Trends of Stability Indices and Environmental Parameters Derived from the Rawinsonde Data over South Korea

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Abstract: In this paper, trends of the widely used stability indices (SIs) and environmental parameters (EPs) were examined by using the 30-year routine rawinsonde data observed in three upper air observatories (Osan, Gwangju and Pohang) over South Korea. To take into account of the contribution of water vapor to a parcel density, we applied the virtual temperature correction in calculating the SIs and EPs. The trends of SIs and EPs indicated significant increases of temperature and moisture contents, especially at the low-to-mid troposphere during the last 10 years. The warming trend in the lower troposphere shows about 3 times greater than that of the global average (+0.10- +0.20°C/10 years), whereas the cooling trend of lower stratosphere demonstrates a similar trend with the global average (−0.33- −0.60°C/10 years). The vertical stability is clearly reduced due to the unsymmetrical change of atmospheric elements. The unstabilizing trend with the increased moisture contents gradually changed the atmospheric environment in South Korea into the conditions favorable for the occurrence of severe weather or intensifications of such events. These trends are consistent with the recent observations, which showed clear increase in the intensity and frequency of heavy rainfalls.

Keywords: rawinsonde, stability indices, environmental parameters, trends, unstabilizing

Introduction

There have been a lot of studies concerning both local and global climate changes based on the observations and various types of numerical models; it is, however, still difficult challenges to understand how and why they occurred and to predict them well in advance because of the complexity and non-linear interactions among the five major components of climate system. Therefore, observational data from various types of observation, such as ground, rawinsonde, satellite data, and general climate model, have been used to detect the trends and causes of climate change (Fu and Johanson, 2005; Derubertis, 2006; Kim et al., 2006; IPCC, 2007; Lanzante and Free, 2008; Eom and Suh, 2009; Lee et al., 2009).

It is well known that the air temperature over South Korea has been significantly increased due to the combined effects of increased greenhouse gases and

urban heat island (Jung et al., 2002; Hong et al., 2006). Many works using observed data showed that the amount, intensity and frequency of heavy precipitation over South Korea also increased clearly (Jung et al., 2002; Kim et al., 2006; Kim et al., 2009). These changes of surface air temperature and heavy precipitation are closely linked with the status of low-to-mid troposphere. For this reason, it is important and requisite to investigate the trends of stability indices (SIs) and environmental parameters (EPs) over South Korea by using long term rawinsonde data. Atmospheric stability index, derived from daily rawinsonde observations, measures the potential for severe weather development. Hence, it is considered to be representative of the synoptic-scale environment (Davis et al., 1997). Also the EPs, such as air temperature, total precipitable water, level of free convection, shows the current status of atmosphere.

In a series of efforts to improve our understanding and forecasting skills by using observation and models, several studies have been conducted to understand the current trends of atmospheric status based on the widely used SIs and EPs, which were

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derived from rawinsonde data. For the purpose of making a background knowledge about the climatological atmospheric conditions, a number of works on the climatology of SIs and EPs derived from rawinsonde data or model reanalysis data have been constructed. In the US, Rasmussen and Blanchard (1998) investigated the baseline climatology of parameters used in supercell thunderstorm forecast and research. Craven and Brooks (2004) also examined the several parameters commonly used to forecast deep and moist convection. Chuda and Niino (2005) showed the Japanese climatology of environmental parameters for mesoscale convection. An attempt was also made to show the European climatology of severe convective storm environmental parameters by using ERA-40 reanalysis dataset (Romero et al., 2007). Eom et al. (2008) investigated the climatology of the widely used SIs and EPs derived from the recent 30 years rawinsonde data over South Korea.

Derubertis (2006) studied recent trends in four common stability indices (lifted index, K Index, convective available potential energy and severe weather threat) over United States. Fu and Johanson (2005) showed that tropospheric temperature trends in the tropics are greater than the surface warming and increased with height using satellite-borne Microwave Sounding Unit (MSU) observations.

There have been some studies to find threshold values using SIs and EPs on days of air mass or frontal thunderstorms over South Korea. Heo et al. (1994), and Kim and Lee (1994) investigated the synoptic and thermodynamic characteristics for air mass thunderstorms in the central region and in the southwestern region over South Korea, respectively. Kim et al. (2006) focused on the thunderstorm accompanied by trough passage during the winter period and suggested simple threshold values, based on specific two days, for Total Totals Index (TTI), K Index (KI) and mixing ratio. A number of studies performed in South Korea have used a limited range of cases and a period of time. Moreover, no attempt has been made to investigate the climatological trends of SIs and EPs over South Korea, although

climatological trend provides a valuable background knowledge about the current climate change over South Korea.

The main goal of this study is to examine the climatological trends of the commonly used SIs and EPs over South Korea. For this goal, we used the 30 years (1978-2007) of observed upper air sounding data from three rawinsonde sites. The analyses mainly focused on the simple linear trends of SIs and EPs.

Data

In this study, the upper air observation over South Korea by Korea Meteorological Administration and U. S. Air Force were used. The analysis period is 30 years from 1978 to 2007. In South Korea, seven observatories make routine upper air observations and their locations with the annual mean precipitation amount are plotted in Fig. 1. However, not all of these upper observation data can be used for trends analysis study because the number of observations are different among these upper observations (Table 1). Baengnyeongdo, Sokcho and Heuksando have a relatively short history of observations starting in 2000, 2001 and 2003, respectively. Because of the

Fig. 1. Spatial distribution of 30-year averaged annual precipitation amount (mm) and location of the seven rawinsonde stations currently operating in South Korea. Contour interval is 50 mm from 1000 mm.

Table 1. List of rawinsonde stations used in this study

Station	Station Number	Latitude, N	Longitude, E	Elevation (m)	Period	Frequency of observations (times a day)
Osan	47122	37.10°	127.03°	52	1978-2007	4
Pohang	47138	36.03°	129.38°	4	1978-2007	2
Gwangju	47158	35.11°	126.81°	13	1978-2007	2-4*

* 4 times a day after 2002

- Bold-faced five-digit station number is used as a region identifier in some figures.

data quality and observation history, we only used the data observed at Osan, Gwangju and Pohang. The data source for this study is the department of Atmospheric Science at Wyoming University in the US [Available online at <http://weather.uwyo.edu/upperair/sounding.html>].

Method

Decision of initial parcel to lift

In the calculation of some SIs and EPs such as lifted index (LI), convective available potential energy (CAPE) and equilibrium level (EL), the selection of which parcel to lift is a crucial problem because it can cause a significant different results (Eom et al., 2008). The representative initial parcel methods employed in previous studies or in the operational use can be classified into three types: (1) surface-based parcel (Romero et al., 2007), (2) mixed layer parcel and (3) most unstable parcel in the lowest 300 hPa (Doswell and Rasmussen, 1994). There is no universal agreement upon what the method must be used. In this study, a parcel with the average properties (potential temperature and mixing ratio) in the lowest 500 m AGL was chosen as an initial parcel (Eom et al., 2008). Therefore, the following SIs and EPs are based on a mixed layer parcel like mixed layer LI (MLLI), mixed layer LCL (MLLCL) and mixed layer EL (MLEL). We applied the virtual temperature correction to include the contribution of water vapor to a parcel density as recommended by Doswell and Rasmussen (1994).

Selected stability indices

Showalter Stability Index (SSI): The SSI is the

stability index most commonly used by the National Weather Service, the USAF Air Weather Service and Navy forecasters (Showalter, 1947). It indicates the general stability of an air mass and should not be used when a frontal boundary or a strong inversion is present between the 850 and 500 hPa levels. The SSI is computed using the layer between 850 hPa and 500 hPa, as follows:

$$SSI \equiv T_{500} - T_{parcel} \quad (1)$$

Lifted Index (LI): LI (Galway, 1956) is a measure of the thunderstorm potential, which takes into account of the low-level moisture availability, and a negative index indicates the possibility of convection. It is the subtraction of the temperature of the parcel at 500 hPa from the environmental temperature at 500 hPa like the following:

$$LI \equiv T_{500} - T_{parcel} \quad (2)$$

K Index (KI): KI (George, 1960) is a measure of thunderstorm potential based on the vertical temperature lapse rate, the amount and vertical extent of low-level moisture in the atmosphere.

$$KI \equiv (T_{850} - T_{500}) + TD_{850} - (T_{700} - TD_{700}) \quad (3)$$

Selected environmental parameters

Temperature at Lifting Condensation Level (LCLT): LCL is the height at which a parcel becomes saturated when lifted dry adiabatically and it is commonly used to estimate the cloud base level. So, the LCLT is the air temperature at the LCL height. Craven et al. (2002) suggested that LCL using a mixed layer parcel has the highest correlation to the observed cloud base.

Table 2. List of stability indices and environmental parameters used in this study

No	Acronym	Description	Unit
1	LI	Lifted Index	*
2	KI	K Index	*
3	SSI	Showalter Stability Index	*
4	EL	Equilibrium Level	m
5	LCLT	Temperature at lifting condensation level	K
6	TPW	Total Precipitable Water vapor for the entire sounding	mm
7	CAPE	Convective Available Potential Energy	J/kg
8	MLMR	Mixed Layer Mixing ratio	g/kg

* Dimensionless unit

Equilibrium Level (EL): EL is the level at which a parcel, which passed through a level of free convection, is raised by moist adiabatically to a level, the temperature of the parcel is the same as that of the environment. If more than one EL exists, the highest one is chosen.

Total Precipitable Water (TPW): TPW is the precipitable water (mm) for the entire sounding and it is defined as (Smith, 1966):

$$TPW \equiv \frac{1}{g} \int_{s/c}^{\infty} \omega dp \quad (4)$$

where ω is mixing ratio.

Results and discussion

Trends of EPs

Figure 2 shows the vertical profiles of 5-year averaged temperature anomalies from the 30 years average based on the data observed at Osan, Gwangju and Pohang. The anomaly profiles showed that there were significant variations in the atmospheric environments from the surface to lower stratosphere with the maximum amplitudes at the surface and at the 20 km. Although the temperature anomalies are not consistent with time and location, the warming of troposphere and cooling of lower stratosphere especially during the last 10 years is very significant (-0.8°C). There are relatively strong cold anomalies in the whole troposphere during 1983-1987 and 1993-1997 as in other studies on the surface air temperature

(Jung et al., 2002). This might be partly caused by the abrupt eruptions of volcanoes such as El Chichon (April 1982) and Mt. Pinatubo (June 1991) and enhanced activities of El nino (Free and Lanzante, 2009). Whereas, the cooling trend at the lower stratosphere is very consistent through the whole analysis period. Generally, increased carbon dioxide (CO_2), as a result of human activities, could cause not only tropospheric heating, but also stratospheric cooling due to the increase of infrared cooling effect. The main reason for the recent stratospheric cooling is due to the destruction of ozone by human-emitted CFC gases (Finger et al., 1995; Ramaswamy et al., 2002).

Figure 3 shows the trend of temperature at the selected 3 levels for the recent 30 years (1978-2007) observed at Osan, Gwangju and Pohang. The time series of temperature profiles show a strong interannual and spatial variations. On average, tropospheric warming trends from 1000 hPa to 300 hPa are found, but the increasing trend of temperature is more significant at the lower troposphere and it decreases with altitude. Whereas cooling trend is occurred in the lower stratosphere around 100 hPa. The warming trend in the lower troposphere is about 3 times greater than that of the global average ($+0.10$ - $+0.20^{\circ}\text{C}/10$ years), whereas the cooling trend of lower stratosphere is similar with that of the global average (-0.33 - $-0.60^{\circ}\text{C}/10$ years) (Karl et al., 2006; IPCC, 2007).

Water vapor plays a major role in the radiation budget and global hydrologic cycle. It is well known that the global warming induced by increased CO_2 can

Fig. 2. Vertical profiles of averaged temperature, mixing ratio and wind (u , v) anomalies in South Korea at a 5-yr interval.

be accelerated by the increased capacity of water vapor (IPCC, 2007). The rawinsonde data is the unique source of the longest record of water vapor throughout the troposphere, although it has a limitation both in the data quality and spatial homogeneity. Figure 4 depicts the trends of mixing ratio (ω) at the selected 3 levels for the last 30 years. As the mixing ratio is directly controlled by the temperature, its interannual variance and trend are drastically reduced with altitude. The increasing trend of ω is relatively large at the lower troposphere and this also decreases with altitude. However, the R^2 is very consistent without regard to the height. Unlike the temperature, the interannual variation of mixing ratio at Pohang is not consistent with that of Osan and Gwangju. It indicates that the quality of mixing ratio

at Pohang should be revisited. Although the trend of equivalent potential temperature (θ_e) is not shown, both ω and θ_e show almost the same trends because the equivalent potential temperature is directly determined by the temperature and moisture. In particular, positive anomalies during recent 10 years are remarkable except 2005, the year with relatively low temperature and mixing ratio (Figs. 3 and 4). Ross and Elliot (1996, 2001) analyzed the trend of tropospheric water vapor using the long term rawinsonde data over North America and Northern Hemisphere. They showed that different increasing trends of water vapor, specific humidity and dew point temperature are found with region to region in the lower to middle troposphere with the temperature over the period.

Fig. 3. Linear trends of temperature (°C) at (a) 1000 hPa, (b) 700 hPa and (c) 100 hPa from 1978 to 2007 at Osan, Gwangju and Pohang. Curved black line and gray line are the averaged anomaly trends and linear regression line, respectively.

Trends of SIs

Thermodynamic SIs, besides EPs, show the unstabilized trends (Fig. 5) due to the increases of

temperature and moisture in the lower troposphere. Both SSI and LI exhibit decreasing trends due to more tropospheric warming in the low level. KI,

Fig. 4. Same as in Fig. 3 except for mixing ratio (w) at (a) 850 hPa, (b) 700 hPa and (c) 500 hPa.

calculated by using lapse rate between 850 hPa and 500 hPa and low-to-mid level water vapor, shows an increasing trend, unstabilizing trend. The magnitude of increasing trend of KI is three times larger than that of the SSI and LI due to the combined effects of

increased temperature and moisture in the lower troposphere. It means that the atmospheric environment over South Korea is more significantly unstabilized than that of other regions due to the strong warming and moistening in the low-to-mid troposphere.

Fig. 5. Same as in Fig. 3 except for (a) SSI, (b) LI and (c) KI.

LCLT and EL are regarded as the temperature at cloud base and the height of cloud top, respectively. Therefore, the increasing trends of LCLT and EL indicate that the probability of deep convection have been increased (Fig. 6). The LCLT and EL of Pohang are excluded because they are not consistent with the Osan and Gangju as shown in Fig. 4. The water vapor

contents for the entire sounding, TPW, has been increased. These kinds of thermodynamic ingredients are characterized by very similar variation patterns and unstabilization due to the increases of temperature and water vapor contents especially in the lower troposphere.

Because most of the severe weather, such as the heavy rainfalls, over South Korea have occurred

Fig. 6. Same as in Fig. 3 except for (a) LCLT, (b) EL and (c) TPW.

during summer season (June, July, August and September; JJAS), the frequency time series of the SIs and EPs over specific threshold values during JJAS were analyzed (Figs. 7 and 8). Table 3 shows the threshold values, based on the convection potential, of three stability indices used in the Korean Meteorological Administration. However, the accuracy

of the threshold values of the three SIs are not significant and dependent on the geographic location (Eom and Suh, 2010). There is no distinct threshold values for the environmental parameters, such as LCLT, EL and TPW. So, three threshold values were selected as 1st, 2nd and 3rd quartile values of lightning occurrence cases instead of the predefined

Fig. 7. Same as in Fig. 3 except for trends of frequency fraction (%) over specific threshold values of (a) SSI, (b) CAPE and (c) KI.

threshold values of SIs (Eom and Suh, 2010). When we take into account of the characteristics of SIs and EPs, the 3rd threshold values of SIs and EPs indicate the most unstable conditions. Not only have the EPs and SIs been unstabilized and moistened, but also has

the frequency over specific thresholds been increased for the last 30 years. Although the linear gradient of frequency fraction over the most stable threshold (th1) is larger than that over the most unstable cases (th3), the unstabilizing trends are very consistent without

(a) LCLT

(b) MLMR

(c) TPW

Fig. 8. Same as in Fig. 7 except for (a) LCLT, (b) MLMR and (c) TPW.

regard to the selected threshold values of SIs and EPs. The consistent changing patterns of the SIs and EPs indicate that the atmospheric environment over South Korea gradually changed into conditions more favorable for the severe weather events, such as heavy rainfalls.

Summary and Concluding Remarks

In this work, trends of the widely used stability indices and environmental parameters were examined by using the recent 30-year routine rawinsonde data

Table 3. Threshold values of stability indices used in the Korean Meteorological Administration

No	Acronym	Stable	Marginal instability	Large instability	Extreme instability
1	LI	>0	0- -4	-4- -7	<-7
2	KI	<15	15-26	26-40	>40
3	SSI	<4	0-4	-3-0	<-3
4	CAPE	0-1000	1000-2500	2500-3500	>3500

observed in the three upper air observatories (Osan, Gwangju and Pohang) over South Korea. To take into account of the contribution of water vapor to a parcel density, we applied the virtual temperature correction in calculating the SIs and EPs.

The trends of SIs and EPs over South Korea during the recent 30 years are summarized as follows. The trends of SIs and EPs show that the warming in the low-to-mid level and the increase in moisture contents for the entire atmosphere. The atmospheric temperature trends are characterized by the tropospheric warming and low stratospheric cooling. This different trends with height are consistent with other results (Gaffeen et al., 2000; Lanzante and Free, 2008). The frequency over specific thresholds of SIs and EPs have been consistently increased without regard to the threshold values and selected SIs and EPs. When we take into account of the facts that these trends noted above were temporarily alleviated by the historical volcanic eruptions such as El Chicon in 1982 and Mt. Pinatubo in 1991, the atmospheric environment over South Korea changed into the conditions favorable for the occurrence of severe weather or intensifications of such events. These trends are consistent with the recent observations, which showed clear increase in the intensity and frequency of heavy rainfalls (Jung et al., 2002; Hong et al., 2006).

Although, this results give some insights about the current trends of atmospheric environments over South Korea, the results of this study should be used with caution because we did not apply the rigorous quality control method to the upper air data. The importance of rawinsonde data quality for the detection of temporal trends in tropospheric and lower-stratospheric temperature is well documented in Gaffeen et al. (2000).

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