

## ***Interactive comment on “Snow density climatology across the former USSR” by X. Zhong et al.***

**X. Zhong et al.**

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Received and published: 29 September 2013

Reply to M. Sturm’s Interactive comment on “Snow density climatology across the former USSR” by X. Zhong et al.

First of all, we appreciate the reviewer for his constructive and insightful comments and suggestions for this manuscript. We consider all comments and suggestions seriously. All comments are very helpful for further revision of our manuscript. We have made all necessary changes based on the reviewer’s comments and suggestion as described below.

M. Sturm’s General Comments: 1) The first is that the authors have missed some good but old references in on snow density. A paper like this, which is fundamentally a

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retrospective paper, needs to be exhaustive in citing the prior literature. There is strong tendency today for researchers to look at the last published paper on a subject and use the references therein as the starting point for their work. The references are:

Bilello, M. A. 1969. Relationships between climate and regional variations in snow-cover density in North America. CRREL Res. Rep. 267. Keeler, C. 1967. Some observations on the densification of alpine snow covers. CRREL Tech. Rep. 197. McKay, G. A., and B. F. Findlay, 1971: Variation of snow resources with climate and vegetation in Canada. Proc. 39th Western Snow Conf., Billings, MT, Western Snow Conference, 17–26. McKay, G. A. and D. M. Gray, 1981: The distribution of snowcover. In Handbook of Snow, 1st ed. D. M. Gray and E. D. H. Male, Eds., Pergamon Press, 153–190.

Reply: We have read these recommended references and we think they are very helpful for further revision of our manuscript and our research. We have added them in “Introduction” section.

2) The second problem is that the text is basically a verbal description of the figures. ...so much so that eventually the reader (or at least this reader) gets numb and confused reading all the numbers and the trend values and so on in the text. The figures are really very good and a reader can glean most that information directly from them. What is utterly missing in the text is what I call the “discerning eye and mind of the scientist.” There is no such thing as data without errors and flaws, particularly data collected across a continent by a legion of unnamed, and probably grossly underpaid, technicians who patiently collected the data through such a turbulent period of Russian history. The text of this (or any paper) has to do more than just describe the results. It has to discuss and interpret them. The current “Discussion-Conclusion” section is nothing more than another Abstract. This data set really demands more. The authors need to think about what the results show and why.

Reply: In addition to the description of figures, we have added more interpretations of

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the results in “Results” section. We added more interpretations of the variability in of distributions of snow density in Fig. 4 in the text:

Snow densities were consistent with the distributions of snow depth, they increased with increasing depth. In the thawing period, snow density increased by higher air temperature. The reasons of snow density did not come up quickly in the eastern Russia were most sites in forested environments, which were less affected by wind speed. And little changes in snow depth and low air temperature led to slow changes in densities in the arctic coast.

We also interpreted why there was a sudden drop in snow density in the 2000s:

From Fig.8, the annual variation of monthly snow density, we can find that there was a significant decrease trend during the 2000s in April, which may be the main reason. We found that density decrease was caused by the sudden increase of new snowfall with low density in April. Furthermore, air temperature increased led to snow depth decreasing significantly, and wind speed reduced clearly from 2000 to 2008, which may be the reasons for the step-change in snow density during the 2000s.

We have expanded discussion, and compared with the results in North America in “Discussion and Conclusion” section:

Our results were consistent with the past Russian results, but lower than the data of North America. We interpreted the differences by method of measurement, sites distribution, meteorological conditions and environment differences. Generally, the courses are about 1000 feet long in North America. However, snow surveys run 1000 to 2000 m in open terrain and 500 m in the forest over the former USSR. In addition, snow course are usually taken near the end or middle of the month and there is one record for each month (one or two records in May and June) in North America. But routine snow surveys run every 10 days in the cold season and every 5 days during snowmelt, this means that snow density is measured three times in one month at least in the former USSR. We averaged snow densities and then got the monthly mean for each

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site. Those differences of measurements may lead to the different outcomes. We compared with results in Brown and Mote (2009; Table 3), monthly mean snow density were 15% lower for tundra snow and 38% lower for ephemeral snow cover over the former USSR. Those due to most sites for tundra snow in the former USSR located at the south of 60°N. Affected by snow depth, air temperature, and wind speed, snow densities for tundra snow across the former USSR were lower than the values in Canada. The areas were smaller and the number of sites was fewer for ephemeral snow in Canada, the local characteristics may be causes of the differences. Differences of monthly mean snow density mainly appeared in May and June for other snow classes, which were affected by wind speed. In the two months, snow melt with high air temperature. Meanwhile, wind speed in Canada was significantly higher than the former USSR, which led to high snow density. Snow densities were lower than the results from the U.S. (Sturm et al., 2010). In addition to the above reasons, it can be explained by environment differences. Of the 1259 stations, 719 both measured in open field and forest areas. We compared the monthly mean snow density of the 719 stations at the two environments for snow classes. The results showed that mean snow densities measured in forest range from 8% to 13% less than those measured in open field. The very low percentages of maritime (3%) and alpine snow cover (8%) and fewer stations may not fully represent the climatology of snow density. Those may result station bias away from higher elevation mountain stations, which may be one reason of densities lower than the data in North America.

3) Which leads to the final and most serious flaw: the densities presented overall are disturbing low... far lower than the general range of the 25,000 data we used in our recent study of bulk densities from the U.S. (Sturm, M., Taras, B., Liston, G. E., Derksen, C., Jonas, T., and Lea, J.: Estimating snow water equivalent using snow depth data and climate classes, *J. Hydrometeorol.*, 11, 1380–1394, 2010) and lower than the approx. 200,000 data Brown used in his work in Canada. The density-time curves are also significantly lower than those from the classic work by MacKay and Findley (1971). Why? Is this real or an artifact of the way the data were collected and reduced? The

authors need to think about this issue and discuss it, as everything else hinges on it. I think after introducing the data, there should be a discussion of the data accuracy today and stretching back through 1968. I realize that the authors did not collect the data, but from the current text I cannot even tell how the bulk density values were derived. I think for each measurement the authors had access to depth (hs) and SWE (SWE). They then computed density from:

$$p_s = \text{SWE} \cdot \rho_i / h_s$$

where  $p$  is density and  $i$  indicates ice and  $s$  indicates snow. The point is that there is no discussion of the quality check/assurance for the data, nor how recent snowfalls can skew these bulk density computations. As a general rule, we tend to measure snow depth reasonably well, but there has been traditionally considerable problems with coring for SWE. In Sturm et al. (2010) there is a brief discussion of these issues. How were the Russian SWE values measured that are used in this study? A case in point is Figure 7 and there is a peculiar drop in density by almost 10% in 2000. I have difficulty even conceiving how the winter weather across a continent would have to change in order to manifest this way. On the other hand, I could well imagine that the Russians changed the core tubes their field people were using in 2000.

Reply: First of all, we had a mistake when computed monthly mean snow density for snow classes. In earlier version, snow density records less than 10 years were not omitted when we did quality control. Then we had corrected the data and the results showed that the densities presented increase, significantly higher than the values before corrected. We compared the results with past data in the former USSR (Bilello, 1984; Liston and Hiemstra, 2011; Bormann et al., 2013) and North America (McKay and Findlay, 1971; Sturm and Holmgren, 1998; Brown and Mote, 2009; Sturm et al., 2010). They were consistent with the past Russian data. While the data across the former USSR still slightly lower than North America except the values for taiga snow from the U.S. The reasons of the differences in snow density across the two regions were added in “Discussion-Conclusion” section:

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Generally, the courses are about 1000 feet long in North America. However, snow surveys run 1000 to 2000 m in open terrain and 500 m in the forest over the former USSR. In addition, snow course are usually taken near the end or middle of the month and there is one record for each month (one or two records in May and June) in North America. But routine snow surveys run every 10 days in the cold season and every 5 days during snowmelt, this means that snow density is measured three times in one month at least in the former USSR. We averaged snow densities and then got the monthly mean for each site. Those differences of measurements may lead to the different outcomes. Compared with results in Brown and Mote (2009; Table 3), monthly mean snow density were 15% lower for tundra snow and 38% lower for ephemeral snow cover over the former USSR. Those due to most sites for tundra snow in the former USSR located at the south of 60°N. Affected by snow depth, air temperature, and wind speed, snow densities for tundra snow across the former USSR were lower than the values in Canada. The areas were smaller and the number of sites was fewer for ephemeral snow in Canada, the local characteristics may be causes of the differences. Differences of monthly mean snow density mainly appeared in May and June for other snow classes, which were affected by wind speed. In the two months, snow melt with high air temperature. Meanwhile, wind speed in Canada was significantly higher than the former USSR, which led to high snow density. Snow densities were lower than the results from the U.S. (Sturm et al., 2010). In addition to the above reasons, it also can be explained by environment differences. Of the 1259 stations, 719 both measured in open field and forest areas. We compared the monthly mean snow density of the 719 stations at the two environments for snow classes. The results showed that mean snow densities measured in forest range from 8% to 13% less than those measured in open field. And the very low percentages of maritime (3%) and alpine snow cover (8%) and fewer stations may not fully represent the climatology of snow density. Those may result station bias away from higher elevation mountain stations, which may be one reason of densities lower than the data in North America.

After introducing the data, we added the description of how the bulk density was col-

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lected in detail (density was measured by gravimetric method with snow tube), and added the discussion of quality check for data in “Data and Methodology” section:

Snow density was made every 100 m at the 500 to 1000 m courses and every 200 m at the 2000 m course. In the comprehensive suite of measurements, bulk density was measured by taking a snow core into a snow tube. Snow depth could be read from the scale on the side of the snow tube. Mass of the snow sample was weighed by a balance. Then bulk density was calculated by dividing weight of core by the corer volume and reported. In the individual measurements of routine snow surveys, random and systematic errors occurred inevitably, leading to underestimate or overestimate densities with snow tube. To minimize errors, quality control of meteorological data had been done before they were stored at the RIHMI-WDC. We implemented the second correction of snow density according to the quality assessment criteria assigned by NSIDC: mean snow densities which exceeded the range of 0-0.6 g cm<sup>-3</sup> were omitted. Furthermore, each site snow density records less than 10 years were excluded, and the data outside the scope of annual mean value plus or minus three standard deviations were also omitted.

In Fig. 7, there is a peculiar drop in density in 2000s. Bulygina et al. (2011) indicate that although the procedure for making snow observations changed in the past, there have been no changes in the observation procedures since 1965. From fig.8 of our text, the annual variation of monthly snow density, we can find that there was a significant decrease trend during the 2000s in April, which may be the main reason. We analyzed the reason of the decrease in April, which was caused by the increase of new snowfall with low density. Then, we analyzed the interannual trends of snow depth, wind speed and air temperature across the former USSR during 1966 to 2008. From the period of 2000 to 2008, air temperature increased obviously which lead to snow depth decreasing significantly. Furthermore, wind speed reduced clearly compared with the past. Therefore, these may be another reason for a sudden drop in snow density during the 2000s.

4) Figure 4 should be turned into a movie so that we can watch how a continental scale snow cover densifies through the winter.

Reply: We added a movie of Fig.4 as a supplement.

Specific Comments:

P. 3380, line 3: this is not quite the right word, as density is the link between depth and SWE.

Reply: We replaced it with linking.

P. 3381, line 5: Again, density is such a fundamental property of snow that relegating it to a factor in retrieving the other properties seems too limited.

Reply: We replaced it with linking.

P. 3381, line 21: The reference list is missing critical citations, and for paper like this needs to be as complete as possible because subsequent authors will look to the list as a starting point for their research. In fact, that is an essential element in such a paper.

Reply: We introduced some references of variations in snow cover in this paragraph, the critical citations about snow density were listed in the next paragraph. We completed the important information of these references in the text. P.3381, lines 20-29 revised:

Across the former USSR, snow cover characteristics, including snow density, are controlled by various environmental conditions. There were many studies indicated that snow cover areas had decreased significantly in Northern Hemisphere, especially in Eurasia (Robinson and Dewey, 1990; Gutzler and Rosen, 1992; Brown, 1997). However, the variations in snow depth, snow cover duration, and SWE presented regional features (Ye et al., 1998; Kitaev et al., 2005; Groisman et al., 2006; Bulygina et al., 2009). These changes in snow characteristics were closely related with climatic

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change (Foster et al., 1983; Groisman et al., 1994; Clark et al., 1999; Robock et al., 2003; Matsumura and Yamazaki, 2012; Cohen et al., 2012; Peng et al., 2013).

P. 3381, line 27: This should delete by.

Reply: We deleted it.

P. 3382, line 6: Insert “the” before “climatology”.

Reply: We inserted it.

P. 3382, line 9: You are missing one of the best studies on the topic. . .sadly neglected these days:

Title: RELATIONSHIPS BETWEEN CLIMATE AND REGIONAL VARIATIONS IN SNOW-COVER DENSITY IN NORTH AMERICA. Personal Author(s) : Bilello,Michael A. Report Date : DEC 1969

Reply: We have added these references which the reviewer recommended to us in the text:

Bilello (1969, 1984) classified the average snow density in four and five general categories over North America and the former USSR, respectively, basing on air temperature and wind speed. He proposed a method for estimating snow density, which related to air temperature and wind speed. McKay and Findlay (1971) estimated the time-density variations in 11 regions across Canada within vegetation and climatic influences. Sturm and Holmgren (1998) analyzed time-density curves for three snow classes in Alaska and Canada, and indicated that the differences in snow density for snow classes were primarily caused by differences in the rheological properties of the snowpack.

P. 3382, line 16: This is only true for the deep maritime snow covers. See Findley and Bilello etc. The basic ingredients for density are depth, temperature wind, and temperature gradient.

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Reply: In the Dai and Che's paper, they performed a regression analysis of snow density, precipitation, air temperature, snow depth, and wind speed, the results showed that snow depth was the primary influence on snow density only in Northeast and Northwest China not all areas of China. We revised.

P. 3382, line 19: SWE is never really measured per se. Observers take a core and weigh it, so it is a gravimetric measurement. It just happens that the spring scales read in SWE units, but it is a weight not a length that is actually measured.

Reply: I agree with you, we revised:

Snow density can be calculated by snow depth and SWE with a gravimetric method.

P. 3383, line 9: It is a little misleading to speak of daily snow density as later you describe the data coming every 5 to 10 days. But more importantly, density rises and falls as it snows and then the snow settles. You should think about the potential variability and whether the monthly means inherit a bias because of this natural process.

Reply: We changed daily snow density to snow density data at every 5 to 10 days interval. Routine snow surveys ran every 10 days in the cold season and every 5 days during snowmelt. That is, there were 3 to 6 times measurements of snow density in a month. In order to eliminate outliers appeared in extreme weather, we used monthly mean snow density. Furthermore, climatology is the long-term averaged level to reflect the variations in spatial and temporal scales. So the potential variability within a month may be insignificant for this reason.

P. 3383, line 26: This description of how the data were collected is not comprehensive enough to assess the errors in density. So depth was measured with a ruler. ...did the observers also take a core at each depth location, and was the SWE and depth reported, allowing you to compute density, or did they actual report density? You need to be very specific here.

Reply: In this paragraph, we added description of how to collect the data with snow

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tube in more detail. And added discussions of quality check of the data:

Snow density was collected every 100 m at the 500 to 1000 m courses and every 200 m at the 2000 m course. In the comprehensive suite of measurements, bulk density was measured by taking a snow core into a snow tube. Snow depth could be read from the scale on the side of the snow tube. Mass of the snow sample was weighed by a balance. Then bulk density was calculated by dividing weight of core by the corer volume and reported. In the individual measurements of routine snow surveys, random and systematic errors occurred inevitably, leading to underestimate or overestimate densities with snow tube. To minimize errors, quality control of meteorological data had been done before they were stored at the RIHMI-WDC. We implemented the second correction of snow density according to the quality assessment criteria assigned by NSIDC: mean snow densities which exceeded the range of 0-0.6 g cm<sup>-3</sup> were omitted. Furthermore, each site snow density records less than 10 years were excluded, and the data outside the scope of annual mean value plus or minus three standard deviations were also omitted.

P. 3384, line 4: This should read “points”.

Reply: We revised it.

P. 3385, line 5: The very low percentage of maritime and alpine snow covers reflects (I think) a station bias away from higher elevation mountain stations. This is worth a comment, as those missing snow covers are still very important, its just they are under-represented in the data set.

Reply: We added the discussion when compared with the data from North America in “Discussion” section:

The very low percentages of maritime (3%) and alpine snow cover (8%) and fewer stations may not fully represent the climatology of snow density. Those may result station bias away from higher elevation mountain stations, which may be one reason

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of densities lower than the data in North America.

P. 3385, line 18: This is very cool series of maps...but there are some puzzling features. First, and I will come back to this later, the densities seem on the low side. Second, the "lag" in the eastern arctic and sub-arctic in achieving higher densities seems strange. Much of this area has wind...and that usually brings the density up quickly.

Reply: We compared the results with past data in the former USSR (Bilello, 1984; Liston and Hiemstra, 2011; Bormann et al., 2013) and they were consistent with the past Russian data. In the eastern arctic and sub-arctic, most sites with snow survey in forested environments (Fig. 2b in Changes in snow cover characteristics over Northern Eurasia since 1966, Bulygina et al., 2011). Snow cover under the protection of trees in forests is less affected by wind speed, solar radiation compared with that in open fields. The variations in snow depth were not significantly with time in these areas. Therefore, snow density increased slowly.

P. 3386, line 27: There is nothing wrong with the preceding write-up, except that it perhaps doesn't get to the heart of the issue of what Figure 4 shows. For example, the density increases starting in an area in western Russia, north of the steppes. This spreads with time outward. Is it because more snow is piling up through the winter...or because that region has had enough warm weather to cause rapid settlement. The taiga I can image is cold and therefore the density tends to plateau through much of the winter....but why doesn't the arctic coast densities come up more quickly?

Reply: We added more interpretations of the variability in snow density in Fig. 4 in the text:

Changes in snow densities with time in western Russia, north of the steppes and in the arctic coast are closely related with the variations in snow depth and air temperature. Snow depth increased significantly from September to March in the western Russia. In spring months, higher air temperature led to snow melt. Both of them caused den-

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sities come up quickly in the areas. However, little changes in snow depth and low air temperature led to slow changes in densities in the arctic coast.

P. 3387, line 26: The authors need to plot the curves of MacKay and Findley (see Fig. 5.11 in the Handbook of Snow) on their Fig. 5 then address why there is clearly a low bias in the Russian data (or a high bias in the Canadian data).

Reply: We had a mistake when computed monthly mean snow density for snow classes. In earlier version, when we compute snow density, snow density records less than 10 years were not omitted when we did quality control. We had corrected the data and the results showed that the densities presented increase, significantly higher than the values before corrected. We compared the results with past data in North America. Some data across the former USSR were still slightly lower than North America but some of them higher than the data from Canada. The reasons of the differences in snow density across the two regions can be interpreted by site distribution, geographical features, method of measurement, and meteorological conditions, which were discussed in “Discussion-Conclusion” section:

Generally, the courses are about 1000 feet long in North America. However, snow surveys run 1000 to 2000 m in open terrain and 500 m in the forest over the former USSR. In addition, snow course are usually taken near the end or middle of the month and there is one record for each month (one or two records in May and June) in North America. But routine snow surveys run every 10 days in the cold season and every 5 days during snowmelt, this means that snow density is measured three times in one month at least in the former USSR. We averaged snow densities and then got the monthly mean for each site. Those differences of measurements may lead to the different outcomes. Compared with results in Brown and Mote (2009; Table 3), monthly mean snow density were 15% lower for tundra snow and 38% lower for ephemeral snow cover over the former USSR. Those due to most sites for tundra snow in the former USSR located at the south of 60°N. Affected by snow depth, air temperature, and wind speed, snow densities for tundra snow across the former USSR were lower than

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the values in Canada. The areas were smaller and the number of sites was fewer for ephemeral snow in Canada, the local characteristics may be causes of the differences. Differences of monthly mean snow density mainly appeared in May and June for other snow classes, which were affected by wind speed. In the two months, snow melt with high air temperature. Meanwhile, wind speed in Canada was significantly higher than the former USSR, which led to high snow density. Snow densities were lower than the results from the U.S. (Sturm et al., 2010). In addition to the above reasons, it also can be explained by environment differences. Of the 1259 stations, 719 both measured in open field and forest areas. We compared the monthly mean snow density of the 719 stations at the two environments for snow classes. The results showed that mean snow densities measured in forest range from 8% to 13% less than those measured in open field. And the very low percentages of maritime (3%) and alpine snow cover (8%) and fewer stations may not fully represent the climatology of snow density. Those may result station bias away from higher elevation mountain stations, which may be one reason of densities lower than the data in North America.

P. 3389, lines 17 to 23: Do the authors believe there was a step-change in snow density across Russia in 1990, because that is what Figure 7 shows. ....except that I am highly skeptical that the graph reflects a real change. For the step to happen, wind and weather would have to change in very distinct ways. This has the hallmark of a change in station methodology, and the authors need to very carefully eliminate that before just publishing the result.

Reply: We researched the references about the snow density measurements and found that Bulygina et al. (2011) indicate that there have been no changes in the observation procedures since 1965. So we excluded the possibility of different measurement techniques were used in 2000s. From fig.8 of our text, the annual variation of monthly snow density, we can find that there was a significant decrease trend during the 2000s in April, which may be the main reason. We analyzed the reason of the decrease in April, which was caused by the sudden increase of new

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snowfall with low density. Then, we analyzed the interannual trends of snow depth, wind speed and air temperature across the former USSR during 1966 to 2008. We found that, from the period of 2000 to 2008, air temperature increased obviously which lead to snow depth decreasing significantly. Furthermore, wind speed reduced clearly compared with the past. Therefore, these may be the main reasons for a sudden drop in snow density during the 2000s. We added the interpretation in the text.

Please also note the supplement to this comment:

<http://www.the-cryosphere-discuss.net/7/C1901/2013/tcd-7-C1901-2013-supplement.zip>

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Interactive comment on The Cryosphere Discuss., 7, 3379, 2013.

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