffs along the eastern side of the valley, and divergent over the western side. This in turn should make the eastern bluffs a preferred location for the development of thunderstorms. It remains for research to provide the answer.

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