STATISTICAL STUDY OF CONVECTIVE AVAILABLE POTENTIAL ENERGY AND DAYTIME THUNDERSTORMS IN SINGAPORE

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1. INTRODUCTION

The climate of Singapore is warm and humid all year round. These conditions are favourable for the development of convective weather. Singapore's weather is influenced by two main monsoon seasons: Northeast Monsoon (NEM) between December and early March, and Southwest Monsoon (SWM) between June and September. The transition period between the monsoons are called Inter-monsoon (IM1 from late March till May, IM2 from October till November).

Convective Available Potential Energy (CAPE), as defined by Williams and Renno (1993) is used to evaluate the convective potential in Singapore. Variation of surface conditions (temperature, relative humidity or mixing ratio) has a major impact on CAPE and development of convective storms (Eltahir & Pal, 1996; Donner, 2003). In other words, CAPE variations are massively controlled by boundary layer (BL) conditions. Nevertheless, the calculation of CAPE throughout this study is consistent.

Williams and Renno (1993) emphasized that finite amount of energy or CAPE is always present and stored in the tropical atmosphere but deep convection does not always occur, due to occasional pronounced capping inversions. This argument is echoed by Sherwood (1999), stating that CAPE is not a useful predictor of deep convection in the tropical atmosphere since other factors appear to have higher impact.

The correlation between CAPE and the intensity of diurnally forced convection in the deep tropics is not as direct as in the mid-latitude region. Golding (1993) investigated the diurnal evolution of thunderstorms "Hector" on Tiwi Islands (a tropical island situated north of Darwin, Australia) and confirmed the fact that with sufficient surface sensible heating, CAPE plays a rather significant role in determining the time of initiation and the intensity of convection. On the other hand, Carbone et al. (2000) found only a weak correlation between CAPE and diurnal thunderstorms over Tiwi Islands.

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Chappel (2001) examined the occurrence of thunderstorms over Darwin and its correlation with CAPE and vertical wind shear. A strong correlation between very high-unmodified CAPE (>3500 J/kg) and "lunchtime" ordinary thunderstorms at Darwin Airport was found. Even though unmodified CAPE is relatively low due to stable capping inversions, severe thunderstorms are sometimes still possible if the capping can be overcome by sufficient sensible heating.

Despite the well-known capability of CAPE in predicting severe thunderstorms, CAPE does not appear to be strongly correlated with the amount of rainfall (Yano, Chaboureau & Guuichard, 2005). Negative correlation was observed between rainfall and quantities that estimate parcel buoyant energy. This similar negative correlation during the warm season of the United States (Peppler & Lamb, 1989), suggested that rainfall is better correlated with humidity of air just above the boundary layer. McBride and Frank (1999) also demonstrated that this is true for tropical maritime convective rainfall.

The objective of this study is to investigate the extent to which CAPE affects daytime thunderstorms in Singapore. An annual variation of average CAPE is also studied and compared with annual rainfall pattern.

2. PROCEDURES

Radiosonde data of year 2002-2011 were collected and CAPE was calculated by Messir-Vision®. Since locally developed diurnal thunderstorm was the focus of this statistics, atmospheric sounding and CAPE at 00UTC (8am LT) were chosen. The values of CAPE were subdivided into five categories: ≤500 J/kg, 501-1000 J/kg, 1001-1500 J/kg, 1501-2000 J/kg and >2000 J/kg. CAPE is referred to as energy on the positive area on the sounding between the Level of Free Convection and the Equilibrium Level, calculated by Messir-Vision® using the 00UTC sounding by lifting the surface air parcel, without any modification to the boundary layer parcel.

Soundings that were taken during any precipitation activity were discarded because they were unrepresentative of the large-scale atmospheric condition. Furthermore, nocturnal thunderstorms (i.e. "*Sumatra*" Squall) also contaminate the morning soundings through the presence of debris clouds, remnant outflow boundaries and mesoscale downdraft. Consequently, only 1089, 964 and 983 days of data for NEM, IM and SWM respectively were left for study. A line graph was plotted to examine the annual variation of CAPE throughout a year.

The precipitation was classified into: no precipitation/ stratiform rain, showers and thunderstorms, according to METARs and radar imagery. The half-hourly METARs of Changi Meteorological Station (WSSS) are the main reference because the station is operated 24 hours a day. Other stations, i.e. Seletar (WSSL), Sembawang (WSAG), Paya Lebar (WSAP) and Tengah (WSAT), though provide hourly METARs, they were only available between 2100-1500UTC (5am-11pm LT). Nevertheless, these observations were taken into account when available.

3. RESULTS AND DISCUSSIONS

3.1 *Annual Variation of CAPE*

The values of unmodified CAPE in Singapore vary throughout the seasons. It ranges between 100 J/kg and more than 4000 J/kg on some days. As shown in Figure 1, the mean value of CAPE appears to change with the large-scale seasonal forcing and the location of monsoon trough or convergence zone.

A slight dip in the value of CAPE to nearly 500 J/kg is observed in late January and early February, which coincides with the dry phase of NEM with fewer thunderstorms. According to the records at Changi Station (Figure 2), February is the month which registers the least number of thunderstorms days (3 days), followed by January (7 days). The decrease in CAPE can be explained by the large scale subsidence inversion and the presence of dry air being advected from the higher latitude. Hence, atmosphere with low moisture inflow in the boundary layer resulted in lower value of CAPE. The average value of CAPE increases in the late February and continues to rise in the subsequent months, reaching above 2000 J/kg. Such significant rise in CAPE occurs at the later part of the Northeast Monsoon, as Inter-monsoon gradually sets in during late March. The average number of thunderstorms also escalates to 14 days in March from a minimum of 3 days in February.

The accumulation of moisture at the low level after the dry phase could be the factor contributing to the rising CAPE. Large CAPE is observed when there is higher than average boundary layer moisture and temperature in the tropical convection (Tompkins, 2001; Chaboureau et al., 2004). Over the Indian monsoon region, high surface temperature and high moisture inflow in the boundary layers from the sea result in larger CAPE at the coastal region of India (Bhownik, 2008).

During the IM months of April and May, average CAPE continues to climb to 2500 J/kg and eventually reaches a peak in June. April and May correspond to the months with highest average numbers of thunderstorms in a year (20 and 19 days respectively). Such sharp increase in both CAPE and thunderstorms is due to the light and variable wind conditions during the IM that leads to higher temperature and moisture in the boundary layer. During the IM, the monsoon trough or convergence zone is also situated close to the equator, accompanied by strong heating from the sun.

From July onwards, average CAPE decreases steadily before reaching a minimum (about 750 J/kg) in late December. This also translates into fewer thunderstorms during the SWM than during the IM1. As IM2 is giving way to the onset of NEM, the average CAPE has a declining tendency where the average number of thunderstorms drops to a low of 11 days in December.

By comparing the annual CAPE variation (Figure 1) with the average monthly total rainfall (Figure 3), it can be clearly seen that the highest monthly total rainfall occurs during the wet phase of NEM, i.e. in November, December and January. However, during this period of time, CAPE is very low. This negative correlation between rainfall and CAPE can also be observed during May and June which have the highest CAPE but lower rainfall amount. Therefore, CAPE does not appear to be an effective thermodynamic index to forecast heavy rainfall.

3.2 *Northeast Monsoon*

During the NEM, moist convection is highly suppressed when CAPE is very low (≤500 J/kg), indicating little potential or no thunderstorms. According to Figure 4, there is only 16% of the time thunderstorms occur when CAPE is ≤500 J/kg; on the other hand, slightly more than half of the time, Singapore experiences fair weather conditions. During the dry phase of Northeast Monsoon, extensive dry air layers are often sighted and may extend from the low-level (below 7000ft) to the upper troposphere. The lack of moisture due to advection of dry air, sometimes accompanied by lower EL, causes very low CAPE as well as suppressed convection.

As illustrated by Johnson, Ciesielski and Hart (1996), advection of dry midlevel air may inhibit deep tropical convection although the area is previously convectively active. McBride and Frank (1999) also found a positive correlation between moisture variation in the lower to mid-troposphere and convective activity. Dry slots or dry inversion (with dew point depression of 10 degrees of more) at the low-level are also known to delay afternoon convection (Shepherd, 2010), until moist air from the boundary layer continuously moistens the dry layer. As CAPE rises to more than 2000J/kg, thunderstorms occur 75% of the time. Therefore, during the NEM, number of thunderstorms increases when CAPE increases.

3.3 *Southwest Monsoon*

During the SWM, 54.7% of the time CAPE is larger than 2000J/kg, and such high percentage is not observed in any other monsoon seasons. The chance of getting thunderstorms rises from 32% to 51% as CAPE increases from ≤500 J/kg to >2000 J/kg (Figure 7). When CAPE is between 501 – 2000 J/kg, the chance of getting thunderstorms and no precipitation are both around 45%. The percentage of getting fair weather drops from 62% to 37% when CAPE increases from ≤500 J/kg to >2000 J/kg. Interestingly, out of the 388 days of fair weather, 196 days happened when CAPE is >2000 J/kg. In other words, large CAPE in Singapore does not necessarily always signify severe thunderstorms. Further studies can be done to examine the reason for such conditions.

"Sumatra" Squall is a very common type of weather phenomenon during the IM and SWM. However, it is eliminated from this study because squall lines usually affect Singapore between early hours and late morning. Therefore, the atmospheric sounding at 00 UTC is no longer a good representation of the atmospheric conditions in the day during the passage of squall lines. Sometimes squall lines occur when the 00UTC soundings are launched and therefore "contaminate" the soundings due to the presence of precipitation as well as remnant rain cloud.

3.4 *Inter-monsoon*

The percentage of getting fair weather drops (from ~45% to ~25% chance) when CAPE increases from ≤500 J/kg to >2000 J/kg. This decreasing trend is similar to the NEM. During the IM1, there were 121 days with no precipitation in Singapore and out of them, 57 days occur when CAPE is more than 2000 J/kg. This number is rather surprising as fair weather is usually associated with low CAPE. The reason is because of the wind conditions including local sea breeze effect. Since winds are generally light and variable during the IM, when the low-level winds blow from the south or southwest and strengthened further by the onset of sea breeze, the area of strong convergence will shift northward to the southern part of Johor, Malaysia. As a result, despite the huge instability, there will be no precipitation in Singapore but heavy thunderstorms develop just north of the island. Strong vertical wind shear, which acts to suppress the growth of convective clouds by "shearing" off the cloud top and limiting the vertical extend of a cumulus cloud (Beringer, Tapper & Keenan, 2001), is not incorporated in CAPE. In other words, CAPE does not take wind change into account, which is an important component in the tropics.

Thunderstorm is the most common type of weather phenomenon during the IM. There were 304 days and 253 days of thunderstorms occurred during the IM1 and IM2. During the IM1, when CAPE is ≤500 J/kg, there are 14 thunderstorms days. The number of day increases markedly to 135 when CAPE is more than 2000 J/kg. For IM2, the number of thunderstorms increases from 24 to 67 when CAPE increases from ≤500 J/kg to >2000 J/kg. As shown by Figure 5 and Figure 6, the chance of thunderstorms increases from 30% to around 70% when CAPE changes from ≤500 J/kg to >2000 J/kg.

4. CONCLUSIONS

In Singapore, CAPE changes with the monsoon seasons. Minimum CAPE is observed during the dry phase of the NEM which corresponds to the least number of thunderstorms. It then increases and reaches a peak in late May and June as IM1 sets in. In general, fair weather conditions usually occur when CAPE is less than 500J/kg. The presence of stable low-level dry layer also increases the chance of fair weather. As CAPE increases to more than 2000J/kg, number of thunderstorms days also rises accordingly. However, this does not always necessarily mean more vigorous convection. Fair weather can occur even though large CAPE is observed. On the other hand, thunderstorms are also observed when CAPE is low. Further studies are required to examine the mechanisms and impact of winds that cause such scenarios. When CAPE falls between the range of 500J/kg and 1000J/kg, it is rather ambiguous as in which type of weather has a higher chance of occurrence. CAPE is also not useful for weather systems advected by winds upstream of Singapore, such as "Sumatra" Squall and NEM surge.

5. LIST OF FIGURES

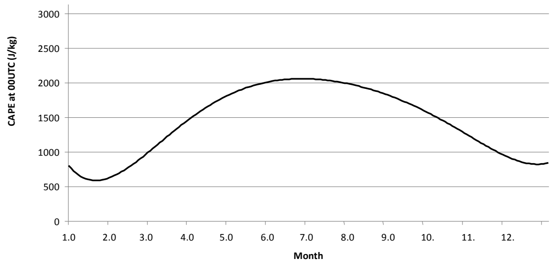

Figure 1: Annual variation of CAPE, averaged between 2002 and 2011, from January till December

Figure 2: Average number of thunderstorms days at Changi station between 2002 and 2011

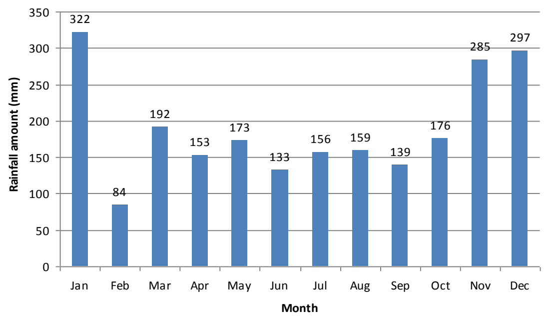

Figure 3: Average amount of rainfall at Changi station between 2002 and 2011

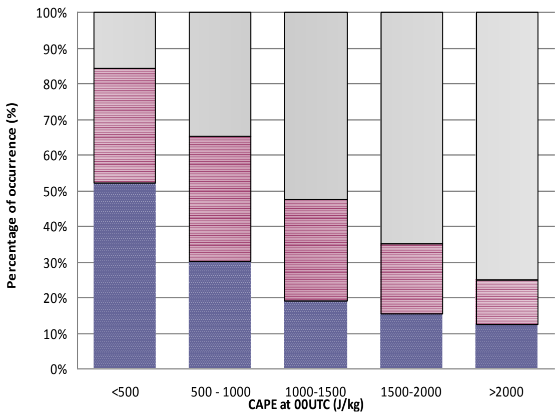

Figure 4: Percentage of occurrence of fair weather (dotted), showers (grid) and thunderstorms (vertical line) versus CAPE during Northeast Monsoons of years 2002-2011

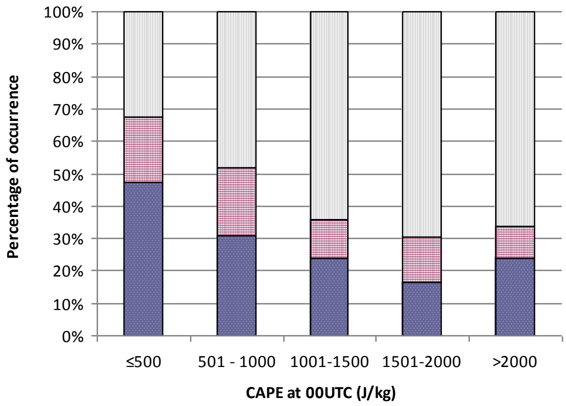

Figure 5: Percentage of occurrence of fair weather (dotted), showers (grid) and thunderstorms (vertical line) versus CAPE during 1st Inter-monsoon of years 2002-2011

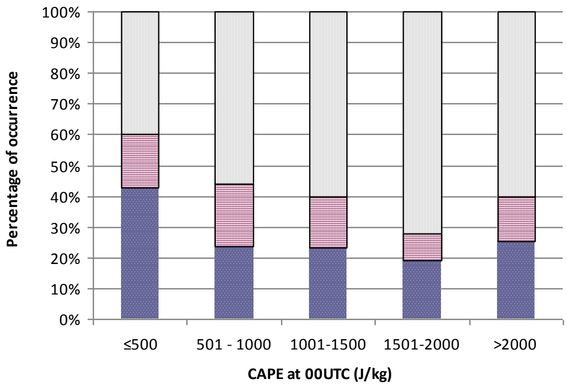

Figure 6: Percentage of occurrence of fair weather (dotted), showers (grid) and thunderstorms (vertical line) versus CAPE during 2nd Inter-monsoon of years 2002-2011

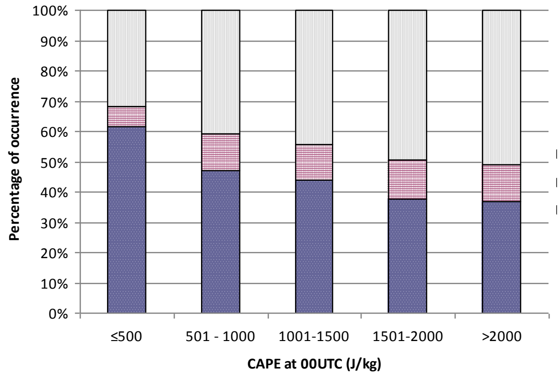

Figure 7: Percentage of occurrence of fair weather (dotted), showers (grid) and thunderstorms (vertical line) versus CAPE during Southwest Monsoon of years 2002-2011

6. REFERENCES

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