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A comparison of stability indices and precipitable water derived from radiosonde data collected at two nearby locations and weather radar data in Brazil

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ABSTRACT

Vertical profiles of environmental and dew point temperature, atmospheric stability indices, and precipitable water (PW) derived from sounding data were analyzed for two radiosonde launch sites located 85 km apart in the State of São Paulo, Brazil. The objective of this study was to determine whether there is a correlation between radiosonde profiles and, particularly, whether the values of commonly used stability indices (K, TT, LI, SWEAT, CIN, and CAPE) and precipitable water (PW) determined for each location were similar. In addition, weather radar data were evaluated to determine the level of correlation between precipitation over the radiosonde launch sites and stability indices. Despite the small distance between the two sites, significant differences were found when these indices and PW were compared. Some of these differences can be explained by the fact that one launch site was located in a large metropolitan area and the other in a smaller city. The comparison of stability indices and PW with precipitation estimates from a weather radar suggested that there is a trend towards a correlation between these parameters. The results suggest that the extrapolation of upper-air sounding data, even at relatively small distance scales, may not always be appropriate.

Keywords: Radiosonde; Atmospheric stability; Stability indices; Weather radar; Precipitation.

Introduction

Over continental and oceanic regions, the formation of precipitation depends on several factors, such as the amount of water vapor in the atmosphere, the availability of cloud condensation nuclei, and occurrence of vertical motions that may lead to the condensation of the water vapor. There are also other conditions in the troposphere that promote the condensation and formation of precipitation. These conditions are related to the concept of atmospheric stability. Atmospheric stability is a measure of how the atmosphere can intensify or prevent the formation of vertical turbulent motions. Generally, when air parcels are considered, the stability of an air parcel is

determined with respect to its surrounding environment taking into account the difference in temperature between the surrounding air and the air parcel or, in other words, whether the environmental lapse rate is greater (instability condition) or smaller (stability condition) than the parcel's lapse rate.

The stability of the atmosphere can be probed using data collected by balloon-borne radiosondes. During its flight, the radiosonde records the vertical profiles of the thermodynamic state of the atmosphere (altitude, pressure, temperature and relative humidity) and the wind direction and speed. Stability indices for the atmosphere can be derived from the vertical

profile measurements. Essentially, the stability indices indicate the ability of air parcels to rise in the atmosphere and are calculated using the differences in temperature between an air parcel and surrounding environment, a comparison between the air temperature at ground level and at higher altitudes, the moisture content of the atmosphere, and wind shear. Several stability indices have been created since the 1950s (see Palarz & Celiński-Mysław, 2017 for a list of the most commonly used stability indices) and new indices are still being developed (Ramseyer et al., 2019; Shastri & Pathak, 2019). The analysis of these indices allows the researcher to determine, for example, the possibility of occurrence of localized storms or severe weather hazards (da Silva et al., 2017). More recently, the profiles collected by radiosondes have also become an important source of data for climate and numerical forecast models because they provide valuable information on the thermodynamic state of the atmosphere up to an altitude of 30 km (Li et al., 2018).

The number of radiosondes launched and upper-air stations is limited by the cost of this type of operation. Worldwide, there are 800-900 upper-air stations that launch radiosondes twice a day (Ferreira et al., 2019). Based on the number of upper-air stations worldwide and frequency of launches, one may estimate that more than 500,000 radiosondes are launched every year. In Brazil, there are about 40 upper-air stations that regularly launch radiosondes; 20 of these stations share data with international meteorological organizations (Moura & Fortes, 2106; BADC, 2019; UW, 2019). The relatively small number of upper-air stations means that the average distance between these stations in Brazil (a country with continental dimensions) for which radiosonde data is readily available is larger than 600 km. Owing to the large distances between upper-air stations, the data collected by radiosondes may not represent correctly the actual conditions of the atmosphere over such large areas. This may have implications on the way the valuable data collected by radiosondes are used and interpreted. As mentioned previously, radiosonde data are fed to meteorological and climate models, thus it would be desirable that a large number of upper-air stations were in operation to better sample the vertical structure of the atmosphere. The data

collected by radiosondes are also used by the civilian and military aviation, as stability indices and vertical profiles can indicate the level of turbulence of the atmosphere (Ko et al., 2019). For this reason, many upper-air stations are located in or near airports in major metropolitan areas. This may affect the data collected by radiosondes because of environmental effects (Yang et al., 2016). Although radiosonde soundings are an important resource for the academic and commercial community, the use of the obtained data may be limited by the number of upper-air stations available and their location.

In this study, the authors hypothesized that there would be differences in the results obtained from radiosondes launched from different sites, even when the distance between sites is relatively small, possibly due to the heat-island effect and local weather patterns, which may significantly alter the vertical data profile collected by radiosondes.

Thus, the aim of this study was to determine how the data collected by radiosondes launched from two different locations compare in terms of commonly used stability indices (K, TT, LI, SWEAT, CIN, and CAPE), and precipitable water (PW).

Materials and Methods

Two radiosonde data sets were used in this study. One data set was collected by radiosondes launched from an upper-air station located in São Paulo; the other data set was collected during a brief campaign of radiosonde launches from the city of São José dos Campos, located 85 km away from São Paulo. Vertical temperature profiles as well as the values of the stability indices K, Total Totals (TT), Lifted Index (LI), Severe Weather Threat index (SWEAT), Convective Inhibition (CIN), Convective Available Potential Energy (CAPE), and Precipitable Water (PW) were determined for each sounding at each location. Additionally, weather radar data were used to determine the amount of precipitation over the radiosonde launch sites. The precipitation estimated using radar data was also compared with the stability indices.

The locations of the two radiosonde launch sites are shown in Figure 1.

Figure 1. Location of the radiosonde launch sites CPM and SJC and the weather radar, RDR, SP, Brazil.

The upper-air station CPM is located in an airport in the city of São Paulo (Campo de Marte, 23.5114° S, 46.6380° W; altitude, 772 m). From CPM, two radiosondes are launched daily at 0000 UTC and 1200 UTC. Fourteen radiosondes were launched at 1200 UTC from the site SJC located in the campus of the Aerospace Technology and Science Department in São José dos Campos (23.2126° S, 45.8668° W; altitude, 660 m). At the SJC, radiosondes were launched from November 17, 2014 to November 21, 2014, November 24, 2014 to November 28, 2014, and December 2, 2014 to December 5, 2014. Vaisala Model RS92 radiosondes (Vaisala, Vantaa, Finland) operating at 400 MHz were launched from both CPM and SJC. This radiosonde model collects data of atmospheric pressure, air temperature, relative humidity, and wind speed and direction (Sun et al., 2019). Hydrogen-filled neoprene balloons with an ascension rate of about 300 m.min⁻¹ carried the radiosondes.

Precipitation estimates were obtained from radar reflectivity data collected by an S-band (2.4 GHz) Doppler weather radar located 50 km and 130 km from CPM and SJC, respectively (radar position, 23.6006° S, 47.0970° W; altitude, 1100 m; see Figure 1). The range of the radar is 250 km. In this study, Constant Altitude Plan Position Indicator (CAPPI)

data at 3000 m generated every 6 minutes were used to calculate accumulated rain over 8-h periods. The resolution of the radar data is 1000 m (pixel size in the radar images). The quality of the data collected by this radar has been verified (Alves et al., 2015) and calibrated using a network of rain gauges (unpublished results). The radar reflectivity data were converted into precipitation rates using the following equation (Dhiram & Wang, 2016):

$$Z = 198 R^{1.57}, \quad (1)$$

where Z is the reflectivity measured by the radar and R is the precipitation rate (mm.h⁻¹).

The stability indices K, LI, TT, SWEAT, CAPE and CIN, and PW were calculated from the vertical profiles of temperature, pressure, and relative humidity collected by the radiosondes (Dong et al., 2018; do Carmo et al., 2019; Guerova et al., 2019; Ajilesh et al., 2020). In the following formulas, the notation used is: T = environmental temperature, TD = dew point temperature, TP = temperature of the parcel, θ = virtual temperature of the environment, θ_p = virtual temperature of the parcel, f = wind speed, w = direction of the wind, and g = acceleration of gravity.

The K index is a predictor for the formation of thunderstorms and heavy rain. Its calculation is based on the vertical gradients of the environment and dew point temperatures between 850 hPa and 500 hPa:

$$K = T850 - T500 + TD850 - (T700 - Td700) \quad (2)$$

K values range from $K = 0$ °C (stable atmosphere) to $K > 40$ °C (storms are likely to occur).

LI is a predictor of latent instability and was developed to aid the forecasting of storms. It is a measure of the stability of the atmosphere between the surface and 500 hPa. The LI value is calculated by the difference in the temperatures of an air parcel dry-adiabatically lifted to its Lifted Condensation Level (LCL) and wet-adiabatically to 500 hPa :

$$LI = T500 - TP500 \quad (3)$$

LI values range from $LI = 0$ °C (stable atmosphere) to $LI < -6$ °C (severe storms are likely to occur).

The TT index is a combination of two components, Cross Totals and Vertical Totals, and is given by:

$$TT = T850 + TD850 - 2T500 \quad (4)$$

TT is used to determine the local potential for thunderstorms development and storm strength. TT ranges from $TT < 44$ °C (stable atmosphere) to $TT > 56$ °C (scattered severe storms).

Differently from the previous indices, the SWEAT combines the TT index, and thermodynamic and kinematics variables to determine the probability of occurrence of severe storms. It is given by:

$$SWEAT = 12TD850 + 20(TT - 49) + 2f850 + f500 + 125(\sin(w500 - w850) + 0.2) \quad (5)$$

Note that SWEAT incorporates the effects of wind shear between the 500 and 850 hPa levels. In Equation (5), the first term is set to zero if the dew point temperature at 850 hPa is negative; the second term is set to zero if $TT > 49$ °C. $SWEAT < 150$ indicates a stable atmosphere, whereas $SWEAT > 300$ indicates that the occurrence of severe weather is possible.

The CAPE index is the amount of buoyant energy that is available for convection, indicating how fast an air parcel can move vertically. It is calculated using:

$$CAPE = g \int_{LFC}^{z_{max}} \frac{T_p - T}{T} dz, \quad (6)$$

where z_{max} is the height at which the temperature of the rising air parcel is the same as the environment and LFC is the level of free convection. For $0 \leq CAPE \leq 1000$ J.kg⁻¹ the atmosphere is stable or marginally unstable; for $CAPE > 3500$ J.kg⁻¹, the atmosphere is extremely unstable.

The CIN index is the energy required to lift an air parcel to its LFC or, in other words, the energy required to initiate convection. CIN measures the unlikelihood of storm development. It is calculated using:

$$CIN = g \int_{z_{ML}}^{LFC} \frac{\theta_p - \theta}{\theta} dz, \quad (7)$$

where z_{ML} is the mixed layer depth. For $CIN < 50$ J.kg⁻¹ minor cumuli can develop, for $200 < CIN < 500$ J.kg⁻¹, storms can develop, and for $CIN > 2000$ J.kg⁻¹, the formation of storms is inhibited because of atmospheric stratification.

The precipitable water (PW) was also determined for each sounding. PW is a measure of the total amount of water vapor in the atmosphere in the vertical direction, between the Earth's surface and the top of the atmosphere (or any two chosen levels). The global PW average measured over long periods is 40 mm/m² or higher in the tropics and as low as 10 mm/m² in polar regions (Zang et al., 2018). The PW is calculated using:

$$PW = \frac{1}{g} \int_{z_0}^{z_{top}} M_r dz, \quad (8)$$

where M_r is the mixing ratio and z_0 and z_{top} are the height of the atmospheric layers.

The Spearman's correlation coefficient (ρ) was used to determine if the sets of stability indices and PW values collected at CPM and SJC were significantly correlated to each other. The statistical package R (R Core Team, 2019) was used for data analysis. The statistical tests were performed at a significance level α of 0.05 ($p \leq 0.05$).

Results and Discussion

The skew-T log-P diagrams (Nychka et al., 2014; Czernecki, et al. 2020) for a total of 24

soundings (12 for CMP and 12 for SJC) were constructed with the vertical profiles of temperature, pressure, and relative humidity (see Figures 2 to 4).

Figure 2. Skew-T log-P diagrams collected at the CPM (red lines) and SJC (black lines) launch sites from November 17 to November 21, 2014. Environmental temperature is shown using solid lines and the dew point temperature is represented with dashed lines.

Of the 14 radiosondes launched from SJC, two failed to transmit data. Note that two radiosondes, launched on 17 November 2014 and 19 November 2014, ceased transmitting data at the pressure levels of 280 hPa and 160 hPa, respectively (Figure 2). In the present analysis, this is not an issue because the stability indices are calculated using measurements obtained below these pressure levels and, essentially, all of the precipitable water in the atmosphere is also concentrated below these pressure levels, as 50% or more of the atmospheric water vapor is found below 850 hPa and more than 90% is found below 500 hPa pressure levels (Makama et al., 2018).

Minimal data smoothing was carried out for better visualization of temperature profiles.

The visual comparison of the skew-T log-P diagrams shows that there was a general agreement between the vertical profiles of both the environmental and dew point temperatures when the data collected at CPM and SJC were compared, indicating that the sensors in the radiosondes performed satisfactorily during most of the flights. The soundings collected on November 17, 2014 exhibited rapid cooling below 750 hPa, at both sites, indicating that there was a layer of dry air at this level over CPM and SJC.

Figure 3. Skew-T log-P diagrams collected at the CPM (red lines) and SJC (black lines) launch sites from November 24 to November 28, 2014. Environmental temperature is shown using solid lines and the dew point temperature is represented with dashed lines. The date of the radiosonde flight is on the top of the respective diagram.

On November 24, 2014, a rapid cooling was observed above 530 hPa in the CPM data. A dry layer was also observed in the SJC data above this level, but the cooling rate is lower than that

observed in the CPM data, suggesting that the relative humidity sensor of the radiosonde launched from CPM was possibly wet during part of the flight.

Figure 4. Skew-T log-P diagrams collected at the CPM (red lines) and SJC (black lines) launch sites from December 2 to December 5, 2014. Environmental temperature is shown as solid lines and the dew point temperature is represented with dashed lines. The date of the radiosonde flight is on the top of the respective diagram.

Relative humidity sensors may display erroneous data (unrealistic rapid cooling) after the radiosonde passes through clouds and the sensor becomes wet (NOAA, 2016; Babić et al., 2019).

This effect does not seem to be present in the other vertical profiles. Overall, there is a good agreement of the typical features observed in the Skew-T log-P diagrams such as inversion layers,

dry air layers, cloud layers, and the tropopause height.

The values of the K, TT, LI, SWEAT, CAPE, and CI indices and PW for the soundings at CPM and SJC, calculated using Equations (2) to (8), are listed in Table 1. The Spearman's correlation coefficients and average values of the

indices and PW are also listed in this table. CAPE and CIN indices were omitted from the analyses due to the large number of zero values.

The comparisons of all indices and PW between both launch sites are shown in Figures 5 and 6.

Table 1. Values of the stability indices and precipitable water (PW) collected at the CPM and SJC launch sites, average values during the period, and Spearman's correlation coefficient.

Sounding date	K (°C)		TT (°C)		LI (°C)		SWEAT		CAPE (J.kg ⁻¹)		CIN (J.kg ⁻¹)		PW (mm.m ⁻²)	
	CPM	SJC	CPM	SJC	CPM	SJC	CPM	SJC	CPM	SJC	CPM	SJC	CPM	SJC
17/11	-18	-13	38	40	6.8	4.1	215	298	0	0	0	0	11.9	15.7
19/11	23	20	38	37	5.5	5.2	233	49	0	0	0	0	21.6	21.6
20/11	28	30	39	41	4.2	4.2	172	141	0	0	0	0	27.4	29.0
21/11	35	32	45	43	1.3	2.5	174	148	0	0	0	0	35.6	34.8
24/11	32	36	43	43	0.6	0.1	279	238	13	218	-9	0	37.6	41.7
26/11	31	33	39	41	1.8	0.7	301	228	72	142	-39	-15	44.5	47.2
27/11	30	33	41	42	1.8	1.0	329	268	0	0	0	-6	31.8	40.1
28/11	20	28	38	40	4.8	2.7	MD	289	0	0	0	-4	25.1	31.5
02/12	12	23	37	35	5.4	5.1	317	294	0	0	0	0	18.3	23.5
03/12	27	28	33	36	6.2	4.8	297	259	1	16	-86	-76	29.2	30.2
04/12	33	35	43	41	-0.3	0.1	222	238	206	973	-6	-17	39.4	42.2
05/12	28	30	37	39	5.8	3.9	322	287	0	0	0	0	28.7	33.0
Average	23.4	26.3	39.3	39.8	3.7	2.9	260.1	222.5	24.3	112.0	-11.6	-9.8	29.3	32.4
ρ^*	0.89		0.93		0.78		0.46		---		---		0.95	

MD - Missing wind data;

* Spearman's correlation coefficient.

Figure 5. Correlation of stability indices (K, TT, LI, and SWEAT) between the launch sites CPM and SJC.

Figure 6. Correlation of the stability indices (CAPE and CIN) and PW values between the launch sites CPM and SJC.

The main findings were:

1) The correlation of the stability indices and PW between sites ranged from fair (SWEAT) to very good or excellent (LI, K, TT, and PW).

2) The correlation coefficients for the stability indices K and TT, which depend only on the values of temperatures (T or TD) at different pressure levels, were higher than the correlation values for the stability indices that depend on the motion of a parcel (i.e., LI) and on the combination of kinetic and thermodynamic properties of the atmosphere (i.e., SWEAT).

3) The average values of these indices during the period of data collection were similar for both sites with the exception of the SWEAT index, which was higher at the CPM site.

4) There was a linear correlation between PW values, but PW values at SJC were consistently higher than those measured at CPM.

5) The average values of the CAPE and CIN indices may indicate that convective motions over CPM were inhibited when compared with those over SJC.

These findings can be explained by the different characteristics of the launch sites. The CPM upper-air station is located in the metropolitan area of São Paulo (population, 21 million). This implies that not only at the moment of the launch but during part of the flight, the measurements collected by the radiosondes were influenced by the city's environmental and atmospheric conditions. On the other hand, the SJC launch site is located in São José dos Campos, a smaller city (population, 722,000). In this situation, the measurements collected by the

radiosonde were less influenced by the local conditions, and the time of flight of the radiosonde over the metropolitan area was smaller compared to that of radiosondes launched from CPM. A common phenomenon associated with large cities is the formation of urban heat islands (Silva et al., 2017). The heat domes and plumes generated by heat islands may have large horizontal dimensions, usually surrounding the city and extending into rural areas up to 3 times the urban's area diameter (Fan et al., 2017); vertically, in tropical cities during the summer, they can reach a height of up to 3 km (García-Franco et al., 2018). High levels of atmospheric pollution may contribute to enhance heat islands (Cao et al., 2016). The presence of an intense heat island over São Paulo during summer months may contribute to an increase in the turbulence of the atmosphere and the production of winds. Thus, the occurrence of more intense winds over São Paulo may explain why the correlation coefficient for the SWEAT index, which depends on the wind shear (Equation 5), was smaller than the coefficients for the other indices, and why the average value of this index was larger for CPM compared to that for SJC. The higher values of PW and its average observed over SJC compared to those for CPM may be explained by the reduced vegetation cover in the region where the CPM upper-air station is located and adjacent areas. The reduced evapotranspiration combined with a strong urban heat island effect, as described previously, may result in a smaller concentration of water vapor in the atmosphere (Wang et al., 2017).

Chakraborty et al. (2017) reported that gaseous and particulate air pollutants can dampen convective motions in the atmosphere. This implies that there should be a negative correlation between stability indices that depend on measurements of convective activity and air pollution levels. CPM is located in a region with consistently higher pollution levels compared to SJC (CETESB, 2018). In this study, this negative correlation was observed for the LI index. LI values on average were larger at CPM indicating an inhibition of convective motions at this location. The average values of CAPE (smaller at CPM) and CIN (larger at CPM) may also indicate a damping of convective motions over CPM.

Using weather radar data, accumulated areal average precipitation was calculated for a

period of 8 hours after the launch of the radiosondes (from 1200 to 2000 UTC) over two areas measuring 20 x 20 km centered at CPM and SJC. The 8-h time interval and the 20 x 20 km areas were selected by convenience as being representative of the period and region sampled by the radiosondes. Examples of accumulated precipitation for November 21 and December 4, 2014 registered by the weather radar, and the locations of the selected areas are shown in Figure 7. The areal average precipitation estimates over the areas depicted in Figure 7 are listed in Table 2. Weather radar data was preferred over rain gauge data because of the radar's largest areal coverage and lack of rain gauge in the SJC area.

Figure 7. Accumulated precipitation for a period of 8 h (1200 UT to 2000 UTC) on (A) November 21, 2014, and (B) December 4, 2014. The areas centered on the CPM and SJC launch sites measure 20 km x 20 km, each. The horizontal dimension of the images is 240 km. RDR marks the position of the weather radar.

Table 2. Average precipitation estimates derived from weather radar data for the CPM and SJC launch sites. Precipitation data accumulated over an 8h-period after the launch of the radiosondes (from 1200 to 2000 UTC). Data collected from November 17, 2014 to December 5, 2014.

Launch Sites	Areal average precipitation (mm)											
	17/11	19/11	20/11	21/11	24/11	26/11	27/11	28/11	02/12	03/13	04/12	05/12
CPM	0	0	0.1	0.5	0.9	3.3	0	0	0	0	5.4	0
SJC	0	0.1	0.6	2.4	0.4	1.8	0	0	0	0	3.6	0

A comparison of the results listed in Tables 1 and 2 and the criteria describing atmospheric stability suggested a trend regarding the occurrence of precipitation and the values of the stability indices and PW. For example, the largest values of the areal precipitation were associated with the largest values of CAPE on November 26 and December 4 at both CPM and SJC. For moderate precipitation, as observed on November 21, the CAPE value was zero at both sites. On November 24, precipitation was lighter than that recorded on November 21 and the values of CAPE were larger than those of November 21. For the other indices and PW, the results were also mixed, with precipitation being recorded for $K > 28^{\circ}\text{C}$, $T > 27^{\circ}\text{C}$, $LI < 5.2^{\circ}\text{C}$, $\text{SWEAT} > 49$, $\text{CIN} < 0\text{ J.kg}^{-1}$, and $\text{PW} > 21.6\text{ mm.m}^{-2}$; however, there were days with $\text{PW} > 28.7\text{ mm.m}^{-2}$ and no precipitation registered by the radar.

Although the sample was small and there was a small number of days with rain, it was possible to observe a correlation, albeit weak, between the occurrence of rain and the stability indices and PW. It is important to note that the stability indices do not have predictive power; instead, they are indicative of the thermodynamic state of the atmosphere that may lead to precipitation (Uma & Das, 2019).

Conclusions

An important issue related to radiosonde soundings is the distance between upper-air stations. This is important because the data collected by radiosondes is usually interpreted as being representative for larger areas. In this study, the comparison of radiosonde soundings obtained from two relatively nearby launch sites revealed that even though the visual comparison of the vertical profiles of environmental and dew-point temperature may show similarities and common features, stability indices and PW derived from these profiles presented some differences. These differences may be explained by local environmental effects, mainly the presence of an intense heat island and atmospheric pollution over

the one of the launch sites located within a large metropolitan area. The results suggest that over this metropolitan area, during the period when this study was conducted, the atmosphere was drier, and that convective motions were damped. The distance effect on the soundings was probably masked by the different environmental conditions prevalent at the radiosonde launch sites.

The comparison of the values of stability indices and PW with precipitation estimates from radar data indicated that there was possibly a trend towards a relationship between the occurrence of precipitation events and these parameters. The radiosonde launches occurred during an unusually dry period, and the small number of rain days did not allow to establish a significant correlation.

The importance of radiosondes launched daily by upper-air stations all over the world cannot be overstated. They are an essential tool to probe the atmosphere in the vertical direction and a source of data for many meteorological, climatological, and commercial applications.

The main limitation of this study was the relatively small number of radiosondes launches. Further studies using a larger number of radiosondes launches carried out in different seasons of the year to collect profiles under diverse meteorological conditions, and the comparison of collected data with those from other launch sites not located within a major metropolitan area are necessary to expand the results and provide a better understanding regarding the influence of the distance between radiosonde launch sites on differences between stability indices among sites.

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