METEOROLOGICAL HAZARDS IN THE TROPICS: SEVERE CONVECTIVE STORMS AND FLASH FLOODS

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Contents

Summary

Deep convective clouds are ubiquitous over much of the Tropics. A small percentage of these convective storms produce severe weather which includes tornadoes, hail with a diameter more than 20 mm, and straight line winds that exceed 26 m s^{-1}. Additionally, even modest-sized convective clouds can produce rain rates that can cause a flash flood if the rains occur over a susceptible watershed. This chapter discusses these types of meteorological hazards; the underlying physics that drives them, where and when such hazards may occur and what factors should be viewed in order to forecast them.

The physics that control the intensity of the vertical velocity in cloud, which in turn affects the frequency and type of severe weather, is presented. Fundamental to the understanding of severe weather and flash floods is how temperature, moisture and winds vary from the surface to the top of the troposphere. The key physics controlling updraft speed is discussed and the reader is introduced to a sounding on a thermodynamic diagram that allows one to determine conditional instability, a measure of how strong the vertical velocities in a convective cloud may become. For each form of severe weather the necessary but not sufficient ingredients are identified. Tornadoes associated with a mesocyclone, a region several km in diameter that is rotating, require a large variation in the speed and or direction of the wind in the lower troposphere. Large hail requires a strong and wide updraft and the formation of hail embryos, an ice particle about 5 mm in diameter. Straight line winds that achieve damaging thresholds often rely on the evaporation of rain into dry air below cloud base. Flash floods, the most frequent form of convective-scale meteorological hazard, are the most difficult to forecast as these situations do not rely on extreme instability. Instead a deep layer of moist air and wind conditions that promotes slow movement of the storms favor heavy rains over a particular region.

The planetary and synoptic phenomena such as the near equatorial convergence zone, the subtropical highs, ocean gyres, the monsoon, jet streams, subtropical depressions and tropical cyclones modulate the environment in which deep convective clouds occur and alter the frequency and intensity of the deep convective clouds. Regions in the Tropics prone to severe weather are identified. Finally some basic considerations to the forecasting of severe weather and flash floods are discussed.

1. Introduction

1.1. Definition of Severe Convective-Scale Weather and Flash Floods

Deep convective storms or cumulonimbi (CBs) in the Tropics redistribute heat, moisture and momentum through the atmosphere and play a vital role in the global energy balance of the biosphere (Riehl and Malkus 1958). A small percentage of these deep convective clouds are responsible for hazardous conditions that encompass both severe convective weather and flash floods. Severe convective weather includes tornadoes and intense waterspouts, hail with a diameter greater than 20 mm, and straight line winds greater than 26 m s^{-1}(Moller 2001). These thresholds are correlated with damage to crops, housing and transportation. A flash flood is a dangerous inundation that occurs over a few hours or less, and is caused by heavy rain over a small area. A flash flood is dependent on the watershed receiving the rain as well as the atmospheric phenomena delivering the rain. The topography of the watershed is crucial in marshaling the runoff and causing a stream or river to overflow its banks. I will group both severe convective weather and flash floods under the label meteorological hazards.

I will restrict discussion to convective and small mesoscale events. The wind damage from tropical cyclones (TCs) can be catastrophic but discussion of this topic is reserved for the TC section of this volume. I will discuss tornado outbreaks embedded in the TC circulation. Floods that cover large areas and for many days to weeks, though of great concern, are generally due to synoptic scale phenomena and are not addressed here.

1.2. Goals

Entire books have been devoted to the topic of severe weather so in this short chapter I can only provide a sketch of the important physics. My goals for this chapter are to:

1) outline the planetary and synoptic scale phenomena that affect the frequency of severe convective-scale weather and flash floods in the Tropics,
2) summarize buoyancy which is a key force that drives vigorous updrafts,
3) describe the basic environmental ingredients that contribute to each hazard,
4) demonstrate that there are long periods and large areas in the Tropics that rarely see conditions that lead to either severe weather or flash floods,
5) speculate on some of the reasons why severe convective storms are so rare in the Tropics, and
6) discuss techniques and observational systems that are relevant to the forecasting and warning of severe weather and/or flash flooding.

2. Phenomena that Affect the Environment for Deep Convection

2.1. Planetary and Synoptic Scale Phenomena

I shall define the Tropics as the latitudinal belt from the Tropic of Cancer to the Tropic of Capricorn, but will also include the foothills of the Himalayas. Wet and dry seasons may exist, but no portion of the considered landmass has persistent winter conditions or witnesses freezing temperatures at the earth’s surface. Summertime Florida peninsula conditions will also be discussed as it has a rich dataset and can thus serve as a proxy for tropical regions that for the most part are plagued by a dearth of observations.

Major planetary and synoptic scale features that are recognizable at the surface or in the upper atmosphere for January and July appear in Figure 1a, b. This figure is based on a wide range of sources but its foundations are based on the texts of Riehl (1954) and Ramage (1971), and the atlases of Sadler (1975) and Sadler et al. (1987). Near the equator but biased toward the northern hemisphere is the near equatorial convergence zone (NECZ) and equatorial trough.

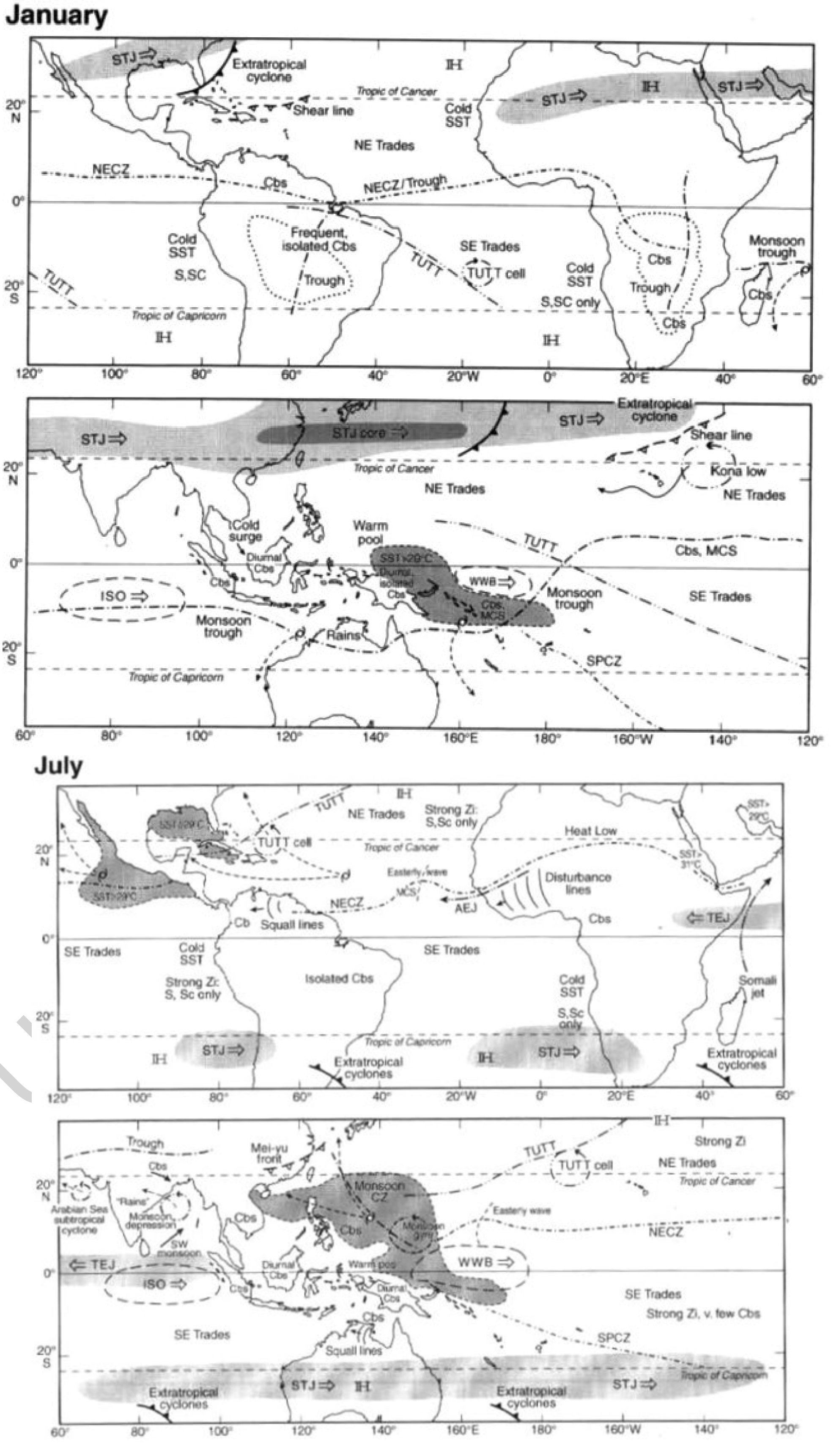

Figure 1. A schematic of the tropical regions in (a) January and (b) July, that show key

planetary scale surface features (NECZ, SPCZ, monsoon and equatorial troughs, heat lows, trade winds, warm and cool SST areas), regions where there are cumulonimbi (Cbs), important upper level features (STJ, TEJ, AEJ, TUTT) and synoptic systems that modulate conditions (Kona low, monsoon depression, extratropical cyclones and their attendant fronts and shear lines, TUTT cells, easterly waves, TCs, ISO, WWB). From Barnes (2001).

Here I avoid the common misnomer intertropical convergence zone since there is only a single Tropics making an *inter*tropical convergence impossible. The NECZ owes its existence to the convergence of the northeast and southeast trades and is a favored region for deep convection. The south Pacific convergence zone (SPCZ) can be seen east of the Australian continent through the year. This is a region of persistent cloudiness that can support deep convection, though much less frequently than the NECZ. In most of the eastern hemisphere the (Figure 1b, lower panel) the heating of the Asian and African continents compared to the adjacent oceans causes the equatorial trough to migrate great distances and is normally referred to as the monsoon trough. The northeast and southwest monsoons are implied by the movement of this monsoon trough. The pre-monsoon seasons for India and northern Australia are periods where instability and the vertical shear of the horizontal wind can reach extreme enough magnitudes to nurture severe convective storms.

Besides the monsoon there are intraseasonal oscillations, and the related westerly wind bursts that modulate stability and winds near the equator. The Madden- Julian oscillation (MJO, also called the intraseasonal oscillation) is a large synoptic scale-sized region favoring deep convection that originates near the east African coast and migrates eastward around the globe with a period of 30 to 50 days. It typically reaches its convective maximum in the Indian Ocean, and becomes more difficult to recognize over the Indonesian archipelago due to the strong diurnal forcing caused by the islands. When the MJO crosses the dateline convection is much reduced due to the presence of cooler water planetary scale subsidence, and weaker low-level convergence. A monsoon gyre (Figure 1b) is another large scale feature that can develop and survive for weeks during the summer in the northwestern Pacific. It is essentially an eddy that develops along the monsoon trough.

Synoptic scale features that impact convection include subtropical or Kona lows, monsoon depressions, easterly waves, shear lines which are dissipated fronts that no longer have a temperature gradient across them and the occasional invasion of a cold front into the Tropics. These synoptic scale features can produce strong enough lifting to destroy the trade wind inversion and allow for deep convection to occur. The odds for severe convective weather and flash floods increase within these synoptic scale phenomena.

Sea surface temperatures (SST) vary in the east-west direction as well as in the expected meridional plane. Deeper convection is supported over the west Pacific warm pool just east of the Philippines and Indonesia year round. Higher SSTs near Central America along the Pacific coast and Gulf of Mexico support enhanced convection during the northern hemisphere summer (Figure 1b, upper panel). Colder waters along the west coasts of South America and Africa inhibit deep convective clouds virtually year round.

Aloft there are several jet streams that alter the shear and upper level divergence and thus play a role in creating an environment for strong convection. The subtropical jets stream (STJ) centered near 300 hPa provides divergence aloft that may trigger convection, especially when it breaks into streaks with sharper speed changes. The tropical easterly jet (TEJ), a consequence of the high aloft that builds over the Tibetan Plateau and nearby regions in the northern hemisphere summer, alters the upper level shear. The reversed surface temperature gradient in Africa where the Sahara is hotter than the equatorial regions, (Figure 1b) causes the formation of the African easterly jet (AEJ), centered near 650 hPa. The AEJ enhances the low level shear and promotes the development of African disturbance lines or squall lines. When the jet becomes unstable easterly waves form that serve as a major organizing phenomena for deep convection in West Africa, the equatorial Atlantic and into the eastern Pacific (Reed et al. 1977). Easterly waves are the chief initiating mechanism for hurricanes in the Atlantic. The tropical upper tropospheric trough (TUTT) forms in the summer hemisphere over the oceans (Sadler 1975). Synoptic scale vortices known as TUTT cells often form and move westward. These TUTT cells erode the trade wind inversion and can trigger heavy rains (Kodama and Barnes 1997) as well as promote cyclogenesis or intensification of a tropical cyclone.

The key point is that the Tropics is far from homogeneous. There are regions that rarely support even modest convective clouds such as the eastern sides of the ocean basins where the diverging trades are collocated with upwelled cold water along the west coasts of the continents. Low stratus and stratocumulus dominate the cloud populations in these regions. Synoptic scale cyclones are needed to modulate the environmental conditions in order to have deep convection and especially severe convection. Planetary features such as the equatorial and monsoon troughs produce conditions that support deep convective clouds frequently (monsoon trough over Africa, Indonesia, and the Amazon). But, as I will demonstrate, these Cbs rarely yield severe weather. Severe convective events occur most frequently in locations where warm, moist air in the lower troposphere is overlain by cooler, drier air. This of course demands that these two layers have had contrasting trajectories or histories which results in wind shear, a change in wind direction and/or speed with height. Tropical locations that have this juxtaposition of air with contrasting histories include northern India and northern Australia prior to the wet phase of the monsoon, the southern part of Brazil and northern Argentina in the lee of the Andes, and the Sahel. The cold fronts associated with extratropical cyclones can still have well-defined traits as they exit the Eurasian or North American continents and impact the western portions of the ocean basins. Flash floods have less environmental demands, and can occur throughout the Tropics. A more complete review of the larger scale forcing in the tropics is found in Barnes (2001).

2.2. The Disposition of Deep Convection in the Tropics

Deep convective cells are the parent storms for all severe weather and many, though not all, of the flash flood episodes. Continental regions that have a high frequency of Cbs include equatorial Africa, the Amazon, Southeast Asia, Indonesia, and northern Australia. Satellite surveys of high clouds show the equatorial and monsoon troughs over the oceans are also active regions of deep convection. While deep convective clouds are almost always associated with severe weather they are not necessary to have flash floods. As will be shown, the ingredients for flash floods contrast those that favor tornado, hail and strong straight line winds.

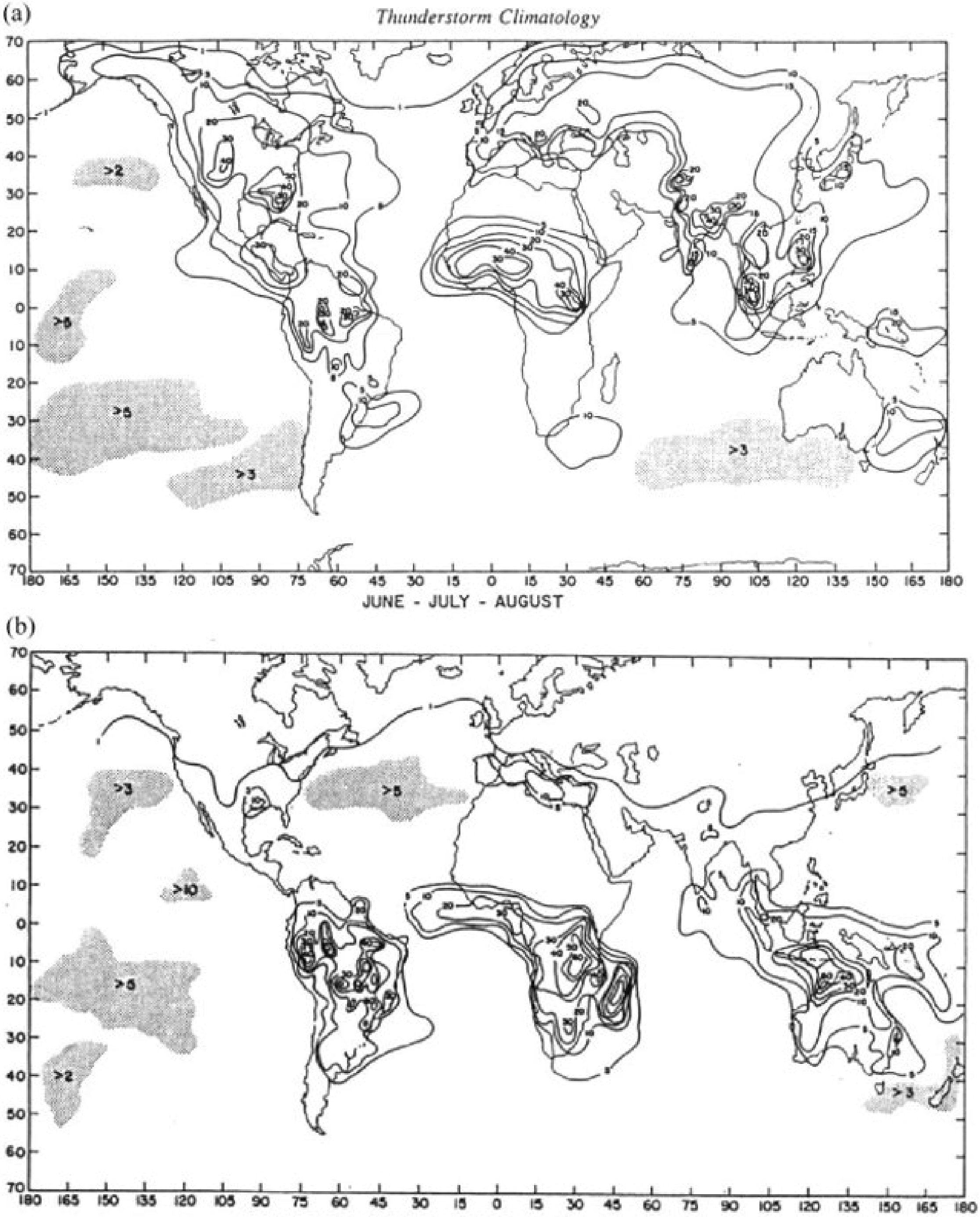

Figure 2. Thunderstorm days (from WMO 1953) for the globe for the (a) boreal summer and the (b) austral summer.

Thunderstorm climatologies are one way of identifying the stronger deep convective cells. Lightning and subsequent thunder needs vigorous enough updrafts ($w > 10 \text{ m s}^{-1}$) to produce a volume above the freezing level (~5.5 km in the tropics) that contains water in both liquid and ice form. Collisions between the ice and the liquid, called super-cooled water as it has remained liquid despite temperatures colder than 0 °C, is crucial to lightning formation. Thunderstorm days frequency (number of days with lighting or thunder observed, WMO 1953) during the boreal summer (Figure 2a) and the austral summer (Figure 2b) show several important trends. First, tropical continental regions contain the maximum frequencies for the globe. Second, these land masses also have far more thunderstorms than the tropical oceans (Sanders and Freeman 1986). Third, the regions of maximum activity migrate with the annual cycle of insolation. The convective activity and rains do lag the insolation maximum by several weeks. Note the very low frequency of thunderstorms over the expansive trade wind regions. While the thunderstorm frequency map does correlate well with a few regions known for severe weather (northern India, highlands of east Africa, northern Australia) it can also mislead. Reports of severe weather from equatorial Africa or the Amazon, despite the high frequency of thunderstorms, is quite rare. Some of this may be due to the acute lack of observing stations and especially quantitative radar sites. Other regions that have few thunderstorms in the tropics do have rare severe events and may often suffer flash floods (e.g., Hawaii). Flash floods, though usually triggered by a convective cell with high rain rates, may also occur with more modest clouds that never produce lightning or cloud tops that reach 10 km.

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Biographical Sketch

Gary M. Barnes received his Ph.D. from the University of Virginia in 1980. He spent 11 years at the National Center for Atmospheric Research in Boulder, Colorado where he served as chief scientist in research aircraft deployed to observe cumulus clouds, thunderstorms, squall lines, tropical cyclones and the boundary layer. Since 1991 he has been on the faculty within the Department of Meteorology, School of Ocean and Earth Science and Technology, at the University of Hawaii. He currently is focused on tropical cyclone research specializing in the interpretation of observations obtained with aircraft in these storms. He is the author or co-author of more than 40 refereed publications and over 70 presentations at national and international scientific meetings.