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Challenges in estimating trends in Arctic surface-based inversions from radiosonde data

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[1] Because of potential connections between changes in the characteristics of surface-based inversions (SBIs) and other Arctic climate trends, and because of the availability of radiosonde observations from the 1950s to present, one might seek to investigate Arctic SBI trends using radiosonde data. However, changes in observational methods, particularly those affecting sounding vertical resolution, introduce artificial changes in radiosonde representations of SBIs that degrade trend estimates. SBI intensity and depth data are particularly sensitive to this problem, but frequency of SBI occurrence is more robust. Most previous investigations of Arctic SBI trends have erroneously neglected or dismissed this issue. Based on SBI data from the few Arctic stations with homogeneous records during 1990–2009, most trends are not statistically significant, and no clear patterns of SBI change emerge. Among the significant trends, we find SBI intensity trends are positively associated with SBI depth trends, but negatively correlated with the surface temperature trends. **Citation:** Zhang, Y., and D. J. Seidel (2011), Challenges in estimating trends in Arctic surface-based inversions from radiosonde data, *Geophys. Res. Lett.*, *38*, L17806, doi:10.1029/2011GL048728.

1. Introduction

[2] While global surface temperature has increased during recent decades, Arctic surface temperature has increased at twice the global-average rate [*ACIA*, 2004; *Intergovernmental Panel on Climate Change*, 2007; *Richter-Menge*, 2010]. Declining sea ice and snow cover [*Screen and Simmonds*, 2010] lead to decreased surface albedo, further enhancing Arctic warming [*Serreze et al.*, 2009]. Recent studies [*Deser et al.*, 2010; *Mernild and Liston*, 2010] have linked key aspects of Arctic climate change, including sea ice changes and snowmelt, to changes in surface-based inversion (SBI) characteristics. However, observational evidence of long-term changes in SBI characteristics is scant [*Pavelsky et al.*, 2011], particularly for the recent two decades.

[3] Previous studies have investigated the climatology of SBIs over portions of the Arctic [*Serreze et al.*, 1992; *Kahl et al.*, 1996; *Bourne et al.*, 2010]. Our recent comprehensive climatological study of Arctic and Antarctic SBI characteristics [*Zhang et al.*, 2011] confirmed and extended earlier work, showing SBIs in both polar regions to be more frequent, deeper, and stronger in winter and autumn than in summer and spring, and compared radiosonde observations of SBI climatology to a reanalysis dataset and two climate model representations.

[4] Four prior studies, all based on radiosonde or dropsonde data, have presented changes in Arctic SBI features, for different Arctic regions and time periods, with different findings regarding SBI trends (Table 1). *Bradley et al.* [1993] found significant reductions in SBI depth in midwinter over the North American Arctic and suggested possible mechanisms, including shifts in atmospheric circulation and increases in cloudiness, ice crystal occurrence, greenhouse gases, and Arctic haze events. *Walden et al.* [1996] re-examined that study using monthly-average profiles and found no significant decrease in inversion heights. They argued that data inhomogeneities due to changes in radiosonde thermistor response time, balloon ascent rate, radio transmission rate, reporting policies, and corrections for thermal lag may have caused the apparent decrease reported by *Bradley et al.* [1993]. *Kahl et al.* [1996] studied long-term changes in low-level inversions over the Arctic Ocean using: (1) daily data for all inversions, including both SBIs and elevated inversions; (2) daily data for SBIs only; and (3) monthly-average data. They also did not discern the reported wintertime decrease in SBI depth but found that Arctic inversions became stronger, more frequent, with a larger proportion of elevated inversions, during 1950-1990. More recently, *Bourne et al.* [2010] reported decreases and multi-decadal variations in SBI frequency and depth over Alaska during 1957–2008, but increases during 1990–2008; this study did not consider data homogeneity issues. Accounting for data inhomogeneity, we evaluate these previous studies and extend them spatially and temporally by presenting trends in SBI characteristics at Arctic radiosonde stations during the recent two decades.

2. Data and Method

[5] Our analysis uses the dataset developed by *Zhang et al.* [2011], who give details regarding data processing, quality control, and the sensitivity of climatological SBI statistics to methodological choices. *Zhang et al.* [2011] identified SBIs by scanning twice-daily radiosonde temperature profiles from the surface upward to 500 hPa in search of temperature inversions (increasing temperature with height). The SBI top is the bottom of the first layer in which temperature decreases with altitude, although thin (<100 m) non-inversion layers are ignored if they are embedded within a deeper inversion layer. Profiles with SBI are used to construct monthly, seasonal and annual time series of SBI frequency of occurrence (f), intensity (ΔT, temperature difference from the surface to the SBI top), and depth (Δz, altitude above ground level of the SBI top). For trend estimates, we created anomaly time series for ΔT and Δz for the 20-year period 1990–2009. Station data were considered sufficient for trend analysis if at least 10 soundings per month, with

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Table 1. Previously Reported Trends in Arctic Surface-based Inversions Based on Radiosonde Data

Reference	Region	Period	Time	SBI trend		
				Frequency	Depth	Intensity
Bradley et al. [1993]	9 North American Stations	1952–1990	Winter 1200 UTC	No systematic changes	−63 – −164 m/decade	
Walden et al. [1996][a]	2 Stations	1953–1990	Winter 1200 UTC		No significant trend	No trend at Barrow; 0.8 K/decade at Eureka
Kahl et al. [1996][b]	Arctic Ocean	1950–1990	4 seasons		No significant changes	0.5–1.8 K/ decade
Bourne et al. [2009]	7 Alaskan stations	1957–2008	December and January	−0.2 – −5.3%/decade	−32 – −118 m/decade	−0.42 – −0.98 K/decade
		~1990–2008		Slight increase	More positive in last decade	Increase

[a] Mean monthly temperature data, not solely SBI cases, used to estimate trends.

[b] Radiosondes from the former USSR ‘North Pole’ series of drifting ice stations and dropsondes from US Air Force ‘Ptarmigan’ weather reconnaissance aircraft.

at least 10 reported levels between the surface and 500 hPa, were available at both 0000 and 1200 UTC, and 18 or 9 years of data were available for 20-yr or 10-yr trends, respectively. Among Arctic radiosonde stations, this requirement eliminated most Russian records from this analysis.

[6] Motivated by *Walden et al.* [1996], who first recognized the problem, *Zhang et al.* [2011] showed that changes in the vertical resolution of archived radiosonde data (due to changes in radiosonde instruments and observing practices [*Gaffen*, 1994]) introduce artificial changes in SBI ΔT, Δz, and, to a lesser extent, f time series; additional examples will be given below. As in *Zhang et al.* [2011], we employed a non-parametric statistical method [*Lanzante*, 1996] to detect change-points in time series of monthly average number of reported data levels below 500 hPa. The detected change-points and station history metadata were then used in visual inspection of time series of SBI features at each station to identify possible change-points associated with detected change-points in vertical resolution. Most Canadian, Greenland and Eurasian Arctic stations are plagued by data inhomogeneities, particularly in SBI ΔT and Δz time series, associated with changes in sounding resolution.

[7] *Walden et al.* [1996] recommended using monthly-average temperature profiles to study trends Arctic inversions to avoid the vertical resolution problem; we compare trend results using this approach to our method using individual SBI profiles below.

[8] *Zhang et al.* [2011] analyzed data from only 39 (of the possible 113) Arctic radiosonde stations with homogeneous SBI frequency time series for 1990–2009. Here we employ data from 30 of those stations (Table 2); nine did not have sufficient data at both 0000 and 1200 UTC.

[9] The *Zhang et al.* [2011] datasets are derived from an enhanced version of the Integrated Global Radiosonde Archive [IGRA, *Durre and Yin*, 2008]. Although IGRA data have relatively high vertical resolution in recent years, the Stratospheric Processes and Their Role in Climate (SPARC) Data Center (http://www.sparc.sunysb.edu/) [*Wang and Geller*, 2003] offers sounding data with even greater detail (about 30 m resolution), but only for 1998–2007. To test whether the vertical resolution of IGRA data is sufficient for estimating SBI trends, we compared trends from IGRA and SPARC soundings for the 7 common stations in Alaska for this 10-year period.

[10] Trends in SBI characteristics were computed using the non-parametric median of pair-wise slopes method [*Lanzante*, 1996] for each three-month season (defined following [*Serreze et al.*, 1992] as January-February-March, etc.) and for annual means, with statistical significance levels based on Spearman rank-order tests.

3. Results

3.1. Radiosonde Data Quality and Homogeneity

[11] For all three SBI parameters, we obtained fairly consistent trends from the IGRA and SPARC sounding data, although most of the trends were not statistically significant for the short (10 year) common period of record. Most (85%) of the trends were of the same sign in both datasets, and estimated f, Δz, and ΔT trends differed by no more than 0.6% decade^{-1}, 7 m decade^{-1}, and 0.05 K decade^{-1}, respectively. These differences are at least an order of magnitude smaller than the 10-year trends (Table 2). On this

Table 2. Seasonal Trends in Surface-based Inversion Frequency (% decade^{-1}), Depth (m decade^{-1}) and Intensity (K decade^{-1}) at Stations With Homogeneous Time Series, Grouped by Region, for Two Periods, and the Average Number of Levels in the Soundings[a]

(a) Frequency trend

	Station			1990–2009									2000–2009								
					JFM		AMJ		JAS		OND			JFM		AMJ		JAS		OND	
Region	Name	Lat	Lon	Levels	Mean	Trend	Mean	Trend	Mean	Trend	Mean	Trend	Levels	Mean	Trend	Mean	Trend	Mean	Trend	Mean	Trend
Alaska	BARROW	71	−157	21.7	57	0.5	33	2.6	27	−4.5	44	**−17.6**	17.9	56	0.7	34	−5.2	26	0.2	37	−16.7
	KOTZEBUE	67	−163	20.7	75	1.5	59	−4.8	30	**−5.0**	62	−2.4	17.8	75	5.3	57	3.1	26	**9.1**	61	17.7
	NOME	65	−165	20.0	65	**−6.4**	45	−4.2	39	**−6.4**	55	**−11.4**	17.2	60	14.0	40	**13.0**	33	**11.8**	50	9.8
	BETHEL	61	−162	20.5	49	8.8	35	3.7	30	2.0	44	**13.0**	17.6	53	1.4	36	201	32	−3.3	50	1.9
	MCGRATH	63	−156	19.2	56	6.8	40	−2.6	38	1.5	52	5.4	16.3	57	−3.7	38	0.6	36	4.9	55	−16.8
	FAIRBANKS	65	−148	19.3	70	2.4	49	4.1	44	7.5	65	1.5	16.6	70	−0.9	50	5.7	46	102	67	−6.5
	ANCHORAGE	61	−150	19.7	56	**−15.1**	40	−6.5	39	−6.4	52	**−10.0**	17.7	48	−14.0	37	−11.4	36	−10.7	47	**−16.2**
Canada	NORMAN WELLS	65	−127	16.0	43	3.3	35	1.4	37	−0.4	41	0.2	17.2	44	9.5	35	−0.5	37	−0.3	41	4.9
	HALL BEACH	69	−81	16.9	80	**4.1**	44	−5.7	40	−1.4	57	−2.9	18.1	81	7.0	43	−6.6	39	−11.9	57	5.3
	CORAL HARBOUR	64	−83	17.7	89	0.8	34	**−7.0**	20	**−4.6**	66	**−5.4**	18.1	89	−0.1	31	−0.6	18	−3.2	63	3.53.5
	EUREKA	80	−86	16.7	86	−0.7	55	−0.3	49	1.8	77	−2.1	17.7	85	2.6	54	7.7	49	18.1	76	−4.7
	RESOLUTE BAY	75	−95	17.1	75	2.1	38	**−4.1**	24	−0.2	60	−9.3	18.1	74	**10.6**	35	−3.7	24	−10.0	57	−20.6
	BAKER LAKE	64	−96	17.3	66	−1.1	33	−4.5	30	2.2	48	−7.8	18.7	64	6.5	30	4.1	32	−5.4	46	−9.3
	FORT SMITH	60	−112	15.9	36	−0.1	32	0.6	36	−1.3	31	3.8	16.8	36	−3.2	32	0.0	35	6.5	34	−3.0
	INUVIK	68	−134	17.3	53	**6.7**	30	1.1	29	2.8	51	3.1	18.2	56	15.3	31	−0.1	30	**12.1**	52	**23.6**
Greenland	EGEDESMINDE	69	−53	14.8	53	**−14.0**	24	**−12.1**	20	3.0	39	−1.1	15.0	46	9.2	18	−3.1	23	7.9	39	**25.8**
	DANMARKSHAVN	77	−19	16.2	79	−2.2	40	−0.3	35	0.1	77	3.2	16.9	78	10.2	39	**−15.4**	35	**27.7**	78	**30.5**
	AMMASSALIK	66	38	14.7	64	−3.5	31	−2.4	35	4.8	62	3.2	15.2	63	**37.8**	30	**20.2**	36	**34.5**	64	**26.3**
Iceland	KEFLAVIK	64	23	15.3	53	**−9.5**	16	**−2.9**	20	2.6	53	−5.1	15.1	47	−8.2	14	−2.1	20	−0.7	51	**−20.3**
Europe	JAN MAYEN	71	−9	16.5	32	2.2	19	−0.8	24	−3.7	30	3.6	16.9	33	7.8	18	−0.6	23	12.0	34	−12.2
	BJORNOYA	75	19	16.3	43	−4.5	22	**−7.9**	24	**−12.3**	41	0.4	16.6	41	**12.3**	18	**−10.2**	20	−18.8	42	−16.5
	SODANKYLA	67	27	15.6	37	**−5.5**	29	1.7	29	2.3	30	**−6.5**	16.1	36	−8.2	29	0.6	29	5.9	27	−4.8
	JOKIOINEN	61	24	18.2	21	0.7	31	1.3	34	−0.6	20	−2.1	20.2	22	−3.6	32	2.6	33	−2.4	19	5.0
Russia	MURMANSK	69	33	12.0	40	−4.7	16	**5.2**	21	0.6	29	−3.1	12.1	39	−13.5	19	−3.1	22	−4.3	28	−16.4
	SALE-KHARD (OBDORSK)	67	67	12.6	73	−6.1	35	3.4	27	0.5	57	**−6.8**	12.8	70	−2.1	37	7.2	28	6.2	54	−12.2
	TURUKHANSK	66	88	11.9	52	−0.8	27	−1.2	24	−2.6	43	0.7	12.0	52	−6.5	26	**−14.2**	20	−3.7	43	6.5
	SYKTYVKAR	62	51	12.0	29	−0.8	37	1.7	37	1.3	21	2.3	12.4	29	**−14.6**	37	−5.7	36	−7.4	19	−20.1
	OLENEK	69	122	11.6	79	−1.7	16	**3.1**	23	2.2	74	**−7.7**	12.0	79	−11.7	18	8.5	26	15.3	70	−2.0
	VERKHOYANSK	68	133	12.3	90	0.9	33	2.9	33	8.2	77	**−7.6**	12.6	90	0.9	32	15.0	38	5.1	74	−10.1
	YAKUTSK	62	130	12.3	75	0.7	29	0.0	36	3.0	56	1.1	12.8	76	9.8	29	4.7	38	7.8	57	4.0

Table 2. (continued)

(b) Depth trend

	Station			1990–2009					2000–2009				
Region	Name	Lat	Lon	Levels	JFM	AMJ	JAS	OND	Levels	JFM	AMJ	JAS	OND
Alaska	BETHEL	61	−162	20.5	**58.9**	**35.0**	**25.2**	33.7	17.6	**150.6**	40.7	3.1	25.2
	MCGRATH	63	−156	19.2	**103.4**	**41.8**	**35.6**	**108.7**	16.3	61.4	−1.7	−16.6	1.8
Canada	NORMAN WELLS	65	−127	16.0	**−80.4**	−28.9	**−51.0**	**−104.6**	17.2	−36.4	−63.5	−54.9	**−192.4**
	RESOLUTE BAY	75	**−95**	17.1	−52.3	**−72.7**	**−55.5**	**−62.6**	18.1	55.8	**−72.2**	−101.1	**−115.3**
Iceland	KEFLAVIK	64	−23	15.3	−8.3	−8.2	−13.1	−12.0	15.1	−20.5	3.3	−19.4	**−43.5**
Europe	JAN MAYEN	71	−9						16.9	0.0	3.7	−37.3	−21.7
	BJORNOYA	75	19						16.6	−17.0	8.8	−36.3	−7.1
	SODANKYLA	67	27	15.6	−37.1	**−20.9**	**−26.1**	**−47.8**	16.1	−31.2	**−27.4**	−7.5	**−106.1**
Russia	MURMANSK	69	33	12.0	11.0	3.3	17.6	20.1	12.1	31.7	**−122.0**	16.	−107.4
	SALE-KHARD	67	67	12.6	8.4	33.4	−14.0	33.8	12.8	−165.4	11.7	32.4	130.1
	TURUKHANSK	66	88	11.9	**65.6**	25.9	35.3	−7.2	12.0	88.2	9.5	**102.2**	114.2
	OLENEK	69	112	11.6	53.0	−71.2	−21.9	2.4	12.0	−14.7	260.2	13.3	−7.5
	YAKUTSK	62	130	12.3	14.1	−4.5	17.7	−13.0	12.8	93.2	−67.9	−19.7	**−117.7**

(c) Intensity trend

	Station			1990–2009					2000–2009				
Region	Name	Lat	Lon	Levels	JFM	AMJ	JAS	OND	Levels	JFM	AMJ	JAS	OND
Alaska	KOTZEBUE	67	−163	20.7	0.0	−0.4	**0.5**	0.0	17.8	2.0	−0.3	0.7	0.2
	NOME	65	−165	20.0	0.2	0.4	**0.5**	0.2	17.2	**1.2**	0.5	0.5	1.4
	BETHEL	61	−162	20.5	0.5	0.8	**0.4**	0.0	17.6	1.8	−0.1	0.4	2.4
	MCGRATH	63	−156	19.2	1.1	0.4	**0.6**	1.0	16.3	2.2	0.3	−0.1	−0.3
	FAIRBANKS	65	−148	19.3	**0.2**	**0.6**	**0.7**	0.5	16.6	−0.8	0.7	−0.4	−0.8
Canada	NORMAN WELLS	65	−127	16.0	−0.2	0.1	0.4	−0.2	17.2	−0.6	0.0	0.9	−1.9
	HALL BEACH	69	−81	16.9	0.0	−0.1	0.6	−0.5	18.1	0.9	0.2	−1.1	−1.2
	CORAL HARBOUR	64	−83	17.7	−0.4	0.2	−0.1	**−0.8**	18.1	0.3	0.3	**−0.8**	**−1.5**
	EUREKA	80	−86	16.7	0.0	0.5	0.2	−0.2	17.7	1.9	−0.2	0.5	−0.9
	RESOLUTE BAY	75	−95	17.1	−0.4	**−0.6**	0.3	−0.3	18.1	0.3	0.2	−0.6	−0.4
	INUVIK	68	−134	17.3	−0.5	0.2	**0.4**	−0.2	18.2	**−1.7**	0.2	0.1	**−2.7**
Iceland	KEFLAVIK	64	−23	15.3	**0.20**	0.0	**0.2**	0.1	15.1	**0.5**	**0.8**	0.3	0.0
Europe	JAN MAYEN	71	−9						16.8	0.0	0.2	0.4	0.3
	BJORNOYA	75	19						16.6	−0.2	0.1	0.1	0.2
	SODANKYLA	67	27	15.6	0.5	0.0	0.0	−0.4	16.1	0.5	0.4	−0.2	−4.8
Russia	MURMANSK	69	33	12.0	0.2	0.1	**0.5**	0.2	12.1	−0.6	**−0.7**	−0.5	**−1.9**
	SALE-KHARD	67	67	12.6	0.5	0.1	0.4	0.7	12.8	−1.7	0.4	0.9	−0.2
	TURUKHANSK	66	88	11.9	0.4	−0.1	0.1	0.6	12.0	−0.4	**−1.7**	0.6	0.5
	YAKUTSK	62	130	12.3	**−1.0**	**−1.3**	−0.6	**−1.7**	12.8	−1.2	−1.4	−1.1	−3.0

[a] Seasonal mean SBI frequencies (%) are shown with the frequency trends. Bold indicates trends significant at 95% confidence level or greater. Blanks denote inhomogeneous time series for which trends were not computed.

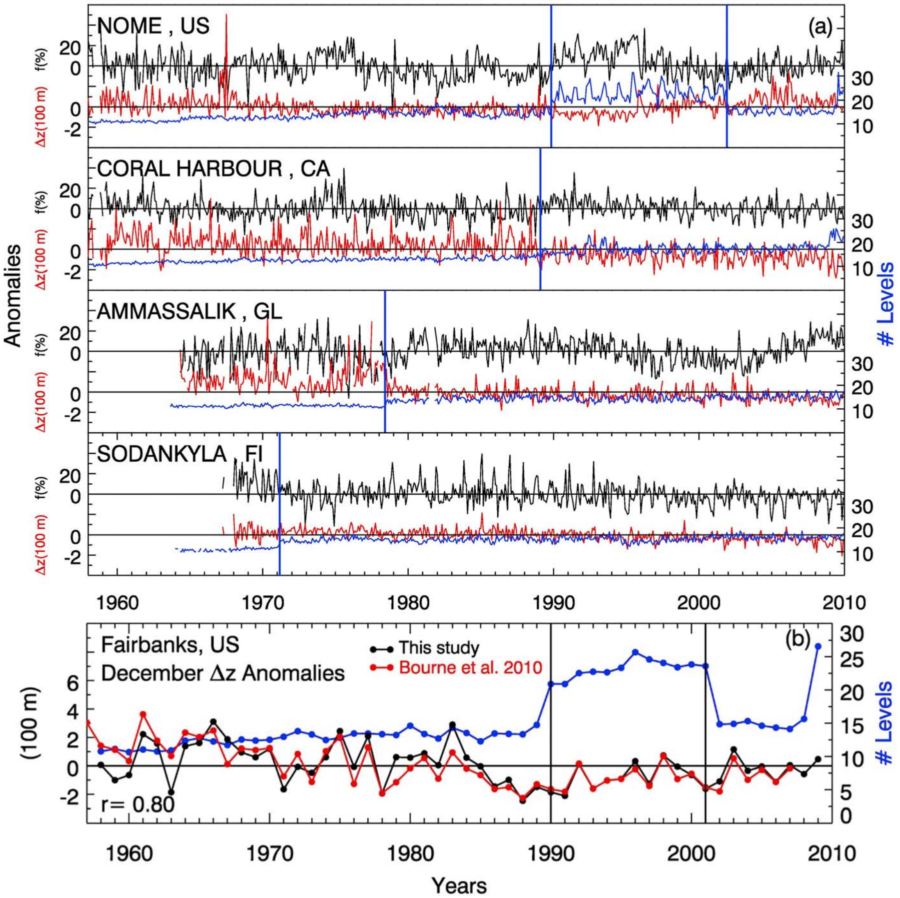

Figure 1. (a) Time series of monthly anomalies of SBI frequency (black) and depth (red) and monthly average number of data levels at or below 500 hPa (blue) at four stations (Nome, Coral Harbour, Ammassalik, and Sodankyla) during the past five decades. Blue vertical lines show statistically detected change-points in the number of levels. (b) Time series of December SBI depth anomalies at Fairbanks, Alaska, from *Bourne et al.* [2010] (red) and from this study (black). As in (a) monthly average number of data levels and associated statistically detected change-points are shown in blue.

basis, we accept the IGRA data as sufficiently detailed for SBI trend estimates for the rest of the network and over longer periods with homogeneous data, and results reported below are all based on IGRA.

[12] To illustrate in more detail than given by *Zhang et al.* [2011, see their Figure 2] the effect of changing sounding vertical resolution, Figure 1a presents monthly time series of SBI frequency and depth anomalies and average number of levels from surface to 500 hPa at four stations: Nome (US), Coral Harbour (Canada), Ammassalik (Greenland), and Sodankyla (Finland) during the past five decades. Radiosonde vertical resolution has changed at all four stations, often abruptly, as confirmed by statistically significant change-points in the number of levels (blue curves). These changes affect SBI depth (red curves) at all stations except Sodankyla, with increasing vertical resolution generally leading to apparent decreasing SBI depth. However, SBI frequency time series are not affected. Therefore, in our analysis, these four stations are all considered homogeneous stations in SBI frequency; but only Sodankyla is considered to be a homogeneous station in SBI depth. Similar analysis was made for each of the 30 stations (Table 2); only 11 and 17 of those stations had homogeneous SBI depth and intensity time series, respectively, during 1990–2009. For the 2000–2009 period, 30, 13, and 19 stations had sufficiently complete and homogeneous f, Δz, and ΔT time series, respectively.

3.2. Reproducibility of Previous Studies

[13] To test our analysis methods, and in light of the data quality and homogeneity issues discussed above, we attempted to reproduce the trends reported by previous studies (Table 1). (We did not address the results of *Kahl et al.* [1996], because the drifting ice station and weather reconnaissance aircraft observing programs are no longer in operation, so their trend estimates cannot be updated.) Using IGRA data from the same stations for the same periods, and attempting to reproduce analysis methods (including using monthly mean data rather than only soundings showing SBIs for comparison with *Walden et al.* [1996]), we obtained very similar trend estimates, with the one exception that we did not find a significant trend in SBI intensity at Eureka, as reported by *Walden et al.* [1996]. This suggests (1) that IGRA's compilation of sounding data and quality control (which was not available for the earlier studies) does not much affect the representation of long-term SBI variations, and (2) that our methods of obtaining SBI characteristics from soundings and of estimating trends are consistent with previous studies.

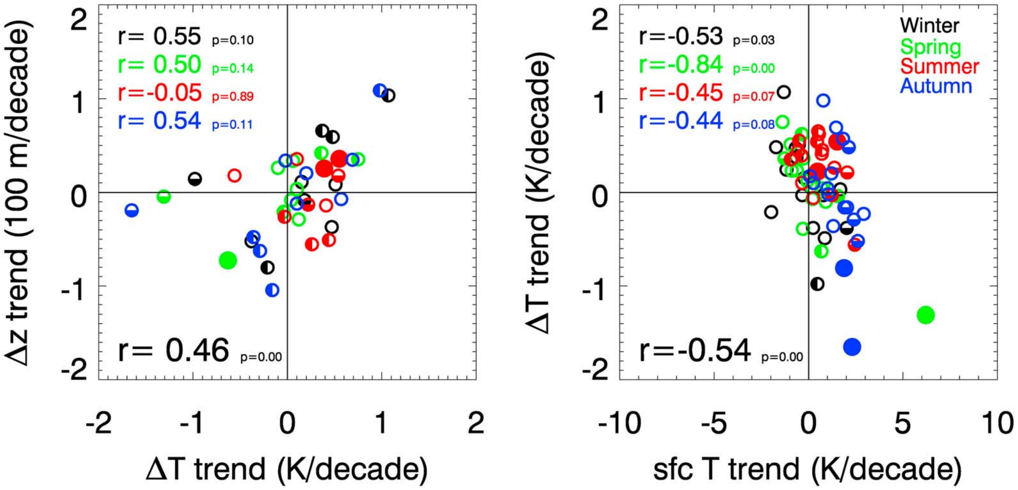

Figure 2. Scatter plots comparing seasonal trends in SBI depth and intensity (left panel) and SBI intensity and surface temperature (right panel). Solid circles denote both trends are significant at the 95% confidence level or greater; open circles mean neither trend is significant; half-filled circles mean one of the two trends is significant. Correlation coefficients for each season are shown at the top of each panel, and correlations of annual trends are at the bottom left.

[14] However, if data homogeneity problems are taken into account, they seriously undermine previously published results. While *Bradley et al.* [1993] recognized the increase in the number of significant levels in their data during 1952–1990, they suggested it had no influence on their finding of decreasing SBI Δz. In contrast, we find that 8 of the 9 stations they examined have inhomogeneous Δz time series over this period, and 4 have inhomogeneous f time series. And 5 of the 7 Alaskan stations analyzed by *Bourne et al.* [2010] have inhomogeneous records for both 1957–2008 and 1990–2008. For example, Figure 1b shows time series of SBI depth anomalies in December at Fairbanks from *Bourne et al.* [2010] (red curve) and from this study (black curve). The same sounding data are used in the two studies, and the time series are highly correlated (r = 0.8), but there are small differences, probably because *Bourne et al.* [2010] converted profile vertical coordinates from geopotential to geometric height and interpolated the data to 50 m height increments, which we did not. However, the time series of number of levels (blue curve) shows higher sounding resolution during 1990–2001 than in other years, and SBI Δz are lower during that period. Hence, the reported decrease in SBI depth in *Bourne et al.* [2010] is likely spurious. In summary, while analysis of contemporary radiosonde data archives results in SBI trend estimates that compare well with earlier estimates using other archives, with the exception of *Walden et al.* [1996], those estimates generally did not consider data inhomogeneities, which can cause artificial trends in SBI properties.

3.3. Arctic SBI Trends Based on Homogeneous Data

[15] Table 2 shows seasonal trends in SBI characteristics from homogeneous station records during two periods, the average number of levels from surface to 500 hPa, and mean seasonal SBI frequency. For 1990–2009, SBI frequency trends, when statistically significant, are four times more likely to be negative than positive, with magnitudes of several percent per decade (compared with climatological values of about 30 to 90%, with higher frequencies in winter than summer). SBI depth increased (by 25 to 109 m decade^{-1}) at two stations in Alaska but decreased at stations in Canada, and Europe (Table 2), and most trends in SBI intensity were not statistically significant. For the most recent decade (2000–2009), the statistically significant SBI frequency trends are more often positive than negative, in contrast with the 20-yr negative trends, highlighting both the sensitivity of trend estimates to data period and the decadal variability of Arctic climate. Stations in Greenland show significant increases of 15 to 38 % decade^{-1} during this period. The majority of SBI depth and intensity trends for this decade are not statistically significant. The shorter data record and smaller sample size increases trend uncertainty. Somewhat similarly, because SBI frequencies are lower in spring and summer, mean seasonal SBI intensity and depth values for those seasons are based on smaller samples than for autumn and winter, which probably makes spring and summer trends more uncertain.

[16] We also examined the correlations among the trends in three SBI properties and their relations with the surface temperature trends. Only two apparent relationships emerged. Correlations between seasonal SBI depth trends and intensity trends (Figure 2, left panel) are near 0.5, except in summer. In contrast, seasonal SBI intensity trends are negatively correlated with surface temperature trends (Figure 2, right panel), especially in spring, with annual r = −0.54. This result is consistent with the finding in *Zhang et al.* [2011], who found that higher surface temperatures are often associated with weaker SBIs on a seasonal and interannual basis.

3.4. Sensitivity of Trends to Methodological Choices

[17] *Zhang et al.* [2011] found that climatological SBI statistics are not very sensitive to the threshold thickness of tolerated embedded non-inversion layers within SBIs for thresholds less than the 100 m value used in that and the current study. Larger threshold values had little effect on SBI frequency statistics but led to higher SBI depth and intensity estimate. Figure S1 in the Supplementary Material[1]

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[1] Auxiliary materials are available in the HTML. doi:10.1029/2011GL048728.

shows analogous results of tests of the sensitivity of SBI trend estimates. With thickness thresholds of 1, 50, 150, 200, and 300 m, seasonal trends in SBI frequency show no bias and very high (0.99) correlations with frequency trends based on the 100 m threshold. SBI depth and intensity trends estimates using thickness thresholds of 150 m or less are also in excellent agreement ($r > 0.95$) with those based on the 100 m threshold, but for 200 and 300 m thresholds, correlations are somewhat lower (0.64 to 0.90).

[18] We also compared 1990–2009 trends in inversion depth and intensity based on monthly average temperature profiles, as suggested by *Walden et al.* [1996], with our results based only on soundings showing SBIs. Figure S2 shows that SBI depth trends agree reasonably well ($r \sim 0.68$) in winter and autumn (when SBI frequencies are largest) but very poorly in summer and spring. The two approaches are in poor agreement for SBI intensity trends in all seasons. Since monthly averages can include profiles without SBIs, their trends are not direct indicators of changes in SBI characteristics.

4. Conclusion

[19] Our attempt to evaluate changes in surface-based inversions (SBIs) using data from Arctic radiosonde stations has revealed constraints posed by the observational record and some limited information about SBI changes since 1990. The main findings are:

[20] 1. Changes in vertical resolution of radiosonde observations can cause inhomogeneities in time series of estimated SBI features. SBI depth and intensity are more sensitive to this problem than SBI frequency. This problem severely limits the value of the radiosonde archive for long-term SBI trend estimates in the Arctic, and previous reported trends are likely to be erroneous.

[21] 2. Seasonal trends in SBI frequency were estimated at about 30 stations with homogeneous records, and trends in SBI depth and intensity were estimated at fewer stations. Most trends were not statistically significant, and few clear patterns of SBI change emerge. SBI intensity trends are positively correlated with SBI depth trends, but negatively related with the surface temperature trends.

[22] 3. Alaskan stations show increases in SBI depth for 1990–2009, while Arctic stations in Canada and Europe show decreases. All three stations in Greenland show increases in SBI frequency over the decade 2000–2009.

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References

ACIA (2004), *Impacts of a warming Arctic: Arctic Climate Impact Assessment*, Cambridge University Press, New York.

Bourne, S. M., U. S. Bhatt, J. Zhang, and R. Thoman (2010), Surface-based temperature inversions in Alaska from a climate perspective, *Atmos. Res.*, *95*, 353–366, doi:10.1016/j.atmosres.2009.09.013

Bradley, R. S., F. T. Keimig, and H. F. Diaz (1993), Recent changes in the North American Arctic boundary layer in winter, *J. Geophys. Res.*, *98*, 8851–8858, doi:10.1029/93JD00311.

Deser, C., R. Tomas, M. Alexander, and D. Lawrence (2010), The seasonal atmospheric response to projected Arctic sea ice loss in the late 21st century, *J. Climate*, *23*, 333–351.

Durre, I., and X. Yin (2008), Enhanced radiosonde data for studies of vertical structure, *Bull. Am. Meteor. Soc.*, *89*, 1257–1262, doi:10.1175/2008BAMS2603.1.

Gaffen, D. J. (1994), Temporal inhomogeneities in radiosonde temperature records, *J. Geophys. Res.*, *99*, 3667–3676, doi:10.1029/93JD03179.

Intergovernmental Panel on Climate Change (2007), *Climate Change 2007: The Physical Science Basis: Working Group I Contribution to the Fourth Assessment Report of the IPCC*, edited by S. Solomon et al., Cambridge Univ. Press, New York.

Kahl, J. D. W., D. A. Martinez, and N. A. Zaitseva (1996), Long-term variability in the low-level inversion layer over the Arctic Ocean, *Int. J. Climatol.*, *16*, 1297–1313.

Lanzante, J. R. (1996), Resistant, robust and non-parametric techniques for the analysis of climate data: Theory and examples including applications to historical radiosonde station data, *Int. J. Climatol.*, *16*, 1197–1226.

Mernild, S. H., and G. E. Liston (2010), The influence of air temperature inversion on snowmelt and glacier mass balance simulations, Ammassalik Island, Southeast Greenland, *J. Appl. Meteor. Climatol.*, *49*, 47–67, doi:10.1175/2009JAMC2065.1.

Pavelsky, T. M., J. Boé, A. Hall, and E. J. Fetzer (2011), Atmospheric inversion strength over polar oceans in winter regulated by sea ice, *Clim Dyn*, *36*, 945–955, doi: 10.1007/s00382-010-0756-8

Richter-Menge, J., (Ed.) (2010), The Arctic [in "State of the Climate in 2009"], *Bull. Amer. Meteor. Soc.*, *91*(7), S79–106, doi:10.1175/BAMS-91-7-StateoftheClimate.

Screen, J. A., and I. Simmonds (2010), The central role of diminishing sea ice in recent Arctic temperature amplification, *Nature*, *464*, 1334–1337, doi:10.1038/nature09051.

Serreze, M. C., A. P. Barrett, J. C. Stroeve, D. N. Kindig, and M. M. Holland (2009), The emergence of surface-based Arctic amplification, *Cryosphere*, *3*, 11–19, doi:10.5194/tc-3-11-2009.

Serreze, M. C., J. D. Kahl, and R. C. Schnell (1992), Low-level temperature inversions of the Eurasian Arctic and comparisons with Soviet drifting station data, *J. Climate*, *5*, 599–613.

Walden, V. P., A. Mahesh, and S. G. Warren (1996), Comment on "Recent changes in the North American Arctic boundary layer in winter", *J. Geophys. Res.*, *101*, 7127–7134.

Wang, L., and M. A. Geller (2003), Morphology of gravity-wave energy as observed from 4 years (1998–2001) of high vertical resolution U.S. radiosonde data, *J. Geophys. Res.*, *108*(D16), 4489, doi:10.1029/2002JD002786.

Zhang, Y., D. J. Seidel, J.-C. Golaz, C. Deser, and R. A. Tomas (2011), Climatological characteristics of Arctic and Antarctic surface-based inversions, *J. Climate*, accepted.

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