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Variability and sensitivity of stability indices at Kototabang (West Sumatera, Indonesia)

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Abstract. Stability index data obtained from the Radiosonde launch at the Space and Atmospheric Observation Station Agam District (West Sumatera-Indonesia) in 30 August to 2 September 2016 (three times launches a day), 5 March to 9 March 2018 (twice launches a day) and 29 April to 2 May 2019 (once launch a day) used Vaisala RS41-SG. The purpose of this study was to investigate the stability indices variations and finding the best indicators for convective disturbances at Kototabang in the tropical region. The stability indices studied were CINH, CAPE, K-index, Ko-index, S-index, SI, LI, TT-index, and the values of temperature, pressure, and height of the stability layers (LCL, LFC, CCL, and EL). K-index, S-index, and TT-index indicated that atmospheric conditions were always unstable. The indices fluctuated slightly as well as temperatures and pressures at stability level. While CAPE, Ko-Index, LI, SI, CINH, temperature and pressure of EL, and the elevations of LCL, LFC, CCL, EL were very fluctuating and showed clearly the stable and unstable conditions. Three different observation periods produced three sets of characters for each index. Based on variability analysis and two assessment derived CAPE, CINH, SI and EL-Z can be used as the rainfall predictors.

1. Introduction

The troposphere is characterized by a decrease of temperature with respect to height with a typical lapse rate of 6.5°C/km. The temperature structure in this layer is a consequence of the radiative balance and the convective transport of energy from the surface to the atmosphere. Virtually all the water vapour, cloud and precipitation are confined in troposphere. Study of atmospheric conditions is important for life sustainability. Because of convective activity, water vapour in atmosphere modifies the air temperature which causes convective indices to also changes [1].

In the study of [2], three instability indices (Boyden index, K-index and Lifted index) are computed based on radiosonde data. Boyden index shows the potential for thunderstorm activity on 6 days of 7 days of observations in Heraklion. K-index shows the possibility of isolated thunderstorm in Izmir on 4 days of 22 observation days, and the Lifted index in Athens indicated stable atmosphere, no thunderstorm possibility. The instability indices is also determined using satellite derived atmospheric profile products provided by the MODIS/AQUA archives. The comparison of the two data shows the three satellite derived instability indices are well correlated with those derived with radiosonde data. It means that this kind of remotely sensed data can make a very good simulation to the assessment instability for large area, contribution significantly to forecasting. The combination of Radiosonde and satellite data provides a better understanding of atmospheric thermodynamics.
Study of stability indices for prediction has been done also by [3, 4, 5, 6, 7]. Seven familiar stability indices (Buoyancy, K-index, Lifted index, Precipitable water, SWEAT-index, Total Totals, Wet-bulb zero) were computed from sounding data for each of 83 days of convection forecasting experiment conducted during summer of 1985 in northeast Colorado [3]. The instability indices compared against the observation of convectively driven weather events to examine their performance as predictors of severe weather (large hail, tornados, high wind) and significant convective weather (nonsevere but important from an economic or public safety standpoint). The SWEAT-index was the best predictor of severe weather and the Buoyancy was the best predictor of significant weather, as the main result of this study.

Another study titled “An evaluation of stability indices for thunderstorm prediction in Greater Cyprus” [4] investigates the effectiveness of a number of forecasting indices for non-frontal thunderstorm activity. The indices include the Humidity Index (HI), the Pickup Index (PI), the K-stability Index, the Yonetani Index in its original II and modified Iic form, and Showalter Stability Index (SSI) for Mediterranean area. This research focus on three months spring period of March, April, and May with data from two periods, 1970-1974 (340 days) and 1984-1988 (380 days). Data concerning this study were obtained as follows: upper data from Acrotiri for first period and Athalassa (near Nicosia) for second period, surface data and the time of beginning and end for each thunderstorm from the stations at Nicosia, St. Nicolas and Phapros, and synoptic data from the Greek Meteorological Service (EMY). One of the principal conclusions of this investigation is the original and modified Yonetani indices were more accurate than the HI, PI and K indices in the forecast of air mass thunderstorms.

An analysis of the conditional instability of the tropical atmosphere can be explored in [5]. This assessment were made possible by availability of a large soundings in tropical region, i.e. the Atlantic sounding were obtained from GATE (Global Atlantic Tropical Experiment) from June to September 1974, the soundings from South America were taken in ABLE (Amazon Boundary Layer Experiment) and the Australian sounding were obtained from AMEX (Australian Monsoon Experiment) in January and February of 1987 and subsequent studies in Darwin in 1988-1990 as part of DUNDEE (Down Under Doppler Electrical Experiment). Additional thermodynamics data were also available from the Line Islands Experiment over the central Pacific Ocean. This study has also made use of Doppler radar data on tropical convection collected with Massachusetts Institute of Technology’s transportable C-band radar during two wet season in Darwin, Australia. The energy realized according to parcel theory when conditional instability is released is CAPE. CAPE evaluated with three methods (pseudo adiabatic, reversible, reversible with ice). At all site examined, CAPE is well correlated with boundary-layer wet-bulb potential temperature ($\Theta_w$) with correlation of 0.8-0.9. CAPE increase for $\Theta_w$ larger than 23°C. This reference showed contribution of wet-bulb potential temperature as a thunderstorm predictor representing CAPE.

A comparison of traditional and newly developed thunderstorm indices for Switzerland using 5 years period (1985-1989) of data is presented in [6]. Thermodynamics and kinematic parameters (K, TT, SI, SLI, DCI, HI, BI, KO, SWEAT and CAPE) calculated from the radiosounding in Payerne (started at 0000 and 1200 UTC) were used to characterize the initiation of convection. The best parameters were evaluated by using three methods: skill scores, probability distribution, and mean temperature soundings and hodographs. The best traditional index to be used at 0000 UTC for a nonthundery or a thundery day is the original Showalter Index and at 1200 UTC it is the SWEAT-index. The most important parameters (stability, wind shear and relative humidity) are combined in new thunderstorm indices especially for Switzerland called SWISS-index. All of traditional and new indices were verified with independent data from 3 years (1990, 1992 and 1993), showing the best result for the new combined indices.

Research in [7] using Rawinsonde data for single location observation that can be used in estimating the probability of thunderstorm occurrence within 100 km from centre location (De Bilt, Netherland). The study using 32 thunderstorm predictors (4 versions of LI, 2 versions of SWISS, BOYD, 2 versions of ADED, KO, PI, 4 version of CAPE, SHOW, TT, 2 versions of YON, RACK, SI, THOM, 2 versions of TEI, BRAD, JEFF, VT, 2 versions of KI, CT, SWEAT, DCI). By using verification parameters such
as the True Skill Statistic (TSS) and the Tiedke Skill Score (Heidke) and NSS (Normalized Skill Score) and based on 10280 six-hourly observation, BOYD-index and LI can equally well be used to predict a thundery case ($\mu > 80\%$, $\mu$ = a new parameter, combination of TSS and Heidke). Relatively poor thunderstorm predictors are DCI, SWEAT and KI, ($\mu$ = 7%, 10% and 18%, respectively).

The research on stability indices in long time period can show a tendency, as [8] and [1] studies. The study on [8] used data from 1973 to 1997. The results show a trend towards increased convection activity in The Plains States (specifically from Texas to Kansas). In the West States there have been some changes in the extreme conditions index, but the index indicates an increase in atmospheric instability. Long-term observations are also shown in [1] for several observation locations in India using data from 1980 to 2016. The results show that IC has tended to decrease in some locations and increase in other locations.

Stability indices were calculated for several observation stations in the southwest Indian bay: Thiruvananthapuram and Cochin, using Radiosonde data for the five pre-monsoon seasons. The calculated indices are Showalter Index (SI), K Index (KI), Lifted Index (LI), Total Totals Index (TTI), Humidity Index (HI), Deep Convective Index (DCI) and thermodynamic parameters such as Convective Available Potential Energy (CAPE) and Convective Inhibition Energy (CINE). Comparison of results shows good suitability between Radiosonde data and MODIS satellites data. Other result, when there is convection activity, LI shows the value <4 and KI has a value from 35 to 40 [9].

The studies of indices stability as described above are important for both research and forecasting, for short period or long period. Due to the lack of the research as in the references for tropics area, especially for Indonesia, the study on this paper can fill the gap even through using very limited data. Detail of data is described later. Adopted from the previous studies, the indices stability obtained from Vaisala radiosonde which was launched in Kototabang was used in this study to describe the stability indices variations and to find the good indicators for rainy time in Kototabang at the tropical region. Kototabang is a Space and Atmosphere Observation Station located at Agam District, West Sumatera-Indonesia (0.20 S; 100.32 W). Kototabang is well known as Equatorial Atmosphere Radar (EAR) site.

2. Data and Method
2.1 Data
As mentioned earlier, the instability indices are evaluated from radiosonde data. Radiosonde was launched by research team in Kototabang (Figure 1), at least once day as seen in fourth column of Table 1. A radiosonde is an electronic device that is used to measure meteorological variables in the atmosphere, is lifted up to the upper atmosphere up to altitude of 20 to 40 km by a weather balloon filled with helium or hydrogen. Radiosonde retrieved the profiles of temperature, humidity, pressure, and wind. These atmospheric profile are used to determine the instability indices. The resolution time of the radiosonde data 10 minutes and the height resolution is 150 m. The period and detailed description of the instrument are shown in Table 1. Based on the rainfall data from Micro Rain Radar (MRR) and Automatic Weather Station (AWS) in Kototabang shown in Figure 2 to Figure 4, the data is classified into data in wet period and data in dry period.
Figure 1. Radiosonde is ready to be released (in Kototabang)

Table 1. Radiosonde data

| Date          | Launched at (LT)      |
|---------------|-----------------------|
| Wet period    |                       |
| August 2016   | 30 08:45, 11:31, 15:35|
|               | 31 07:27, 11:58, 19:01|
| September 2016| 01 07:08 10:55, 15:08|
|               | 02 07:22, 11:07, 18:55|
| Wet period    |                       |
| March 2018    | 5 09:59, 12:27        |
|               | 6 07:25, 11:41        |
|               | 7 08:26, 12:39        |
|               | 8 08:45               |
|               | 9 08:27, 11:49        |
| Dry period    |                       |
| April 2019    | 29 12:00              |
|               | 30 12:00              |
| May 2019      | 01 12:00              |
|               | 02 12:00              |

- Radiosonde: Vaisala RS41-SG, S/N: M2710588
- Weight of balloon: 200 gr
- Frequency: 400.15-406 MHz
- Gas: Hydrogen
- Location: Space and Atmosphere Observation Station Agam District (855.0 m above mean sea level; 0.20 S; 100.32 W)
Figure 2. Rainfall data derived by MRR for 2016

MRR and AWS are sources of rainfall data. MRR retrieves quantities rain rates, drop size distributions, radar reflectivity, fall velocity of hydro meteors and other rain parameters simultaneously on vertical profiles up to several kilometres above the radar. It operates in electromagnetic radiation at a frequency of 24 GHz. The radiation is transmitted vertically into the atmosphere where a small portion is scattered back to the antenna from raindrops or other forms of precipitation. The data resolution is 2 minutes. AWS is an automated version of traditional weather station, either to save human labour or to enable measurements from remote areas. Most AWS have thermometer for measuring temperature, anemometer for measuring wind speed, wind vane for measuring wind direction, hygrometer for measuring humidity and rain gauge for measuring rainfall. All the AWS parameters are measured only on the surface and the time resolution is 1 minute.

Figure 2 shows the rainfall measured by MRR in 2016. As shown in the figure, a heavy rainfall of more than 25 mm/hour occurred during the day on 30 August and 1 September 2016. Light rainfall (5 - 10 mm/hour) is recorded every day on period of 2016. In Figure 3, AWS records rainfall during the observation period in 2018, which is four days. Then, the observation period in 2016 and 2018 is marked as a wet period. In observation period of 2019, there was only one rainy day with very short rain (Figure 4), this period was marked as dry period.
2.2 Method

For the first sensitivity assessment, CV indices were compared to CV rainfall. Stability index which has close CV to rainfall CV is a good indicator for the rainfall.

Coefficient of variation (CV) is defined as the ratio of the standard deviation (σ) to the mean (μ). It shows the extent of variability in relation to the mean of the population.

\[
CV = \frac{\sigma}{\mu}
\]  

(1)
The second assessment was to compare rain event from AWS/MRR with the number of stability index. The stability indices compared was the stability index with time adjacent to the occurrence of rain. For example on 30 August 2016 it rained at 14:00 LT, then compared with the stability indices at 11:35 LT. When the rainfall events are in accordance with the unstable conditions indicated by the stability index, then the stability index is considered a good indicator and gets a score of 1. If the stability index shows a stable condition even though it rains then the stability index is a poor indicator and given a score of 0. This study only involved rainfall data without thunder or lightning data, unlike [4] and [7].

The stability indices studied are Convective Available Potential Energy (CAPE), Convective Inhibition (CINH), K-index, Ko-index, S-index, Showalter index (SI), Lifted index (LI), Total Totals (TT-index), the temperature, the pressure, and the height of the stability layers (Lifting condensation level/LCL, Level of free convection /LFC, Convective condensation level /CCL, and Equilibrium level /EL). More details about the indices are described on Appendices.

3. Result
3.1 Variability of stability indices
The temperature, pressure and height of the stability layer determined from radiosonde data are shown in Figures 5, 6 and 7. Pressure of LCL, LFC, and CCL fluctuating on small variation as shown on Figure 5. The differences between maximum value and minimum value of pressure of LCL, LFC and CCL are 133 mb, 212 mb and 186 mb, respectively, meanwhile pressure of EL has bigger difference (Figure 5). Maximum of EL-P is 821.32 mb while the minimum is 92.49 mb, the difference is 728.84 mb. On the Figure 6, temperature of EL more fluctuating than temperature of LCL, LFC and CCL. CCL-T has a lower variation compared to LFC-T, LCL-T and EL-T, with a difference of 8.87 K between maximum and minimum. The differences between maximum and minimum of the LCL, LFC and EL layers are 10.53 K, 13.22 K and 101.25 K, respectively.

One of the three data set used corresponded to dry period and two others corresponded to wet period. The pressure of the stability layer commonly smaller on dry period, meanwhile the temperature of the layers did not have a specific behavior against dry/wet period. The height of the stability level were higher on dry period (Figure 7). TT-index on dry period was higher than wet period. K-index and S-index on dry period were lower than wet period. CINH on dry period was higher (positive) than wet period. CAPE on dry period was less than wet period. LI and SI were negative on dry period. Ko-index did not have a specific behavior against dry/wet period. The indices are shown in Figure 8 and Figure 9.
Figure 5. Pressure of LCL, LFC, EL and CCL

Figure 6. Temperature of LCL, LFC, EL and CCL

Figure 7. Height of LCL, LFC, EL and CCL
SI shows both values, positive and negative. This means that the atmosphere was stable at one time and unstable at another time. The negative LI denoted unstable condition. The chances of a severe thunderstorm are best when the lifted index is less than or equal to -6. For this study, LI has small negative value on 30 August 2016 at 08:45 LT, 11:31 LT and 15:35 LT, on 31 August 2016 at 19:01 LT, on 1 September 2016 at 07:08 LT, at 10:55 LT, on 2 September 2016 at 07:22 LT, at 18:55 LT, on 5 March 2018 at 09:59 LT, at 12:27 LT, on 6 March 2018 at 07:25 LT, at 11:41 LT, on 9 March 2018 at 11:49, on 29 April 2019 to 2 May 2019 at 12:00 LT. Most likely a thunderstorm occurred on 2 September 2016 at 18:55 LT, on 6 March 2018 at 11:41 LT, 29 April 2019 and 30 April 2019 at 12:00 LT. Ko-index always showed unstable conditions with the high possibility of thunderstorms, except on 30 August 2016 at 08:45 LT, 31 August, 2016 at 19:01 LT and 2 September 2016 at 18:55 LT. Negative CINH is a sign for a stable condition or weak convection. CINH that related to stable condition were on 30 August, 2016 at 08:44 LT, on 31 August, 2016 at 19:01 LT, 1 September 2016 at 07:08 LT, on 2 September 2016 at 07:22 LT and on 7 March 2018 at 08:26 LT. CINH at other times indicates unstable conditions.
S-index and K-index has similar value. S-index and K-index generally indicated the highly possibility (more than 60%) of thunderstorm, except on 2 September 2016 at 07:22 LT and on 2 May 2019 at 12:00 LT. TT-index indicated the possibility of a thunderstorm on 31 August, 2016 at 19:01 LT, 1 September 2016 at 15:08 LT, 2 September 2016 at 18:55 LT, 6 March 2018 at 11:41 LT, 7 March 2018 at 08:26 LT, 8 March 2018 at 08:45 LT, on 29 April 2019 to 2 May, 2019 at 12:00 LT. Based on CAPE, the atmosphere was in stable to extreme instability.

For variability assessment, the following indices: S-index, K-index, TT-index, pressure and temperature of LCL, LFC and CCL, have small variations for three period of data used. Whereas CAPE, CINH, So-Index, SI, LI, EL-P, EL-T and LCL-Z, LFC-Z, CCL-Z and EL-Z, varies greatly.

### 3.2 Sensitivity assessment

By using equation (1), CV is obtained for rainfall and stability indices. The comparison of CV is shown in Table 2.

| CV of stability index | CV of rainfall |
|-----------------------|----------------|
| LCL-P                 | 0.0472         |
| LCL-Z                 | 0.2544         |
| LFC-P                 | 0.0608         |
| LFC-T                 | 0.0110         |
| LFC-Z                 | 0.2817         |
| CINH                  | (-) 2.1534     |
| TI                    | (-) 4.3703     |
| SI                    | 34.9400        |
| K-index               | 0.0918         |
| TT-index              | 0.0423         |
| S-index               | 0.0814         |
| Ko-index              | (-) 3.2940     |
| CCL-P                 | 0.0643         |
| CCL-T                 | 0.0087         |
| CCL-Z                 | 0.3070         |
| EL-P                  | 0.8820         |
| EL-T                  | 0.1839         |
| EL-Z                  | 0.5393         |
| CAPE                  | 0.9840         |

The CV of stability indices which closed to rainfall CV are CV for LCL-Z, LFC-Z, CINH, LI, SI, Ko-index, CCL-Z, EL-P, EL-T, EL-Z and CAPE. The other indices have too small variation that inappropriate with rainfall variation. Then, the indices can be treated as an indicator for convective disturbances/rainfall due to their sensitivity for the changes of rainfall are CAPE, Ko-Index, LI, SI, CINH, EL-T, EL-P, LCL-Z, LFC-Z, CCL-Z and EL-Z.

For the second assessment, the number of indices compared to the event of rainfall. The interpretation result showed on Table 3.
| Date       | Rain/ No rain | Time (LT)          | Stability Index                                                                                     | Interpretation of stability index                                                                 |
|------------|---------------|--------------------|-------------------------------------------------------------------------------------------------------|------------------------------------------------------------------------------------------------------|
| August 2016 | Rain          | 14:00 – 23:00 (disc.) | CINH~0, LI~ -1, SI<1, K-index>35, TT >42, S-index >38, Ko-index >83 (neg.), EL-Z >15km, CAPE>2200 | tend to be unstable, there is the potential for thunderstorm/rain                                    |
| 31         | Rain          | 16:30 -16:50       | CINH~0, LI~ 2, SI~ 2, K-index>32, TT >41.5, S-index >35, Ko-index >5228 (neg.), EL-Z >14km, CAPE>1300 | tend to be stable, there is no potential for rain, but the Ko-index indicates the potential for rain |
| September 2016 | Rain      | 05:30, 09:00, 11:30-14:30, 15:00, 16:00, 21:00 | CINH~0, LI~0,9, SI~ 0.2, K-index>34, TT >42, S-index >37, Ko-index >31 (neg.), EL-Z >16km, CAPE>4400 | tend to be unstable, there is the potential for thunderstorm/rain                                    |
| 02         | Rain          | 14:00, 18:30-20:00 | CINH~0, LI~0,6, SI~ 1, Ko-index>39, TT >31, S-index >35, Ko-index >459631 (neg.), EL-Z >15km, CAPE>3356 | tend to be unstable, there is the potential for thunderstorm/rain                                    |
| March 2018  | Rain          | 05:33, 11:21-11:37, 17:21,18:12, 19:17 | CINH~0, LI~0,2, SI~ 0.2, K-index>37, TT >42, S-index >39, Ko-index >38 (neg.), EL-Z >15km, CAPE>3124 | tend to be unstable, there is the potential for thunderstorm/rain                                    |
| 6          | No data       | -                  | CINH~0, LI~1.5, SI~1.7, K-index>36, TT >46, S-index >40, Ko-index >304 (neg.), EL-Z >16km, CAPE>5827 | tend to be unstable, there is the potential for thunderstorm/rain                                    |
| 7          | Rain          | Early morning (01:54-04:54 disc., 18:47-22:03 (disc.) | CINH~0, LI~0,2, SI~ 1.6, K-index>34, TT >43, S-index >37, Ko-index >77104 (neg.), EL-Z >16km, CAPE>6828 | tend to be unstable, there is the potential for thunderstorm/rain                                    |
| 8          | Rain          | 17:25 and 17:40    | CINH~0, LI~0,1, SI~ 0.2, K-index>32, TT >44, S-index >35, Ko-index >2179 (neg.), EL-Z >15km, CAPE>3003 | tend to be unstable, there is the potential for thunderstorm/rain                                    |
| 9          | Rain          | 10:51 – 11:13, 14:20, 15:41 | CINH~0, LI~0,6/0.2, SI~ 1.1/0.5, K-index>38/34, TT >42/43, S-index >36/40, Ko-index >304/19950 (neg.), EL-Z >15/3840 m, CAPE>2747/66 | tend to be unstable, there is the potential for thunderstorm/rain                                    |
| April 2019  | No rain       | -                  | CINH~0, LI~3.5 SI~3.8, K-index>36, TT >48, S-index >39, Ko-index >38 (neg.), EL-Z >3415m, CAPE>39 | tend to be stable, there is no potential for rain                                                    |
Pressure, temperature and height of the LCL, LFC and CCL individually do not show specific behaviour towards rainfall. But rain is always related to the smaller difference between LCL and LFC, but does not apply otherwise. Small differences between the LCL and LFC not always related to unstable condition/rain event.

Most of CAPE and CINH related with rainfall. CAPE and rainfall relationship were missed only once (31 August 2016). CINH misses three time. When atmosphere stable and no rain occurred, CINH expected to be negative more than (-) 15. LI misses at least twice (expected to be negative for unstable conditions/rainfall event). SI misses on 29 April 2019. TT-index always greater than 30 which means are always unstable, even when CAPE is small or there is no rain. S-index must be greater than 35 and must be paired with a high CAPE. Ko-index must be negative significantly but should be paired with a high CAPE. El-Z must be more than 14 km for unstable conditions which produce rain. Missed indices value is thought to originate from the launch time which is not in accordance with the rain cloud life time. Therefore, score of 1 obtained by CAPE, CINH, SI, and EL-Z while the others got a score of 0. CAPE, CINH, SI and EL-Z are more appropriate indices as rainfall indicator because of fewer errors and not depend on other index.

4. Conclusion
Three set of data created the three set of indices character. This result shows that the indices vary against time. The pressure and the temperature of three stability layers (LCL, LFC and CCL) have small variations. This means that temperature and pressure of LCL, LFC and CCL cannot imitate rainfall variation or the indices are not good indicator for rainfall. On the other hand, CAPE, Ko-Index, LI, SI, CINH, EL-Z, EL-P, LCL-Z, LFC-Z, CCL-Z and EL-Z have large fluctuation.

The qualitative analysis above corresponds to the results of the first assessment using coefficient of variation (CV). The good indicator for rainfall based on CV are CAPE, Ko-Index, LI, SI, CINH, EL-Z, EL-P, LCL-Z, LFC-Z, CCL-Z and EL-Z.

CAPE, CINH, SI and EL-Z derived a score of 1 with second assessment. This shows that CAPE, CINH, SI and EL-Z are good indicator for unstable condition accompanied by rainfall.

Combining the variability analysis and two quantitative assessment, CAPE, CINH, SI and EL-Z can be declared as the rainfall predictors of Kototabang.

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5. Appendices

Description of Stability Indices

Convective available potential energy (CAPE) sometimes, simply, available potential energy (APE), is the amount of energy a parcel of air would have if lifted a certain distance vertically through the atmosphere. CAPE is effectively the positive buoyancy of an air parcel and is an indicator of atmospheric instability, which makes it valuable in predicting severe weather [10].

\[
CAPE = \int_a^b g \left( \frac{T_{v,parsel} - T_{v,lingkungan}}{T_{v,lingkungan}} \right) dz
\]

**Table A.1** Classification for CAPE

| CAPE (J/kg)       | Instability      |
|-------------------|------------------|
| 0 < CAPE ≤ 1000   | weak instability |
| 1000 < CAPE ≤ 2500| moderate instability |
| 2500 < CAPE ≤ 4000| strong instability |
| 4000 < CAPE        | extreme instability |

Convective inhibition (CINH) represents the “negative” area on a sounding that must be overcome for storm initiation, the opposite of convective available potential energy (CAPE), which is expressed as B+ or simply B [11]. As with CAPE, CINH is usually expressed in J/kg but may also be expressed as m^2/s^2, as the values are equivalent. In fact, CIN is sometimes referred to as negative buoyant energy (NBE).

**Table A.2** Classification for CINH

| CINH (J/kg) | Thunderstorm Possibility |
|-------------|--------------------------|
| CINH ≤ 15   | Only minor cumuli develop |
| 15 < CINH ≤ 50 | single cell thunderstorms possible |
| 50 < CINH ≤ 200 | multi cell thunderstorms possible |
| 200 < CINH   | stability of stratification too high to overcome no thunderstorms develop |

K-index has proved useful in indicating the probability of air mass thunderstorms. As the K-index increases, so does the probability of having an air mass thunderstorm. The K-index is derived arithmetically, was introduced by [12] using following equation:

\[
K\text{-index} = (T_{850} - T_{500}) + T_{d,850} - (T_{700} - T_{d,700})
\]

- The temperature difference between 850 hPa (5,000 feet (1,500 m) above sea level) and 500 hPa (18,000 feet (5,500 m) above sea level) is used to parameterize the vertical temperature lapse rate,
- The 850 hPa dew point provides information on the moisture content of the lower atmosphere,
- The vertical extent of the moist layer is represented by the difference of the 700 hPa temperature (10,000 feet (3,000 m) above sea level) and 700 hPa dew point [12].

**Table A.3** K Index and thunderstorm probability [13]

| K-index | Thunderstorm Probability (%) |
|---------|------------------------------|
| <15     | near 0                       |
| 15-20   | 20                           |
| 21-25   | 20 to 40                     |
| 26-30   | 40 to 60                     |
**Showalter index (SI)** is a dimensionless number computed by taking the temperature at the 850 hPa level which is then taken dry adiabatically up to saturation, then up to the 500 hPa level, which is then subtracted by the observed 500 hPa level temperature. If the value is negative, then the lower portion of the atmosphere is unstable, with thunderstorms expected when the value is below \(-3\) \[14\]. The application of the Showalter index is especially helpful when there is a cool, shallow air mass below 850 hPa that conceals the potential convective lifting. However, the index will underestimate the potential convective lifting if there are cool layers that extend above 850 hPa and it does not consider diurnal radiative changes or moisture below 850 hPa \[11\]. The Showalter Index is the simplest measure of the local static stability of the atmosphere. Positive values indicate the lifted parcel is colder than its new environment, and thus the atmosphere is stable. Cumulonimbus generally fail if the Showalter Index is greater than 4 \[15\].

**Lifted index (LI)** is the temperature difference between the 500 mb temperature and the temperature of a parcel lifted to 500 mb. Negative values denote unstable conditions. LI is more of a measure of actual "instability" than CAPE because it represents the potential buoyancy of a parcel at a level, whereas CAPE is integrated through the depth of the troposphere. The LI is the sample sounding above is about \(-10\) C, lifting the "non-virtual" surface parcel. Lifted Index (LI) has proved useful for indicating the likelihood of severe thunderstorms. The chances of a severe thunderstorm are best when the lifted index is less than or equal to \(-6\). This is because air rising in these situations is much warmer than its surroundings and can accelerate rapidly and create tall, violent thunderstorms. Values less than \(-9\) reflect extreme instability. An LI of between 0 and 2 indicates that there is a small chance of having a severe thunderstorm. Air mass thunderstorms can occur when the LI is slightly positive. The lifted index (LI), usually expressed in kelvins, is the temperature difference between the temperature of the environment \(T_e\) and an air parcel lifted adiabatically \(T_p\) at a given pressure height in the troposphere, usually 500 hPa (mb). When the value is positive, the atmosphere (at the respective height) is stable and when the value is negative, the atmosphere is unstable. Thunderstorms are expected with values below \(-2\), and severe weather is anticipated with values below \(-6\) \[16, 17\].

**Total Totals (TT)** of greater than 48 indicates favourable conditions for development of severe thunderstorms, a value of 55 indicates favourable conditions for tornadoes. Notice that increasing the dew point at 850 mb or decreasing the temperature at 500 mb (temperatures at 500 mb are usually less than 0°C) makes the atmosphere more favourable for thunderstorm development. Dry air over warm moist air is unstable \[11\].

\[
TT = T_{850} - T_{500} + T_{d,850} - T_{500} = T_{850} + T_{d,850} - 2T_{500} \quad (A.3)
\]

The following three thresholds are usually applied:
- TT ≥ 44K thunderstorms possible
- TT ≥ 50K severe thunderstorms possible
- T ≥ 55K severe thunderstorms likely

**Ko-index** is the temperature after condensation of all water vapour without changing the pressure at one particular level. \[18\] describes the potential instability between lower and higher levels of the atmosphere. The air package gets all condensation energy and is moved afterwards to 1000 hPa. During stable situations \(\theta\) is increasing with height. For a potential unstable air mass we get a decrease. The formula indicates that negative values are related to a decrease of \(\theta\) between lower and middle altitudes. In the Ko-index the potential equivalent temperatures (\(\theta\)) at 1000, 850, 700 and 500 hPa are considered. The Ko-index is defined as:

| 31-35 | 60 to 80 |
|-------|---------|
| 36-40 | 80 to 90 |
| >40   | near 100 |
The following thresholds are being used:

- $K_0 > 5$: no thunderstorms possible
- $5 > K_0 > 2$: thunderstorms possible
- $2 \geq K_0$: severe thunderstorms possible

**S-Index** uses the same variables as K-index but in different proportions. SI is introduced by the German Military Geophysical Office [19]. It is defined as:

$$S-Index = \left[ \frac{(T_{850} - T_{500}) + (T_{d,850} - T_{500}) - (T_{700} - T_{d,700})}{\text{T}_{850}-\text{T}_{500}} \right] \begin{array}{c} 0 \quad \text{if} \quad T_{850} - T_{500} > 25 \\ 2 \quad \text{if} \quad 25 \geq T_{850} - T_{500} \geq 22 \\ 6 \quad \text{if} \quad 22 > T_{850} - T_{500} \end{array}$$

$LCL$ (Lifting condensation level) is the level at which a lifted parcel becomes saturated, and is a reasonable estimate of cloud base height when air parcels experienced forced ascent. The LCL is this example is for the lifted surface parcel [11].

$LFC$ (Level of free convection) is the level at which a lifted parcel begins a free acceleration upward to the equilibrium level. Preliminary research suggests that tornadoes become more likely with super cells when LFC heights are less than 2,000 m above ground level, and thunderstorms are more easily initiated and maintained when LFC heights are lower than about 3,000 m. The LFC is this example is for the lifted surface parcel. The smaller the difference between the LCL and LFC, the more likely deep convection becomes [11].

$EL$ (Equilibrium level) is the level at which a lifted parcel becomes cooler than the environmental temperature and is no longer buoyant (i.e., "unstable"). The EL is used primarily to estimate the height of a thunderstorm anvil. Note: the "virtual" and "non-virtual" lifted parcels both end up with the same EL. This happens because the virtual temperature converges to the actual temperature when temperatures are very cold (less than -20°C) and moisture effects become negligible [11]. Some stability indices definition adopted from [20].

6. References

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