Rapid Change in Surface-Based Temperature Inversions across the World during the Last Three Decades

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ABSTRACT: Surface-based inversions (SBIs) are significant and common natural phenomena in the planetary boundary layer, and they play essential roles in weather and climate. This study used radiosonde data from 493 radiosonde stations worldwide from the Integrated Global Radiosonde Archive during 1989–2019 to investigate the variations in surface-based inversions from a global perspective. The results indicated that, from 1989 to 2019, the SBI frequency increased and the SBI strength variations with fluctuations and SBI depth decreased over the study period. However, the spatial distribution of frequency, strength, and depth did not have consistent trends. In comparison with the Southern Hemisphere, SBIs in the Northern Hemisphere occurred more frequently and were stronger and deeper. In terms of stations over land and the ocean, we found that the SBI frequency over the ocean has increased faster than that over land in the past 15 years and that the SBI strength over land was almost 2 times that of the ocean. The amplitudes of the annual cycle of SBI characteristics over land were greater than over the ocean in both hemispheres, and the frequency, strength, and depth were greater over land. This study investigated surface-based inversions from a global perspective and filled a gap in the current research on SBIs.

KEYWORDS: Land surface; Inversions; Climate change; Temperature; Radiosonde/rawinsonde observations; Trends

1. Introduction

Temperature inversion is defined as a temperature increase with altitude, which represents stable conditions and is very common in the atmosphere. According to the formation mechanism of temperature inversions, they can be divided into diverse types, such as frontal inversions, subsidence inversions, radiative inversions, and valley inversions. Frontal inversions and subsidence inversions are caused by vertical or horizontal movement of air masses. Radiation inversions often occur at night. Valley inversions are a type of radiation inversion that occur in valley areas (Ji et al. 2019).

Temperature inversions, especially surface-based temperature inversions (SBIs), which we investigated in this study, are closely related to many processes in the climate system, and they have great potential of influencing weather and climate, as they limit the diffusion of energy, mass, pollutants, cloud formation, and destruction of ozone in the atmosphere (Zhang et al. 2011; Devasthale et al. 2010). Current studies on temperature inversions have focused on their relationship to air pollution and large-scale circulation (Bailey et al. 2011; Li et al. 2015; Zang et al. 2017; Feng et al. 2020; Devasthale and Thomas 2012). Air pollution is largely associated with anthropogenic emissions, but the primary cause of severe pollution is meteorological conditions, especially low-level temperature inversions (VanReken et al. 2017; Hou and Wu 2016). Temperature inversions cause atmospheric stability, limit vertical and horizontal dispersion, and trap pollutants in the inversion layer. A study in Ontario, Canada, observed increases in NO2 and PM2.5 of 49% and 54%, respectively, during nighttime inversion episodes (Wallace and Kanaroglou 2009). Li et al. (2019) used high-quality and continuous radiosondes to investigate the effects of low-level temperature inversions on aerosols and found that the mean surface aerosol number concentrations increased when SBIs were present. They also found that the effects of SBIs on surface aerosol concentrations were weakest in summer (18.1%) and strongest in winter (58.4%). Health problems are associated with air pollution caused by temperature inversions, and high concentrations of air pollutants may lead to asthma. However, previous studies have not considered temperature inversions or the number of days they occur as independent variables that contribute to asthma rates. Beard et al. (2012) provided evidence that temperature inversions in winter are associated with increased asthma rates. Low-level temperature inversions play a vital role in urban areas, and Fast et al. (2005) found that a strong urban heat island effect coincided with the persistence of strong temperature inversions. A study in Alaska discussed whether the presence of an urban heat island affects surface-based temperature inversions because low-level temperatures affect the inversion structure and strength (Bourne et al. 2010).

Radiosonde observations have been widely used to investigate temperature inversions (Bradley et al. 1992; Zhang et al. 2011; Zhang and Seidel 2011; Bourne et al. 2010; Miller et al. 2013), and many studies have used satellite data to analyze temperature inversions (Boylan et al. 2015, 2016; Wallace and Kanaroglou 2009; Devasthale et al. 2010). Boylan et al. (2016) examined Antarctic SBIs using measurements from dropsondes, ERA-Interim, and Infrared Atmospheric Sounding Interferometer (IASI) level-2 products. The results showed that using IASI and ERA-Interim data to detect inversions has a high probability of detecting SBIs but severely
overestimates the depth and underestimates the strength for both datasets. This is primarily due to the existence of extremely shallow inversion layers that neither satellite nor reanalysis products can resolve. Stryhal et al. (2017) also argued that soundings have several advantages compared with other measurements because the vertical resolution of radiosonde measurements is considerably higher, and surface stations often have long-term continuous radiosonde data.

As mentioned earlier, SBIs have a significant limitation on the dispersion of substances in the boundary layer, especially pollutants. Under global warming, high concentrations of greenhouse gases have increased the global mean surface temperature. The surface temperature affects the surface-based inversion layers. This indicates that surface temperature changes and climate changes influence the characteristics of the SBIs, such as SBI depth and SBI strength (Abdul-Wahab et al. 2004). Caserini et al. (2017) analyzed the frequency of days characterized by daytime temperature inversions in the Po valley and found that under RCP8.5 and RCP4.5 temperature inversions will increase with time. Stone and Kahl (1991) mentioned that low-level temperature inversion characteristics may be a valuable indicator of climate change. The climatological characteristics of SBIs are related to sea ice and planetary albedo, which are essential factors in climate feedback mechanisms (Zhang et al. 2011).

SBIs are most related to human activity and limit the diffusion of energy and pollutants in the near-surface layer. The characteristics of SBIs have been discussed in many studies, especially regarding SBIs in polar regions; SBIs frequently occur in the Arctic and Antarctic (Zhang et al. 2011; Boylan et al. 2015), which is due to strong radiation cooling (Miller et al. 2013). Strong SBI strength leads to a considerable negative longwave feedback, which then influences surface temperature and sea ice changes in the Arctic (Boë et al. 2009). Furthermore, polar regions play important roles in climate systems, and high northern latitudes are warming at more than twice the rate of the rest of the world (Serreze and Francis 2006). The frequency of SBIs is approximately 80% at nighttime and up to 50% during the daytime in polar regions (Seidel et al. 2010). In short, it is essential to study SBI variations and their general characteristics, but we found that previous studies were limited to some regions, even to a single station (Zhang et al. 2011; Boylan et al. 2015, 2016; Zhang and Seidel 2011; Bourne et al. 2010; Miller et al. 2013). Observational evidence of long-term SBIs worldwide is scant. Our research aimed to determine the variations in SBIs from a global perspective, including annual and interannual variations. Understanding the long-term changes in SBIs can help us to better understand their impacts on air quality, atmospheric stability, human health, and some of the potential impacts of climate change.

2. Data and method
   a. IGRA sounding data

Radiosonde data can represent the real state of the atmosphere. They are typically launched two times per day (0000 and 1200 UTC) and provide detailed profiles of pressure, height, temperature, humidity, wind, and so on (Seidel et al. 2010). This study used the Integrated Global Radiosonde Archive (IGRA) from the National Climatic Data Center (NCDC; now the National Centers for Environmental Information). The IGRA has the most comprehensive dataset of sounding sites globally and consists of more than 1500 stations; it uses quality control methods to obtain quality-assured data. Data from 11 different sources are contained in the IGRA, and the quality assurance algorithms include checking for fundamental sanity, station elevation, internal consistency, repetition of values, climatology, data completeness, and additional checks on temperature. Data from the IGRA include mandatory pressure levels (1000, 925, 850, 700, 500, 400, 300, 250, 200, 150, 100, 70, 50, 30, 20, and 10 hPa) and additional levels suggested by the U.S. National Weather Service (7, 5, 3, 2, and 1 hPa) (Durre et al. 2006).

This study selected 493 stations where more than 70% of the total soundings for the given stations and investigation period had at least 10 levels at or below 500 hPa. These stations had continuous records from 1989 to 2019, and their distribution is shown in Fig. 1. The use of radiosonde data to investigate the global climatology of SBIs may cause some deviation due to sparsely distributed stations. Even so, it is the most suitable data to estimate the characteristics of SBIs: satellite data are limited to clear-sky conditions and are highly affected by cloud cover. Reanalysis data do not represent the most realistic state of the atmosphere; for example, Zhang et al. (2011) confirmed that ERA-Interim data show the same seasonal variation and spatial patterns in polar regions, but the data also have biases in the magnitude of SBI frequency, strength, and depth and in simulations from climate models. ERA-Interim reanalysis can detect the occurrence of temperature inversions. However, the performances of reanalysis data were not the same for different seasons, regions, and inversion types (Palarz et al. 2020).

b. Data processing

Following the algorithm from Kahl (1990) to detect SBIs, the algorithm used to detect inversions examines every temperature profile to determine whether temperature increases with altitude from the surface. A surface-based inversion layer is defined as the bottom of the inversion layer as the surface. The top is the bottom of the first subsequent layer, in which the temperature decreases with altitude. Note that a
very thin noninversion layer (<100 m) embedded within the SBI is considered to be part of an inversion layer (Zhang et al. 2011; Kahl 1990; Guo et al. 2020). Zhang et al. (2011) examined the sensitivity of climatological SBI statistics to the thickness of noninversion layers embedded within the SBIs and eventually allowed noninversion layers of less than 100-m thickness to be within SBIs.

Many researchers have studied the climatological characteristics of SBIs using radiosonde data, but changes in vertical resolution may cause erroneous trends (Zhang et al. 2011; Zhang and Seidel 2011). Zhang and Seidel (2011) found that changes in the vertical resolution of radiosonde observations can cause inhomogeneities in time series when estimating SBI features. Moreover, a fine resolution is important for accurately determining the temperature SBI depth and inversion layer structures (Li et al. 2019). Profiles were interpolated to 50-m height increments using cubic spline interpolation to reduce the effects of the resolution. Bourne et al. (2010) investigated Alaska surface-based temperature inversions by interpolating sounding profiles to 50-m height increments, and Li et al. (2012) used cubic-spline interpolation to refine data. To ensure the accuracy of the results, we selected profiles with at least 10 levels over the entire altitude range and at least 3 levels below 1500 m.

SBIs can be described by three characteristics: frequency, strength, and depth (Boylan et al. 2015; Zang et al. 2017; Guo et al. 2020; Palarz et al. 2020). Therefore, the following three parameters were calculated: 1) the SBI frequency is defined as the number of profiles with an inversion divided by the number of total profiles, 2) the SBI strength is the temperature difference between the top of the inversion layer and the bottom of the inversion layer, and 3) SBI depth refers to the difference in height between the top and bottom of the inversion layer.

3. Characteristics of SBIs on a global scale

The SBI frequency showed a long-term increase from 1989 to 2019, and it varied between 50.9% and 57.4%, indicating that more than one-half of the records had SBIs over the global stations (Fig. 2a). In contrast to the overall increasing frequency of SBIs, the frequency decreased yearly during the first 10 years of the investigation period, reaching a minimum value of 50.9%. Conversely, the SBI frequency increased from 1998 to 2019. From this “decrease–increase” phenomenon, we can see that the frequency trend seems sensitive to the chosen research period, which was presented by Bourne et al. (2010). They investigated Alaska surface-based inversions during the 1957–2008 period and argued that inversion parameters displayed multidecadal variations rather than straightforward trends. However, in terms of long-term change, the tendency to increase is undeniable, and the frequency has increased by 3.1% in the last 10 years. Caserini et al. (2017) analyzed future projections of temperature inversion over the Po Valley basin in Italy. Their results showed that the number of days that temperature inversions occurred would increase under RCP4.5 and RCP8.5 (Caserini et al. 2017). These results indirectly prove that the increasing frequency over the globe that we obtained is plausible.

The interannual variations in the surface-based temperature SBI strength are shown in Fig. 2b, with an average SBI strength of 3.34 K. The SBI strength displayed a maximum value in 1989 and decreased until 1997. The difference between the maximum and minimum values of temperature strength was 0.73 K. From 1997 to 2019, SBI strength increased, but with some stagnant periods, such as 2000–03 and 2008–13, and the changes during these periods were no more than 0.01 K. Overall, global SBI strength had no significant increasing or decreasing trend. It is also noteworthy that from 1989 to 1997 there was a substantial decrease in strength.

Unlike the other two parameters of SBIs, the SBI depth subsequently decreased over the 31 years with a maximum value of 271.9 m and a minimum value of 201.9 m. The average SBI depth was 229.0 m. In the last five years, the SBI depth stagnated at approximately 202.7 m. The most significant decrease in depth occurred in the early part of the study period (1989–95), after which the depth began to decrease.
slowly. The correlation coefficients of surface air temperature (SAT) and SBI depth and frequency were calculated. SBI frequency and SAT were significantly positively correlated (0.59), whereas SBI depth was significantly negatively correlated with SAT (−0.82). The increase in SAT was accompanied by an increase in SBI frequency and a decrease in SBI depth. This makes physical sense because the SBIs are mainly caused by longwave radiative loss. These results were in good agreement with those of Bourne et al. (2010), who argued that when surface temperatures are warm (cold), the SBI depth is small (large).

It is known that the global average SBI frequency was increasing. However, the SBI frequency at most stations showed increasing trends except for a few stations in North America and Australia (Fig. 3a). Moreover, the SBI frequency in North America near polar regions had increasing trends. The global distributions of SBI strength displayed different trends, as we expected. There were 249 stations that showed increasing trends and others that showed decreasing trends. In the 50°S–50°N region, most of the SBI strength tended to be positive, while trends of decreasing SBI strength occurred more frequently in high latitude areas (Fig. 3b). A visual inspection of Fig. 3c implies that the SBI depth seemed to be decreasing globally, with 85% of the stations showing decreasing trends while a few stations displayed increasing trends in central Asia and North America.

4. Characteristics of SBIs in different regions

a. Comparison of SBIs in the Northern and Southern Hemispheres

As shown in Fig. 4, more SBIs occurred in the Northern Hemisphere than in the Southern Hemisphere, and SBIs were also stronger and deeper in the Northern Hemisphere. Their frequency varied between 53.7% and 61.0% in the Northern Hemisphere and 32.4% and 42.3% in the Southern Hemisphere. More than half of the records detected by stations in the Northern Hemisphere showed SBIs, but only one-third showed SBIs in the Southern Hemisphere. The values and trends of frequency in the Northern and Southern Hemispheres were dissimilar: SBI frequency decreased until 2000...
and subsequently increased thereafter in the Northern Hemisphere. The SBI frequency interannual variability in the Northern Hemisphere seemed similar to the global variation in frequency, primarily because the Northern Hemisphere owns more stations with a value of 420. The frequency maximum in the Northern Hemisphere appeared in 2019, unlike in the Southern Hemisphere, where the maximum occurred in 2001. The SBI frequency detected by the Southern Hemisphere stations often displayed stagnant conditions during the investigation period. After the first stable period (1991–97), the SBI frequency reached its maximum value in 2001 (Fig. 4). In 2005, the frequency decreased to a low level, and five years later, the SBI frequency in the Southern Hemisphere increased to another stagnant period. Likewise, there were no significant changes in the SBI frequency in the last four years.

The SBI strength in the Northern Hemisphere was numerically greater than that in the Southern Hemisphere. However, variations in SBI strength over the 31 years displayed consistencies at stations in both hemispheres (Fig. 4b). From 1989 to 1997, the SBI strength exhibited a significant decreasing trend in both hemispheres; the SBI strength in the Southern Hemisphere decreased by 0.83 K, while the strength in the Northern Hemisphere decreased by 0.71 K. Since then, the SBI strength of both hemispheres began to increase in a tortuous manner. At the same time, the increasing trend was more pronounced in the Southern Hemisphere than in the Northern Hemisphere, although the trend fluctuated more in the Southern Hemisphere. The strength in the Southern Hemisphere (3.47 K) was close to that in the Northern Hemisphere in 2011 (3.59 K), and by 2019 the strength in the Southern Hemisphere (3.56 K) was equal to that in the Northern Hemisphere (3.56 K). Overall, the SBI strength in the Southern Hemisphere displayed sudden changes during the 2010–12 and 2016–19 periods.

As in the case of the other parameters, SBIs in the Northern Hemisphere were deeper than those in the Southern Hemisphere: the average depth in the Southern Hemisphere was 168.1 and 239.9 m in the Northern Hemisphere, and the SBI depth displayed large values in the early part of the period in both hemispheres (Fig. 4c). The most significant decrease in SBI depth occurred in the Northern Hemisphere from 1990 to 1995, and until 2000, the SBI depth remained almost unchanged. SBI depth in the Northern Hemisphere slowly decreased, with small increases neglected from 2000 to 2015. On average, the SBI depth detected by the Northern Hemisphere radiosonde stations presented a stagnant condition in recent years. In the Southern Hemisphere, SBI depth decreased in the early four years and suddenly increased until 1994. The SBI depth decreased from 181.8 to 168.8 m between 1994 and 1998. There were no significant changes in SBI depth during 1998–2003, and we note that SBI depth decreased by 13 m in the following 16 years.

The annual variations in the three inversion temperature parameters in the Northern Hemisphere are consistent with those in the Southern Hemisphere. In the cold seasons in the Northern and Southern Hemispheres, the SBI frequency was greater than that during the warm seasons. This is because radiative cooling of the surface is one of the fundamental processes responsible for SBI formation; in cold seasons, the net outgoing infrared radiation generally exceeds the incoming solar radiation (Zhang et al. 2011; Guo et al. 2020). The frequency in the Northern Hemisphere decreased before June and increased thereafter, reaching its lowest level in June (40.7%). The annual variation in SBI frequency was more significant in the Southern Hemisphere than in the Northern Hemisphere. In the Southern Hemisphere, the SBI frequency varied in the range of 20.8%–43.3% in a year, with an annual cycle amplitude of 11.3%, while that in the Northern Hemisphere was 7.1%. In the Northern Hemisphere, SBIs occurred one-half of the time in a month (January to February and October to December). The frequency in the Northern Hemisphere was greater than that in the Southern Hemisphere, especially in December and January (approximately 54% in the Northern Hemisphere and approximately 21% in the Southern Hemisphere). However, in June and July, the SBI frequency in the Southern Hemisphere exceeded that in the Northern Hemisphere.
The annual variations in the SBI strength in the two hemispheres are shown in Fig. 5b. Compared with the Southern Hemisphere, the annual variations in the Northern Hemisphere were more pronounced. SBI strength in the Northern Hemisphere was highest in January, and the temperature difference between the upper and lower layers of the inversion layer reached 4.3 K. Since then, it has decreased until June. The strength hardly changed from June to September and increased again from September to December, from 2.7 K in September to 4.2 K in December. On average, in the Southern Hemisphere, the strength increased from 2.5 K in January to 2.7 K in February. However, the strength in March was lower than that in February, and the strength increased again in April. From May to August, the SBI strength in the Southern Hemisphere was almost constant at approximately 3.3 K. After August, the strength gradually decreased to 2.1 K in November and then increased slightly (2.2 K) in December. Similar to the annual SBI frequency variations, the strength in the Northern Hemisphere was generally greater than that in the Southern Hemisphere during the year, but from May to September, the strength in the Southern Hemisphere exceeded that in the Northern Hemisphere.

The SBI depth in the Northern Hemisphere also displayed an apparent annual cycle, similar to the other SBI parameters in the Northern Hemisphere. However, the annual variations in depth in the Southern Hemisphere were minimal. The same variation decreased and then increased, and the SBI depth in the Southern Hemisphere varied from the largest depth in January (280.4 m) to the smallest depth in August (196.6 m). Similar to the strength variations, the depth was almost unchanged from June to August (approximately 197.1 m). When compared with the Northern Hemisphere, the annual changes in the Southern Hemisphere were less drastic, with a maximum of 177.0 m and a minimum of 144.5 m. Compared with the Northern Hemisphere, the annual changes in the Southern Hemisphere were less drastic, with a maximum of 164.6 m and a minimum of 134.0 m. Note that the variations in depth in the Southern Hemisphere were smaller than those in the Northern Hemisphere throughout the year, even when the Southern Hemisphere maximum and the Northern Hemisphere minimum appeared. Moreover, in the Southern Hemisphere, the amplitude of the annual cycle in frequency was significantly greater than the strength and depth variations.

b. Comparison of SBIs over land and the ocean

Figure 6 presents the interannual variations in temperature inversion characteristics obtained from radiosonde stations over the ocean and land. In terms of the frequency of temperature inversion occurrence, the SBI frequency was higher over land than over the ocean. The frequency over land varied between 54.8% and 60.5%, while the frequency over the ocean varied only between 35.1% and 47.5%. We can see that the curve of the frequency over land in 1989–2019 was similar to that in the Northern Hemisphere in Fig. 4a. This was mainly because most of the selected stations in the Northern Hemisphere were over land (distribution of stations can be seen in Fig. 1). However, there were some slight differences between them: during the increased SBI frequency from 2000 to 2006, the frequency over land increased faster at both ends of the investigation period and slowly in the middle period. After the frequency increased to a relatively high value (59.4%) in 2006, the frequency decreased until 2013. Afterward, the frequency over land showed an increasing trend, reaching a maximum value of 60.5% in 2019. Compared with the changes in the SBI frequency over land, stations over the ocean detected greater variations in SBI frequency. In the 1989–98 and 2005–10 periods, there were increased and then decreased fluctuations. Furthermore, there was also a small fluctuation around 2014. The decrease in 1996–98 was the most dramatic in the entire study period, with the SBI frequency decreasing from 42.0% to 35.5%. From 2000 to 2005, the SBI frequency decreased slightly (decreased by 1.2%) but could be considered almost constant. After 2005, the frequency began to show a significant increase. Although there
were some fluctuations in this increasing trend, the increase in the frequency over the past 15 years was greater over the ocean than over land.

From Fig. 6b, we can see that the interannual trends of SBI strength over land and the ocean were similar, and the SBI strength over land was greater than that over the ocean. The SBI strength over land varied between 3.4 and 4.2 K, whereas that over the ocean varied between 1.7 and 2.5 K. There were three “decreasing–increasing” cycles of SBI strength variation over land: 1991–2000, 2002–08, and 2013–17, as shown in Fig. 6b. During the period from 2009 to 2013, the SBI strength over land was almost constant. The maximum value of SBI strength over land over the 31 years was in 1989, and the minimum was in 1997, with an average value of 3.8 K for the entire 31-yr period. The variations in the SBI strength over the ocean for the investigation period were not as drastic as those over land, but many fluctuations accompanied the trend over the ocean. The maximum value occurred in 2018, and the minimum value occurred in 1998. The strength did not change from 1996 to 1999, nor did it change from 2008 to 2012. From Fig. 6b, it also seemed that the two curves had no apparent increasing or decreasing trend.

Decreasing trends in SBI depth over the 31-yr period were evident for both the ocean and land, and the decreasing trend was stronger over land than over the ocean. The SBI depth decreased by 71.5 m over land and 67.0 m over the ocean for the 31-yr period; although the SBI depth decreased over both land and the ocean, their trends were different. Over land, the decrease was faster until 1995, and the SBI depth remained almost constant until 2000. Afterward, the depth decreased, but the changes in depth over the last five years were not significant. The changes over the ocean were very drastic before 1995, and the SBI depth decreased by 39.6 m in 7 years. However, after 1995, the depth decreased very slowly, with a change of 24.5 m in 24 years. SBI frequency, depth and strength detected by stations over land were significantly greater than those detected over the ocean. This can be used to explain why more SBIs occurred frequently in the Northern Hemisphere and were stronger and deeper in the Northern Hemisphere. Eighty-two percent of all stations in the Northern Hemisphere were located on land (Fig. 1). Over the ocean, inversions were much less commonplace because of high wind speeds, high humidity, large cloud cover, and large heat capacity (Palarz et al. 2018).

The annual frequency, strength, and depth of SBIs over land and the ocean in the Northern and Southern Hemispheres were investigated. As shown in Fig. 7, the amplitude of the annual cycle in SBI frequency was greater over land in the Southern Hemisphere than in the Northern Hemisphere, 16.1% in the Southern Hemisphere and 6.8% in the Northern Hemisphere, with the amplitude in the Southern Hemisphere being more than twice that in the Northern Hemisphere. The annual cycle of SBI frequency over land in the Northern Hemisphere was very pronounced and presented a single peak distribution (Fig. 7b). However, this was not the case for the variations in strength over land in the Southern Hemisphere, with a small peak evident in February from 2.8 K in January to 3.2 K in February to 2.9 K in March. The strength then increased after March and reached a maximum of 3.8 K in August, after which it began to decrease with a small increase in December. Note that, in addition to frequency, the annual amplitudes of strength and depth over land in the Southern Hemisphere were smaller than those in the Northern Hemisphere: the amplitude of the strength annual cycle over land in the Northern Hemisphere was 0.71 K and that in the Southern Hemisphere was 0.24 K. In contrast, in the Southern Hemisphere, the values of SBI strength over the ocean began to increase in February and remained constant from May to September and decreased thereafter. The annual variations in SBI depth were almost unchanged, and stations over the ocean in the Northern Hemisphere had deeper SBIs than those in the Southern Hemisphere (Fig. 8c). Overall, the variations in SBI characteristics over the ocean were not as

![](image)
drastic as those over land in both the Southern and Northern Hemispheres, and the values of frequency, strength, and depth were greater over land.

5. Conclusions

Surface-based inversions are common phenomena in the atmosphere. Their appearances cause matter and energy to be trapped near the surface, which are important for determining the vertical dispersion characteristics in the atmosphere. In addition, SBIs in polar regions are also associated with sea ice concentration, and climate change in polar regions is faster than in the rest of the world. The existence of SBIs in polar regions will have an impact on the global climate. This article is based on the radiosonde data of 493 stations worldwide from the IGRA to document the global characteristics of SBIs from 1989 to 2019. Each profile was interpolated to 50 m. The primary conclusions of this study are as follows:

Globally, the SBI frequency has been increasing, with a maximum of 57.4% in 2019. The strength varied between 3.0 and 3.8 K over the past 31 years, and the strength decreased by 0.73 K before 1997. Subsequently, the changes in strength were accompanied by fluctuations. The interannual variations in depth showed a noticeable decrease; the most significant decrease in depth occurred in the early part of the study period (1989–95), and there were no apparent changes in the last five years. The correlation coefficients showed that surface air temperature was significantly positively correlated (0.59) and significantly negatively correlated with SBI depth (−0.82). Most stations showed increasing SBI frequency trends except at stations in North America and Australia. Eighty-five percent of the stations showed decreasing trends in SBI depth, while the global distributions of SBI strength displayed different trends, as we expected.

SBIs in the Northern Hemisphere occurred more frequently than those in the Southern Hemisphere and were stronger and deeper. The frequency in the Northern Hemisphere was approximately 29.0% higher than that in the Southern Hemisphere, and their trends were not coincident, while the strength variations were similar. SBI depth had decreasing trends in both hemispheres. However, the SBI depth in the Southern Hemisphere has remained unchanged in the last five years. On average, the SBI frequency in both hemispheres showed a clear annual cycle, and the seasonal features of the three inversion parameters in the Northern Hemisphere were consistent with those in the Southern Hemisphere. Numerically, the SBI parameters in the Northern Hemisphere were greater than those in the Southern Hemisphere in a year. However, the frequency in June and July in the Southern Hemisphere and the strength in May to September exceeded those in the Northern Hemisphere.

The frequency, strength, and depth of SBIs over land were also greater than those over the ocean. In terms of frequency, the increasing trend over the ocean for the past 10 years was stronger than that over land. The interannual variations in strength over land and the ocean were similar, but the SBI strength over land was almost 2 times as high as that over the ocean. Depth over land decreased more than that over the ocean from 1989 to 2019.

The frequency, strength, and depth of SBIs over land and the ocean in the Northern and Southern Hemispheres were investigated, and it was found that, in addition to frequency, the annual amplitudes of strength and depth over land in the Southern Hemisphere were smaller than those in the Northern Hemisphere. The variations in SBI characteristics over the ocean were not as drastic as those over land in both hemispheres, and the frequency, strength, and depth were greater over land.

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Data availability statement. Datasets analyzed during the current study are available in the Integrated Global Radiosonde Archive (IGRA; https://www1.ncdc.noaa.gov/pub/data/igra/derived/derived-por/).
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