ROLE OF A TROPICAL "MARITIME CONTINENT" IN THE ATMOSPHERIC CIRCULATION [1]

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ABSTRACT

Thunderstorm frequency and amount of moisture above 500 mb. both indicate that the equatorial regions of South America and Africa and the "maritime continent" of Indonesia and the Carolines generate a much greater amount of heat for export than do equatorial oceanic regions.

Over the maritime continent in January 1963, heat generated from excessive rains was efficiently transported northward and through conversion of potential to kinetic energy probably helped maintain an intense subtropical jet stream. In January 1964 *drought* over the maritime continent was accompanied by a relative *accumulation* of heat in the upper troposphere, associated with inefficient poleward transport, and a much weaker circulation. Most winters over the western Pacific and southeast Asia fluctuate between situations typical of January 1963 and January 1964.

Since the troposphere over the maritime continent in winter is probably the single greatest source of energy for the extratropical circulation, the proposed Marshall Island experiment should be modified to include Indonesia and be rescheduled to include winter.

1. INTRODUCTION

Since World War II, students of tropical meteorology, particularly in the United States, have concentrated on the oceanic Tropics. The valuable results stemming from their investigations are epitomized in an excellent text (Riehl [11]). However, scientific arguments for continuing to emphasize the oceanic Tropics, i.e., freedom from orographic distortion, tropical hurricane generation, importance of air-sea interaction processes, and relatively uniform observing networks, all need to be reevaluated in terms of recent developments.

Until 1965, middle latitude meteorologists ignored the Tropics, banishing them to the limbo of vague boundary conditions. The outnumbered tropical meteorologists reciprocated by seldom looking beyond Cancer or Capricorn. But now the Global Atmospheric Research Program (GARP) is bringing the two groups together to plan and execute a series of tropical experiments designed to determine the nature and extent of interactions between low and high latitudes. The first experiment, in the Line Islands, has been completed; Barbados is the site of the next two experiments; the fourth and largest is tentatively planned for the Marshall Islands.

Are these the best locations—or has the tradition of research in the oceanic Tropics influenced their selection? In the remainder of the paper I try to answer this question by 1) considering the geographic distribution of near-equatorial energy sources; 2) presenting a case study of large-scale wintertime atmospheric interactions between the "maritime continent" of Indonesia and the Carolines (part of a single winter monsoon regime), and higher latitudes; 3) advancing a hypothesis on wintertime interactions over the western Pacific and southeast Asia; 4) evaluating the relative importance of the maritime continent and other tropical regions in wintertime interaction with higher latitudes; and 5) recommending a modified Marshall Islands experiment.

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2. GEOGRAPHICAL DISTRIBUTION OF NEAR-EQUATORIAL ENERGY SOURCES

Byers [3] succinctly summarizes processes leading to export of sensible heat poleward from low latitudes. Sufficient heat must be transported to the *high* troposphere to first counteract radiational cooling of 1.5°C. per day and leave enough over for export. Möller [7] points out that radiational cooling might be significantly reduced by the presence of cirrus or cirrostratus. Thunderstorms, by massively releasing latent heat and by creating dense cirrus shields, are the most important mechanism for supplying surplus heat to the upper troposphere.

Whipple [12] deduced that the diurnal variation of electrical potential gradient over the oceans could be accounted for by the afternoon thunderstorms over central Africa, South America, and Indonesia outweighing the much rarer thunderstorms over the oceans. Figure 1 and table 1 illustrate the preponderance between 10°N. and

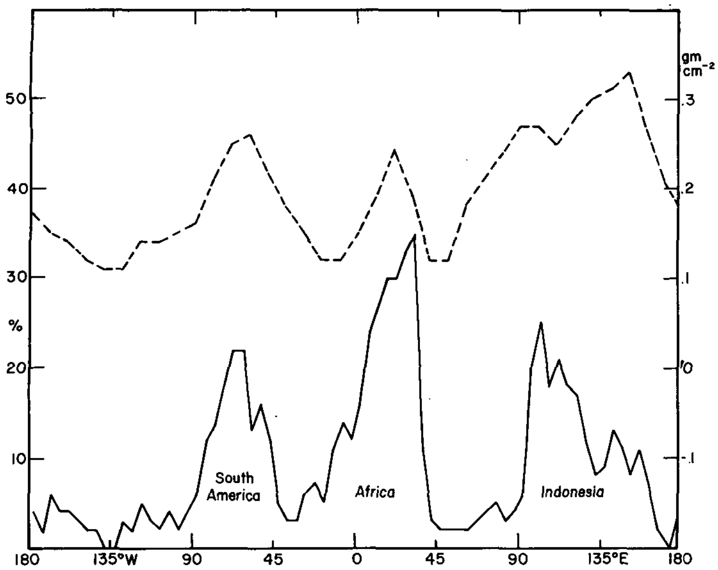

FIGURE 1.—The equatorial belt between 10°N. and 10°S. Annual percentage of days with thunder by 5° long. intervals (solid line). Based on Braak [2], World Meteorological Organization [13], [14]. Mass of water vapor in gm. cm.$^{-2}$ above 500 mb. by 10° long. intervals (dashed line). Averages of February, April, and June 1962, from Raschke and Bandeen [10].

TABLE 1.—*Percentage contributions to the annual total of thunderstorms between 10°N. and 10°S.*

Pacific Ocean	10	South America	20
Atlantic Ocean	3	Africa	35
Indian Ocean	5	Indonesia	27
Total	18	Total	82

TABLE 2.—*Percentage contributions to the mass of water vapor above 500 mb. between 10°N. and 10°S. (average of February, April, and June 1962)*

Pacific Ocean	23	South America	16
Atlantic Ocean	4	Africa	14
Indian Ocean	14	Indonesia	29
Total	41	Total	59

10°S. In these latitudes, the continents extend over 175° of long., the oceans over 185°.

Thunderstorms neither precipitate equally, nor do they release equal amounts of latent heat. Annual rainfalls over the three continental regions (South America: 1.5 to 2 m.; Africa: 0.4 to 3.2 m.; Indonesia: 1.5 to 4 m.) indicate that proportionately more latent heat is released over Indonesia than the percentage in table 1 suggests. Raschke and Bandeen [10] confirm the relative importance of the maritime continent (fig. 1 and table 2).

I have implied that over the continents, most of the rain falls from thunderstorms. However this assumption is far from valid over the open oceans (Fanning Island averages 1992 mm. of rain, and only one thunderstorm day a year). Using continental rainfall as a crude measure of latent heat released to the high troposphere I have tried to relate rainfall variation to the variation of energy generated over and exported from the maritime continent.

3. JANUARY 1963 AND JANUARY 1964 OVER SOUTHEAST ASIA AND THE WESTERN PACIFIC

In January, the southeast Asia winter monsoon reaches its greatest strength. At low levels, strong northeast winds, blowing outward from the intense Siberian anticyclone, back and weaken on approaching the Equator, but still dominate Indonesia as the wet northerly monsoon. In the high troposphere a subtropical jet stream extends from the southern Himalayas to the northern Ryukyus. South of the jet stream, a ridge along 10–13°N. separates the westerlies from easterlies over Indonesia. From the Bay of Bengal eastward to 160°E. southerly mean flow across the ridge presumably transports much of the heat which, through conversion of potential into kinetic energy, helps maintain the exceptionally vigorous circulation to the north. Even gross features of the transport and its fluctuations have not been described.

By a fortunate accident, January 1963 and January 1964 (during the period of the International Indian Ocean Expedition) are well suited for a comparative study. Over the Northern Hemisphere in the regime of the upper westerlies, *January 1963* (O'Connor [9]) "was memorable for the extreme severity of the cold weather which simultaneously gripped North America, Europe, and the Far East." Over the western and central Pacific the jet stream was much stronger and farther south than normal while an intense blocking ridge persisted over the eastern Pacific. At the surface, both the Siberian High and Aleutian Low were unusually intense (Japan Meteorological Agency [5]). Rains were above normal over the maritime continent, being very heavy over eastern Malaysia, and below normal over New Guinea. *January 1964* (Andrews [1], Japan Meteorological Agency [6]) was a much milder month. Over the Eastern Hemisphere meridional flow prevailed with the subtropical jet in about its normal position. The Aleutian Low lay farther east than usual and pressure gradients between it and a near normal Siberian High were only half as steep as in January 1963. Rains over the maritime continent were much below normal, except for New Guinea; central Indonesia suffered the worst drought in living memory.

Figure 2 depicts mean resultant circulations at 200 mb. for January 1963 and January 1964. The circulation in 1963 is much more intense (fig. 3). The poleward component across the subtropical ridge averaged 13 kt. in 1963 and only 7 kt. in 1964. Lower levels present the same picture (see above and table 3). Over the maritime continent rainfall in 1963 exceeded the 1964 amount by at least 200 mm. (fig. 4). If converted to mechanical energy

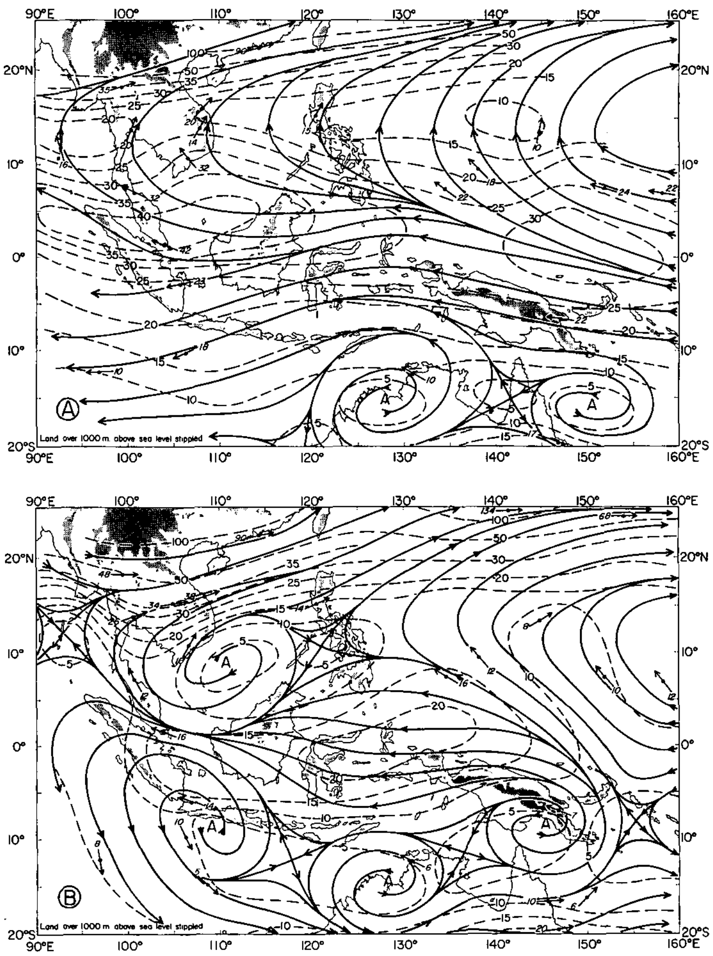

FIGURE 2.—Mean resultant circulations at 200 mb. Isotachs labeled in kt. (A) January 1963; (B) January 1964.

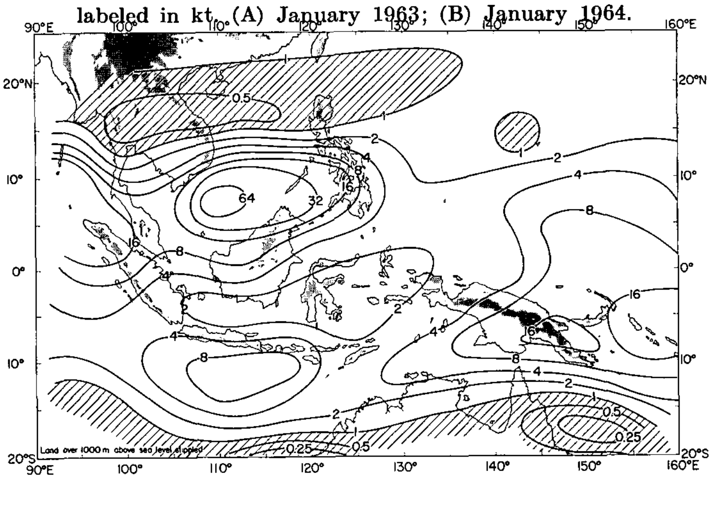

FIGURE 3.—Ratio of January 1963 kinetic energy to January 1964 kinetic energy at 200 mb.

TABLE 3.—*Mean northerly component of the surface wind (kt.) over the South China Sea*

	January 1963	January 1964
Pratas 20°42′N.; 116°43′E	19.3	8.4
Paracels (Sisha) 16°51′N.; 112°20′E	10.8	4.6

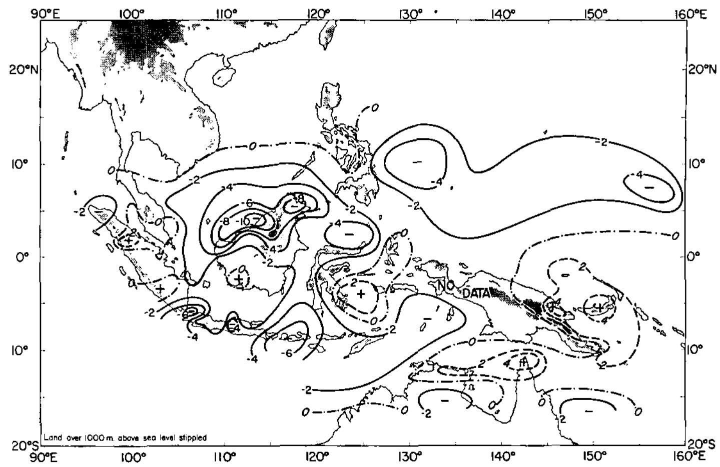

FIGURE 4.—Monthly rainfall. Change from January 1963 to January 1964 in decimeters. Rainfall over the ocean was measured only at island stations. Despite unrepresentativeness, the *differences* between 1963 and 1964 in island rainfalls probably approximated differences over the surrounding ocean.

this difference could account for the difference in circulation intensity between the 2 months.

However, it is the 200-mb. temperatures and pressures (fig. 5) that suggest important details of interaction between Tropics and higher latitudes. Height gradients were steeper in 1963 than in 1964, conforming to the stronger circulation.

North of 20°S., 200-mb. temperatures were higher and heights were greater in 1964. In the Tropics the largest positive differences, occurring over the maritime continent, coincide with the largest *negative* differences in latent heat release. This apparent paradox demands explanation.

In *January 1963*, some "cause," probably of middle latitude origin, linked heat source over the maritime continent and heat sink in the region of the subtropical jet stream so effectively that despite the heavy rains no heat accumulated over the maritime continent. Consequently, lapse rates continued to favor deep clouds and rain.

Presumably the vigorous circulation embodied relatively strong surface northerlies, which in turn evaporated relatively large amounts of water from the ocean to maintain heavy rains over the maritime continent. Energy deriving from the rains then acted to keep the circulation vigorous. Heat source and sink were relatively close, connected by a vertical circulation predominantly in the *meridional* plane, upward over the maritime continent, downward south of the jet.

The jet stream, displaced southward and exceptionally strong, was hydrodynamically unstable on its southern side. As a possible consequence, the intense blocking ridge, extending from Alaska southward, persisted throughout January 1963. Conceivably, then, energy exported from the maritime continent significantly contributed to establishing and maintaining the block.

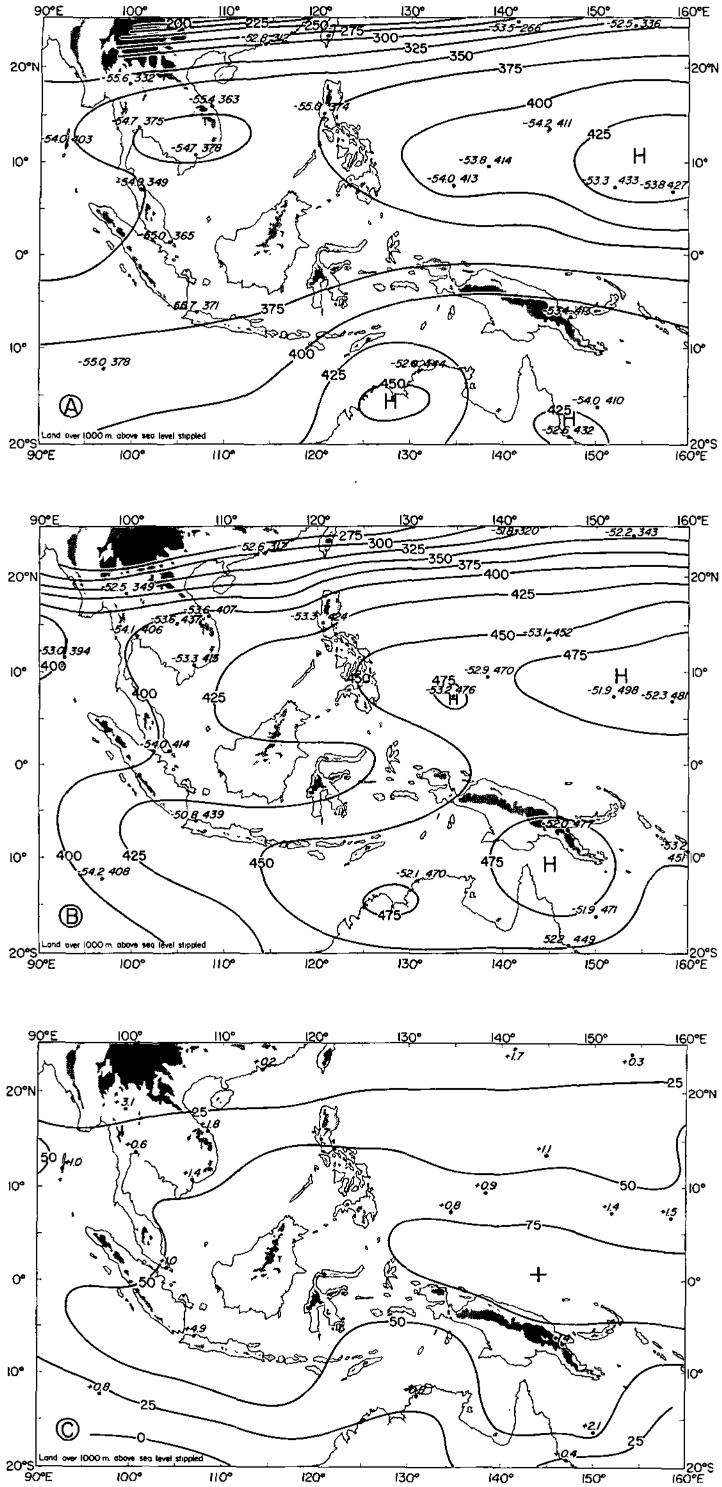

FIGURE 5.—Mean heights at 200 mb. (A) January 1963; (B) January 1964. Contours labeled in gpm. exceeding 12,000 gpm. Temperatures in °C. Differences in averaging procedures and the effect of low latitudes prevent geostrophic correspondence with figure 2. (C) Change from January 1963 to January 1964; isopleths labeled in gpm., temperatures in °C.

In *January 1964*, movement of heat from source to extratropical sink was severely restricted. Thus despite the drought over the maritime continent, released latent heat accumulated in the high troposphere. Lapse rates were less than in January 1963, and therefore not so favorable to convection. Nevertheless, they still exceeded the saturation adiabatic lapse rate. The feeble circulation embodied relatively weak surface northerlies, which by evaporating relatively small amounts of water from the ocean could have further inhibited rains over the maritime continent.

The vertical circulation probably included a significant component in the zonal plane, upward over New Guinea and downward over central Indonesia. This component would be ineffective in dispersing surplus heat or in reinvigorating the horizontal circulation.

Over the maritime continent, 200-mb. temperatures were from 1 to 2°C. higher in January 1964 than in January 1963 (fig. 5C). Let us allow the unlikely explanation that the difference could be wholly accounted for by much greater radiational cooling in January 1963. Even then, an assumed average precipitation excess of 200 mm. in that month (fig. 4) implies that at least 400 cal. $cm.^{-2}$ day^{-1} heat excess over January 1964 was available to fuel the circulation. That this excess was supplied from the ocean is shown by the fact that surface temperatures over the China Seas averaged 1.5°C. lower in January 1963 than in January 1964.

4. NORMAL WINTER SEQUENCE OVER SOUTHEAST ASIA AND THE WESTERN PACIFIC

January 1963 and January 1964 were exceptional months. However, if one assumes that they typify extremes between which circulation in most winters oscillates, events might unfold as follows:

Onset.—During the second half of October the subtropical jet is suddenly established south of the Himalayas (Yeh [16]) and the first northeast monsoon outbreak reaches the South China Sea. The sink has moved closer to the source and a meridional circulation develops as monsoon rains start over the maritime continent.

The jet may be partially cut off from its heat source as a result of shifts in the westerly longwave pattern; over the maritime continent, heat accumulates in the upper troposphere, rainfall patterns change, and the total circulation weakens. Another rearrangement and the sequence repeats.

Midseason.—With the sink well developed and surface outflow from the Siberian High strong and persistent, breaks are rare; over the maritime continent rainfall reaches a maximum, the meridional circulation is effective, and the subtropical jet attains maximum strength.

Late season.—Situations similar to that of January 1964 become increasingly common as the sink moves north, the surface northerlies die down, and heat accumulates above the maritime continent.

This sequence implies that changes over the region are triggered by events in middle latitudes but that intensity and persistence of a new regime might be influenced by the response from low latitudes. I am now less puzzled by the considerable weather fluctuations over the maritime continent between one winter and another or within a single winter, despite the fact that tropical storms or other moving disturbances are extremely rare.

Lack of adequate data has forced me to ignore the Southern Hemisphere during this season. Although the omission is likely to be unimportant, because mean charts show the meridional circulation to be largely confined to the Northern Hemisphere, in some years the Southern Hemisphere could be significantly involved.

5. RELATIVE IMPORTANCE OF THE MARITIME CONTINENT AS A WINTERTIME ENERGY SOURCE

Mean surface and upper tropospheric charts show that the wintertime meridional circulation is stronger over southeast Asia and the western Pacific than anywhere else. Cause and effect are entangled and large-scale topography is important. No physical barrier such as the Himalayas nor moisture barrier such as the Sahara interposes between the Siberian cold pole and the Equator. Besides, nowhere else in low latitudes is found a vast array of mountainous islands. Over the maritime continent in a normal winter, massive orography powerfully aids convection of deeply moist air, and released heat is efficiently drained away. The general view provided by figure 1 probably inadequately represents the scale of energy export from the maritime continent, particularly in winter.

6. THE TROPICAL METEOROLOGICAL EXPERIMENT

Present plans.—Three working groups (National Center for Atmospheric Research [8], World Meteorological Organization [15], ICSU/IUGG Committee on Atmospheric Sciences [4]) have recommended similar areas in the Marshall Islands for TROMEX. A western boundary is set by the WMO working group at 120°E., and at 135°E. by the NCAR group. In addition the NCAR group has apparently concentrated on the summer and been influenced by typhoons and the distribution of existing aerological stations.

Suggested modifications.—The experiment should be extended westward to 95°E. and probably be restricted to 160°E. in the east. It should be performed preferably during winter when *average* gradients are steepest and therefore most easily measured and meridional exchange is most vigorous. Typhoon-associated gradients are certainly steep but for most of the time during summer almost all of the western Pacific is typhoon-free and gradients are nearly flat. The fact that land-based observations are rare in Indonesia is not a valid reason for ignoring what is probably the most important energy source in the atmosphere. A synchronous satellite, equipped with a TV camera and radiometers, positioned over the Equator at 120°E., or a combination of orbiting satellites, would do much toward filling a data void.

7. CONCLUDING REMARKS

Research interests of tropical and middle latitude meteorologists have seldom overlapped. The former have concentrated on the oceanic Tropics and particularly on typhoons, the latter have tried to ignore the Tropics. Now, both groups are emphasizing interaction between low and middle latitudes, a change which in my opinion should modify the tropical meterologists' research priorities. The tropical continents demand at least as much study as the tropical oceans, and winter as much study as summer.

Although this paper omits much more than it includes, it suggests further work along the following lines:

1) Search for recognizable day-to-day or week-to-week relationships among the rainfalls of tropical South America, central Africa, and the maritime continent, and interactions with higher latitudes. For example, can all three equatorial regions experience prolonged heavy rains at the same time, and if they do, what is the effect on the total circulation?

2) Comparison of the general circulation roles of the maritime continent and the Line Islands. The northeast monsoon corresponds to the northeast trades. Although rainfalls are comparable, orography is absent and thunderstorms are extremely rare over the Line Islands.

3) Determining whether in Indonesia nocturnal thunderstorms over the channels and enclosed seas release about as much latent heat as afternoon and evening thunderstorms over the islands. Should they, energy generation over the maritime continent would possess a 12-hr. period in contrast to a 24-hr. period over South America and Africa. The effects on energy export should then be evaluated.

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