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Review

Significance of the Lifted Index in Atmosphere

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ABSTRACT
This article is a literature review that congregates views, results and thresholds of the atmospheric Lifted index presented by a few researchers till date, which will stimulate further research. The Lifted Index is a useful tool to predict latent instability of the atmosphere, to predict severe local storms and thunderstorms and elicit light on the behavior and few processes occurring in the atmosphere. This review discusses the significance of the Lifted Index during instability (stable/unstable) of the atmosphere, thunderstorms, tornado outbreaks and also the future direction of work.

Key words: Lifted index, Thunderstorms, Convective system, Atmospheric instability, Atmospheric convection

INTRODUCTION

The atmosphere is air consisting of a mixture of gases that envelopes the planet Earth and make it available to breathe, saves us from the sun's extremely harmful heat and unsafe radiation. The atmosphere starts from the surface of the Earth and extends vertically to hundreds of kilometers. Since the Earth is spinning on its axis, revolving around the sun and possesses an oblate shape, the radiation received from the Sun is spatially and temporally non-uniform. That is, the equator receives more radiation than the poles. Such non-uniform radiation incidents on the earth make up the basis for differential heating, thereby producing many physical and chemical phenomena in the atmosphere. Some of the phenomena are the development of differential temperature and pressure differences in all directions. The incident radiation from the Sun on the Earth increases the temperature in the atmosphere, the air gets rarefied and it is lifted up. Poles receive less radiation and have low temperatures. As the temperature decreases, the air condenses and sinks. The disproportionate Sun's radiated energy passes through the atmosphere and heats the atmosphere causing different layers. They are Troposphere, Stratosphere, Mesosphere and Thermosphere. These different layers are separated based on a variation of temperature with altitude. The separation of layers was denoted with a pause. In order to study different processes like precipitation, thunderstorms, lightning etc., occurring in the troposphere, researchers formulated some atmospheric indices. One of these indices is the Lifted Index (LI). This review is an attempt to summarize the results and variations of this atmospheric index.

THE FORMATION, ROLE AND PURPOSE OF THE LIFTED INDEX

Many atmospheric phenomena like convection, precipitation, clouds, thunderstorms, tornadoes, winds, dynamic, thermodynamic and kinematic etc., occur in the lowest layer, (Troposphere). One has to look through the lower layer considering its importance and the factors that influence it. The variations occurring in this layer have been observed by many researchers using atmospheric instability indices (Galway 1956, Booth 1970, Fujita et al. 1970, Chakraborty et al. 2017, Fernando et al. 2021). One of the atmospheric indices, LI is useful in describing convection, thunderstorms and instability of the atmosphere. The LI can be used as the synoptic diagnosis of tornado outbreaks.

The initiation of indices started at the Severe Local Storms (SELS) Unit at the National Severe Storms Forecast Center (NSSFC). Several meteorological quantities have been derived to predict the instability of the atmosphere. Meteorologists developed a few atmospheric indices like the Showalter index (SI), LI, Total totals index (TTI) to predict thunderstorms (Showalter 1953, Galway 1956, Miller 1972). LI is an improvement to the SI developed by Galway (1956) regularly used for the analysis and to predict severe local storms, latent instability to give support to forecast severe thunderstorms over the United States. This method used temperature during the afternoon to consider and to justify maximum temperature during the afternoon and employed the lowest 3000 feet above the surface of the Earth to determine dry adiabatic lapse rate in order to formulate LI. Now this index is calculated as the difference between the environmental temperature at 500 hPa and the air parcel temperature at 500 hPa lifted from 3000 feet above the surface of the Earth. The procedure to calculate LI using a skew T-log P diagram is: First, locate the temperature and dew point on the surface in the diagram. Lift the parcel from the surface following adiabatic lapse rate and simultaneously lift the parcel from dew point from the surface following mixing ratio. When the parcel's temperature following adiabatic lapse rate intersects with the mixing ratio line, at this point the parcel saturates and this point is called lifted condensation level (LCL) which represents convective cloud base. From LCL the parcel is continued to lift following moist adiabatic lapse rate till the parcel reaches 500 hPa. At this 500 hPa pressure level, the air parcel temperature is noted. LI is calculated by subtracting air parcel temperature from the environmental temperature both at 500 hPa (equation 1). While raising the parcel from the surface, the dew point is accounted for hence; LI is insusceptible at different pressure levels within the planetary boundary layer. The calculation of LI is represented as

$$LI = [T\,(500\text{ hPa env}) - T\,(500\text{ hPa parcel})] \text{ in } (^{o}C) \quad \dots (1)$$

where T (500 hPa env) is the ambient temperature at 500 hPa and T (500 hPa parcel) is the temperature of an air parcel which is lifted to 500 hPa from the Earth's surface (https://www.weather.gov/lmk/indices) (Table 1).

Table 1. The threshold values of LI

Threshold values of LI (^{o}C)	Status of atmosphere
LI > 0	Stable but weak convection possible for LI =1-3 if strong lifting is present
0 to -3	Marginally unstable
-3 to -6	Moderately unstable
-6 to -9	Very unstable
below -9	Extremely unstable

These LI values are based on lifted parcels using the average lowest 50 to 100 hPa moisture and temperature values. In general, LI is calculated at different levels by taking the surface level at 850 hPa. It was mentioned surface base LI and the best LI for different situations in the atmosphere like stability during tornado outbreaks (https://www.weather.gov/lmk/indices). The limitation of LI is that it can be calculated if the data is available below 3,000 feet and at 500 hPa as noted by Fujita et al. (1970). They also noted the difficulty of gathering the mean potential temperature of the lowest 3,000 feet layer, the mean mixing ratio of the same layer, and the 500-hPa temperature data required for the LI computation. On realizing the difficulty in calculating the value of LI during severe storm development, another predictive parameter, namely, the best lifted index (BLI) was developed by collecting data on the tornado outbreak (Fujita et al. 1970).

LIFTED INDEX AND ITS IMPLICATIONS

LI measures, characterizes and predicts atmospheric stability. Now, we analyze the various studies signifying the use of LI based on different atmospheric phenomena.

Severe local storms

Severe local storms are extremely damaging. Tornadoes, severe storms with large hail, or damaging winds are examples of severe local storms. They usually move along narrow paths and affect a relatively small geographical area, causing loss of life and property (http://teachmefinance.com/

Scientific_Terms/Severe Local Storm.html). To ensure the safety of communities from severe local storms, it is important to predict, understand their patterns, monitor them, and understand the causes of these events. The latent instability of the atmosphere at noon can be estimated using morning LI data. LI can be used to predict latent instability of the atmosphere during afternoon hours (Galway, 1956). The growth of a convective system can be identified using LI prior to 3 to 4 hours (Umakanth et al. 2019). Therefore, with the help of LI, we can identify and predict severe weather events and severe local storms.

Using LI with humidity parameters

The refractivity-based lifted index (RLI) was used to detect the increase in atmospheric instability. This index was tested with the help of COSMIC radio occultation-derived refraction profiles over the Indian region. A comparison of the refraction-based lifted index (RLI) with the traditional temperature profile-based lifted index (LI) revealed that RLI is better reproducible than LI. Negative values of RLI have indicated increase in rainfall events and the possibility of heavy rainfall. Negative values of LI are not susceptible to rainfall events although the environment is sensitive to convection (Jagadheesha et al. 2011). When the LI data is analyzed with other parameters like the total precipitable water (TPW) and average relative humidity (ARH) then it will be useful for identifying the probability of occurrence of rainfall events. LI, TPW and ARH can also be potential parameters to measure the occurrence and intensity of rainfall which is shown in (Table 2) (Sharma et al. 2009).

During severe convective activity

LI was found to be the best indicator of convective activity; the threshold value is (LI $\leq$ +2) which indicates the occurrence of convective activity (Booth 1970). LI values in areas of high instability were -4 to -12 and deep convective clouds were formed in the unstable air (Schmetz et al. 2002).

During the development of tornadoes

Tornadoes usually develop on warm and humid days. During these days, as the temperature increases, thunderclouds keep forming. Inside these thunderstorm clouds, warm, humid air rises while cold air falls with rain or hail. Wind speed and its direction also change with height. Due to all these conditions, air currents inside the thunderclouds start rotating. Although the spinning currents start horizontally, they can turn vertically and drop down from the cloud becoming a tornado. Many factors such as wind shear, moisture content, temperature, and upward-moving air are important and useful for monitoring tornadoes. LI is one of the factors that meteorologists can consider when assessing the likelihood of the formation of the tornado. During heavy thunderstorm development and destructive tornado formation, LI values $\leq 0^{o}$C have been observed (Miller 1967, 1972, 1975) (Table 3).

On 13th January, 1972, at 0725Z, a destructive tornado struck the southeast corner of Alabama. It caused extensive damage and destroyed several helicopters. Tornado activity ceased for approximately 4.5 hrs and then resumed at 1215Z and continued for the remainder of the 13th and into the early morning hours of the 14th January. 20 tornadoes occurred during the period 13th January

Table 2. Probability of rainfall events (%) with different conditions of LI applied with TPW, ARH during May to August 2007 over India and the surrounding region (Sharma et al. 2009)

LI along with TPW, ARH	Rainfall	Intensity of rain rate < 2mm/hr	Intensity of rain rate > 2mm/hr
LI < -2	40	38.5	1.54
LI < -2, TPW > 40	42.9	41	1.9
LI <-2, TPW > 50	53	50.5	2.4
LI < -2, TPW > 40, ARH > 65	56.4	53.9	2.2
LI < -2, TPW > 40, ARH > 75	63.7	60.4	4
LI < -2, TPW > 40, ARH > 80	70	66.6	4.2
LI < -2, TPW > 40, ARH > 90	89.6	79.3	10

Table 3. LI values during severe local storm conditions in the atmosphere over some locations in the US (Miller 1967, 1972, 1975)

Severe weather situations	Years	Locations	LI (°C)
Heavy thunderstorm, tornadoes	3 Dec 1964	Shreveport	-6 (0000Z)
Severe thunderstorms, tornadoes,damaging wind storm	11 Feb 1965	San Antonio	-6 (1200Z)
Severe thunderstorms, tornadoes,damaging wind storm	11 Feb 1965	Shreveport	0 (1200Z)
4 strong, 7 moderate, 2 weak tornadoes	8 Jun 1966	Topeka, Kansas	0 (1200Z)
12 strong, 3 moderate, none weak tornadoes	9 Jun 1966	Topeka, Kansas	-6 (0000Z)
Destructive Tornado	21 Feb 1971	Northeastern Louisiana, Mississippi	-5 (1200Z)
Severe thunderstormsand destructive tornado	22 Feb 1971	Northeastern Louisiana, Mississippi	-7 (0000Z)
Destructive tornado	13 Jan 1972	Alabama	-5 (1200Z)
Destructive tornado	13 Jan 1972	Alabama	-5 (0000Z)

1200Z to 14th Januray 1125Z. LI values of -5°C were observed at 0000Z and 1200Z (Miller 1975). LI can identify destructive tornadoes.

LI values are more negative during tornado development. During the development of heavy thunderstorms and tornadoes in Shreveport on 3rd December 1964, Miller observed that when the air mass was critically unstable, the LI value was (-6°C). In the well-known Miller forecasting scheme, the LI value (-2°C) was used as an upper bound for severe storm formation (Miller 1967, 1972, 1975), whereas, from 1966 to 1969 over two-thirds of the United States, the predicted value of LI for severe storms and tornadoes was found to be ≤ 0°C (David and Smith 1971). Model-output lifted index values of ≤ +2 were used as a guideline to guide thunderstorm forecasts in the Gulf Stream region (Ellrod and Field 1984). The LI is also useful to identify synoptic tornado outbreaks. A tornado outbreak is the occurrence of multiple tornadoes spawned by the same synoptic scale weather system. During the tornado outbreak, the LI changed from 0 to -6°C over the affected area. In one of the outbreaks which produced 55 tornadoes characterized by rapidly deepening surface low-pressure area, upper-level diffluence between the sub-tropical and polar jets, mid-level polar jets had an isotach maximum exceeding 46 m/s and surge of surface dew points greater than 15°C, resulting in the LI ranging from -4 to -10°C over a broad area (Ferguson et al. 1983, 1985).

During severe thunderstorms

LI is very helpful in understanding cloud-to-ground lighting, precipitation, storms, lighting, flash rate density and lighting patterns. In the case of the relationship between precipitation and cloud-to-ground lighting for the months of April to October for the duration of 1989 to 1993 over six regions in the south-central United States, it is observed that the monthly pattern of LI in April (LI: 1 to 7°C) and lower negative LI values in July (LI: -7 to -1°C). It has been also observed that statistically significant differences in LI values for different categorized days based on the higher ratio of precipitation to the cloud to ground lighting and also revealed higher LI for greater atmospheric stability and unstable atmosphere on low ratio days (Sheridan et al. 1997). LI is the best tool to identify the development of thunderclouds producing lighting which is transformed from the convective cloud (Tinmaker et al. 2007). The flash rate density (FRD) and LI parameters are useful for understanding thunderstorm development and convective activity in the atmosphere. The FRD has been compared with LI from 1995 to 2014 over Andhra Pradesh, India. It was observed that the correlation coefficient between LI and FRD is (-0.72). It also revealed that there is a higher probability of extreme lightning when LI values are lower (Umakanth et al. 2020). The distribution of LI values corresponding to lightning strikes is normally distributed. LI is a good index to forecast the events of thunderstorms over Sri Lanka during the monsoon periods. It has been observed that negative LI values (-6°C) during the conditions of monsoon occurring in the months of October and November in the Sri Lanka region for three consecutive years from 2015 to 2017. In this region, thunderstorm events were mostly observed during the hours of 9 to 13 UTC (Fernando et al. 2021). The rate of likelihood of thunderstorm occurrence in the pre-monsoon season over northwest India and identified values of LI are less than 0°C (Dhawan et al. 2008). In one of the studies on thunderstorms, the characteristic variation in frequently occurring thunderstorms over Kolkata, India is scrutinized during pre-monsoon and monsoon precipitation quantity for the period 1997 to 2008 and revealed an increase in the LI (Saha et al. 2014). Using the thresholds of LI has a better probability of detection for thunderstorms. Threshold values of LI are also useful to distinguish thunderstorms and ordinary precipitation clouds. More negative values of LI indicate most of the thunderstorms and strong instability (Li < -9°C), moderate instability (-3 to -6°C) and marginal instability (-3 < Li < 0°C) (Markova and Mitzeva 2012, 2013). LI is useful for classifying and identifying stratiform or ordinary precipitation in different seasons (Monsoon, Pre-monsoon) and different geographical regions (seaside, coastal and inland regions). Radiosonde and precipitation data were used to classify stratified and convective precipitation events based on stability indices over Eastern Spain (Ituríoz et al. 2007). It revealed the annual distribution of precipitation is in agreement with the instability criteria of surface-based LI. LI having a negative value indicates the likelihood of convection. More convective events occurred in August, September and October. The probability of occurrence of convection is more at the seaside than in inland regions. For the most part, the rainfall is convective during summer, while rainfall during winter is generally stratiform.

Rainfall, seasonal rainfall and trend

Analysis of the relationship between LI and seasonal rainfall is valuable in understanding and predicting the climate patterns of any region. It is also very important to assess changes in atmospheric instability over time. LI trend analysis provides a lot of information to meteorologists and weather forecasters. Some applications related to LI trend analysis and the relationship of LI with seasonal precipitation are presented below.

The thermodynamic structure of the atmosphere over the tropical regions is mainly due to convection which is frequently connected with the formation of clouds and rainfall. Diurnal variation of atmospheric stability indices was observed from 17 to 19 August 2011 in the Indian tropical region, Gadanki (13.5°N, 79.2°E) using radiosonde and microwave radiometer data. LI values ranging from -4 to -8°C are observed which indicates that convective activity is high and thunderstorms are likely. The variation of stability indices reported strong diurnal variation in LI with the maximum in the local time afternoon hours of 1400 to 1700 hrs. LI showed best-estimated areas of instability in the afternoon that was associated with storm activity (Ratnam et al. 2013). Diurnal variation of LI was also observed during different seasons from October 2010 to October 2011 using radiosondes in every month except November 2010. LI varies between -3 to -5°C indicating dominant convective movement and there are chances of thunderstorms in the pre-monsoon but lower values of LI during the monsoon in contrast to the pre-monsoon periods and also noticed low thunderstorm activity when the monsoon is well-established range. This study also shows that LI values are positive during the winter season (Ratnam et al. 2013). LI is useful in indicating the probability of convective systems causing rainfall during the pre-monsoon season. LI as low as 0°C is sufficient to produce severe weather. LI for the Chandigarh region indicated a moderate probability of occurrence of a severe convective system, while for the Ladakh region, it indicated no probability of occurrence of any convective system (Koutavarapu et al. 2022). In the pre-monsoon (March, April, May) season, more negative LI values were observed during the month of May compared to April. The pre-monsoon season has LI values (-6 to -2°C) on rainy days and LI values (-4 to 7°C) on non-rainy days (Umakanth et al. 2022). LI acts as an indicator and helps in identifying the state of the atmosphere in a region for different seasons and different months and determining the nature of rainfall (Mwinuka et al. 2021). During the Jan, Feb, Mar (JFM) and Feb, Mar, Apr (FMA) seasons, the average LI value was below 0°C in all local climate zones of Tanzania and the atmosphere was more convective. The atmosphere was moderately unstable during JFM and FMA but was weakly unstable during Mar, Apr, May (MAM) and Oct, Nov, Dec (OND) seasons. LI values between 0 and -3°C show that the atmosphere is marginally unstable during the JFM.

LI fluctuates due to convection fluctuations in the atmosphere and other atmospheric effects. Long-term trends of LI have been studied in several regions of India using IGRA data from 1980 to 2016. A decreasing trend in LI is observed in some inland areas and an increasing trend is observed in some coastal areas. Minimum values of LI (-8°C) were observed at certain places in India (Rahiman et al. 2017). Changing trends in LI over Indian regions were examined using radiosonde LI data for the period 2000 to 2015. An increasing trend in LI is observed in the Indian eastern coastal regions (Kolkata, Visakhapatnam and Chennai), but no change in LI trends is observed in the western coastal regions (Ahmedabad, Thiruvananthapuram and Mumbai). In these 16 years, it was observed LI has increased from 3 kelvin to 6 kelvin which expresses a decrease in convection over Kolkata and Ahmadabad (Chakraborty et al. 2017). Annual spatial distribution of LI decrease approximately 0.5% of LI per year with more convection at the curved Himalayan range towards the northwest of India, whereas over the South China Sea, it increases approximately 0.3% of LI per year with a decrease in lightning flash rate. LI has identified enhanced convective instability during the pre-monsoon season over the eastern coastal areas of India and the Bay of Bengal, demonstrating spatial distribution. Negative LI values of approximately -4°C were observed over the ocean surface during the monsoon season, but positive LI values of approximately 4°C were observed over inland surface Indian regions. After monsoons and during the winter season, there are positive LI values. However, a different situation occurred in the Tibetan Plateau during winter, indicating LI values around -2 to -3°C, pointing to the development of disturbed weather (Saha et al. 2017).

Atmospheric oscillation and stability indices

Regular atmospheric oscillations occur every year in the form of convection and precipitation. Atmospheric oscillations are caused by changes in atmospheric parameters such as pressure, temperature, wind patterns, and moisture content that alter convection and precipitation patterns in different locations over time. Atmospheric oscillation can be observed through some atmospheric indices. Semiannual and annual oscillations in the atmosphere have been observed through the LI at six different Indian stations using IGRA data for the period 1996 to 2016 (Parveen et al. 2022). They have identified varying amplitudes in annual and semiannual with the values of 6.041°C and 3.643°C, respectively, over the Indian station Kolkata. They also revealed these amplitude values are more in comparison with other Indian stations. They have noted a low value of 2.403°C in annual oscillations over the Indian station Chennai and low value of 1.342°C in semiannual oscillations over the Indian station Bengaluru. They have also revealed more amount of convection and precipitation yields over the Indian coastal station Kolkata because the maximum and minimum values of LI have large variations when compared with other Indian stations. With the help of semi-annual and annual oscillations in LI, we can understand, observe and identify convection and precipitation patterns. Based on the analysis of amplitude variation of LI, we can better predict climate and it can be useful for meteorologists.

Estimation of LI using NWP

Predicting the weather for the next few days is known as weather forecasting. Numerical methods are used for weather prediction. Numerical Weather Prediction is a method developed for weather prediction. In the context of LI, NWP models can also be used to predict LI. Lestari and Wandala (2018) estimated LI at 20 places over Indonesia using two numerical weather prediction models, Weather Research Forecasting (WRF) and Global Forecasting System (GFS) and assured the outcomes with LI observation from radiosonde from 12th March, to 16th

April, 2017. The performance of the WRF model is better than that of the GFS model. The estimated LI of the WRF model can provide good performance for thunderstorm forecasting in Indonesia in the future. The estimated LI of the WRF model can provide good performance for thunderstorm forecasting in different regions in the future. We need to observe the WRF model to check the performance of this model in different seasons and different locations.

FUTURE ASPECT

- Urbanization is increasing over time and causes climate change. LI may be influenced by urbanization so checking the changes in the values of LI in the urbanized areas is important to understand interactions between them for accurate weather prediction in urban areas.
- The value of LI can be affected by the local topography of any place (water bodies, built-up areas, land use land cover, vegetation, villages, urbanization areas and industrial sites). The relationship of LI with local topography is important and a research gap for monitoring and understanding climate patterns at any location.
- LI is useful for meteorologists and researchers in understanding weather patterns and dynamic convective systems. Aviation meteorologists can use LI with other humidity parameters (Td, PW, RH) for aviation safety and weather forecasting.
- The relationship between changes in atmospheric instability indices (SI, LI, KI, TTI, SWEAT, CIN, CAPE, BRN, etc.) and air pollutant concentrations (SO_2, NO_2, CO, O_3, etc.) for different seasons and different regions could be studied in details. Long-term trends of atmospheric instability indices and air pollutant concentration variations are very important and useful for understanding climate patterns and controlling air pollution.

CONCLUSIONS

LI has been used as a forecasting tool to predict various atmospheric phenomena (severe storms, precipitation, tornadoes, severe local storms, atmospheric oscillations, atmospheric instability, understanding the probability of storms, severity of storms, and forecasting) at many locations, for many different periods. LI has shown efficiency in detecting or predicting the above-mentioned atmospheric phenomena. LI helps forecasters and meteorologists understand the likelihood of convective activity. Even though sophisticated technology is swirling around this planet, unfortunately, we are unable to detect the cataclysm of atmospheric events. It is noted that LI can be computed when the data below 3000 feet and at 500 hPa is available. Another difficulty in the computation of LI would arise due to diurnal variations of the air temperature for the complete 24 hours and also due to the mixing ratio in its vertical distribution. These factors constraints the thermodynamical characteristics at the time of storm formation. They also noted the practical difficulty in predicting mean potential temperature, mixing ratio and temperature at 500 hPa which are used to perform LI computation.

It was difficult to find the correct reason for failures to locate the problem concerning atmospheric events, now we possess the best indicator of convective activity, LI, useful to predict atmospheric phenomena prior to a few hours of calamity or atmospheric catastrophic events. Few abilities of LI are, it has a lot of potential in predicting latent instability during all hours, formation of deep convective clouds, provides the best and much more realistic results to classify and account for low-level moisture, development of summer thunderstorms and ordinary precipitating clouds, gives us a clear indication of the development of convective system and recognizes the status of the atmosphere before 3 to 4 hours and to determine the nature of rain. Having this vast treasure of qualities of LI, there is still a room to search for this index during atmospheric events using sophisticated technology and further studies are needed in this direction to further cement the place of LI.

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Conflict of Interest: Authors declare that they have no conflict of interest.

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