On the variability of temperature profiles in the stratosphere: Implications for validation

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On the variability of temperature profiles in the stratosphere: Implications for validation

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[1] Defining space-time collocation criteria for the validation of measurements requires the information about natural variability of geophysical parameters. In this paper, we analyzed the variability of the small-scale structure of temperature fields in the stratosphere using temperature profiles from radio-soundings at Sodankylä (vertical resolution ~10 m) with a small time difference between sonde launches. We found that the small-scale structures in temperature profiles become different when the horizontal separation of measurements exceeds 20–30 km. The set of the collocated temperature profiles has allowed obtaining experimental estimates of the horizontal structure function of temperature fluctuations. The spectral analysis of the profiles has shown that vertical wavenumber spectra of temperature fluctuations are similar, even for profiles separated significantly in space and time (a few hundreds of kilometers, a few hours). Implications of these results for validation of high-resolution profiles are discussed. **Citation:** Sofieva, V. F., F. Dalaudier, R. Kivi, and E. Kyrö (2008), On the variability of temperature profiles in the stratosphere: Implications for validation, *Geophys. Res. Lett.*, *35*, L23808, doi:10.1029/2008GL035539.

1. Introduction

[2] Temperature profiles in the stratosphere contain mesoscale fluctuations that are caused mainly by gravity waves and, to a lesser extent, by advection of air masses and turbulence. Modern instruments are able to resolve the fine structure in temperature profiles. However, validation of high-vertical-resolution temperature profiles is a complicated task, because the small-scale structure is not constant. In order to define the time-space window for selecting collocated measurements, the expected difference between temperature profiles in close collocation and with a small time difference should be known. To find out, we analyzed the temperature profiles from the radio-sondes launched with small time difference at Sodankylä station (67°N, 27°E).

2. Data

[3] We selected data from soundings at Sodankylä with a time difference of $\Delta t < 420$ min (7 hours) between balloon launches. During the years 2006–2007, altogether 172 profile pairs were found. Sodankylä station launches operational PTU radiosondes on regular basis at noon and at midnight (twice per 24 hours). Additional special sonde launches mostly related to various atmospheric sounding campaigns are also frequently performed, especially at winter/springtime, the majority of them being ozonesondes. The ozonesondes include radiosonde in the payload for data transmission and for the measurements of pressure, temperature, humidity and wind parameters. The majority of the collocated launches were made during the installation and testing of the automated sonde launching system in Sodankylä during 2006–2007 and during ozonesonde campaigns in March–April 2006 and in February–March 2007. The information about the collocated soundings is collected in Table 1.

[4] All analyzed measurements were performed with the Vaisala RS92-SGP radiosonde with DigiCora III ground equipment. Data were recorded with a 2 second time resolution, which corresponds to the vertical resolution of ~10 m, provided the average sonde ascent velocity is 5 m/s. Information about the geolocation was obtained by a global positioning system (GPS), which has been integrated in each individual radiosonde of that type. The estimated random error in RS92 measurements is less than 0.3 K in the stratosphere according to the World Meteorological Organization radiosonde intercomparison [*Nash et al.*, 2006].

3. Results

3.1. Simple Comparison of Temperature Profiles: Structure Function

[5] Figure 1 shows several profiles ordered according to an increasing delay in launch time of the sondes. The profiles measured on 11.04.2007 (1 min time difference between sonde launches) are practically identical. Visual agreement between profiles rapidly drops with increasing time separation. For example, the time difference for the 01.11.2006 profiles is only 22 min, but the small-scale structures in these two profiles are significantly different. The spatial separation at each altitude level with respect to the Earth $d_{Earth} = \left|\overrightarrow{\Delta s}\right|$ computed using information about sonde geolocation is shown in the right panels (green lines). It is small, not exceeding 10–15 km for all examples shown in Figure 1. However, air parcels probed at a given place with a time difference Δt become separated in the atmosphere due to displacement by wind, $\vec{v}\Delta t$. The distance with respect to air, $d_{air}(z) = |\overrightarrow{\Delta s}(z) + \vec{v}(z)\Delta t(z)|$, which takes into account advection of air masses, characterizes the horizontal separation of measurements in the atmosphere at each altitude level z. d_{air} is indicated by blue lines in Figure 1 (right). It was calculated using the information about wind speed and direction provided in the radiosonde data. Variations in wind speed and balloon ascent velocity

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Table 1. Number of Radio Sounding Pairs at Sodankylä With a Time Difference of Δt < 420 Minutes

		Per Month												Per Time Separation		
Year	Per Year	J	F	M	A	M	J	J	A	S	O	N	D	<30 min	30–120 min	120–420 min
2006	62	–	2	10	18	5	1	4	3	5	2	5	7	29(47%)	14(23%)	19(30%)
2007	110	10	39	12	5	3	10	9	12	3	1	3	3	17(16%)	20(18%)	73(66%)

with time cause changes in d_{air}. Comparing the information about wind speed in collocated profiles, we found that the uncertainty in d_{air} is ~2–5%. In calculation of d_{air}, we took into account possible variations of $\Delta t(z)$ at different altitudes caused by slightly different ascent velocities of the balloons. As seen in Figure 1, the small-scale structure in temperature profiles can differ significantly when the separation exceeds ~20 km.

[6] Furthermore, for each collocated profile pair, the variance of temperature difference $\langle (T_1 - T_2)^2 \rangle$ was computed, for three altitude intervals: 10–15 km, 15–20 km and above 20 km. Being presented as a function of the corresponding separation distance, this gives an experimental estimate of the structure function:

$$D_T(r) = \left\langle \left(T(\vec{r}_1) - T(\vec{r}_2) \right)^2 \right\rangle, \tag{1}$$

where $r = |\vec{r}_1 - \vec{r}_2|$ is the horizontal separation with respect to air. The separation distance is assigned as the mean one corresponding to each altitude range. In the calculation of the structure function D_T, we assumed that the fluctuations are homogeneous and isotropic in the horizontal plane, thus D_T depends only on the separation of the measurements. Stars in Figure 2 (top) show the values of $D_T(r)$ computed

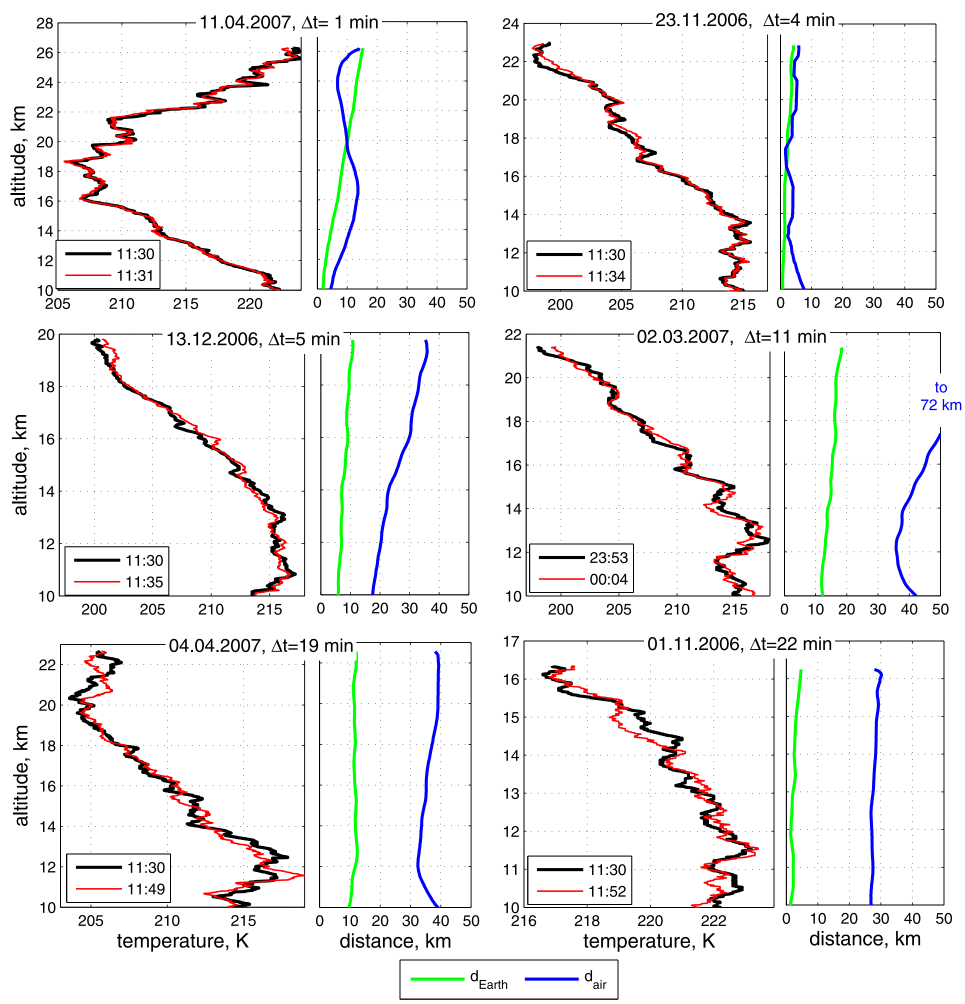

Figure 1. (left) Examples of Sodankylä radiosonde temparature profiles corresponding to small time difference between sonde launches. (right) Distances with respect to Earth d_{Earth} and with respect to air d_{air}.

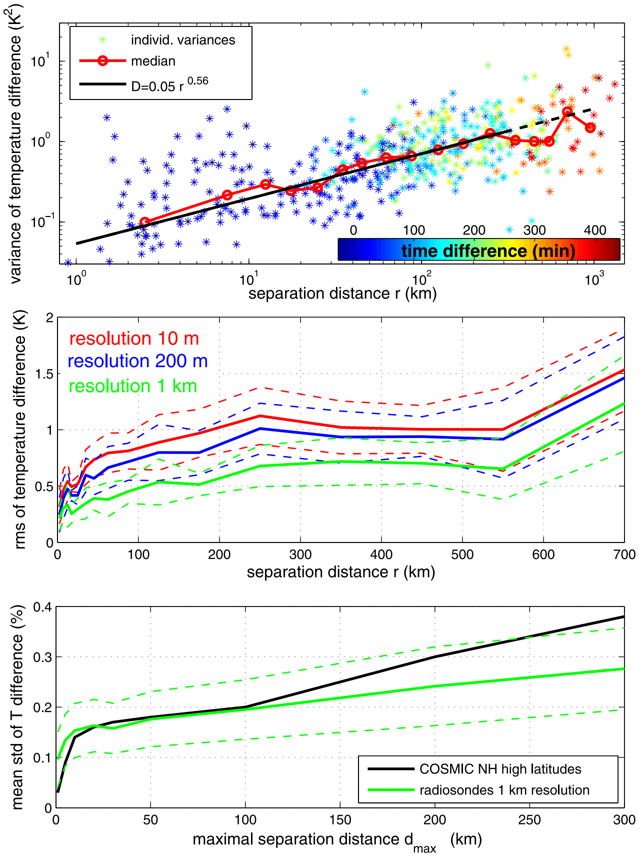

Figure 2. (top) Experimental estimates of the structure function $D_T(r)$ (equation (1)), stars: $D_T(r)$ values computed using collocated profile pairs, the color indicates time difference; red line: median $\langle D_T(r)\rangle$, circles mark the mid points of the bins used for data averaging; black line: the fit by the power function. Only data with r<300 km were used in the fit (solid line), the extension of the fit to r>300 km is indicated by dashed black line. (middle) Rms of temperature difference in collocated profiles as a function of separation distance, on a linear scale, calculated using the above-mentioned bins, Solid lines: median, dashed lines: inter-quartile range. Red: original resolution (~10 m), blue: vertical resolution 200 m, green: vertical resolution 1 km. (Red lines represent the same data in top and middle subplots). (bottom) Mean std of temperature/refractivity difference (in %) for profiles pairs with the separation distance smaller than $d_{\max}$, presented as a function of $d_{\max}$. The black line shows the COSMIC data for the Northern Hemisphere high latitudes adapted from *Anthes et al.* [2008].

using individual profile pairs. Although each profile pair yields three points in D_T estimates corresponding to the selected altitude layers, we do not distinguish different altitudes and assume that the three D_T estimates represent the structure function for the lower stratosphere. The division into three layers reduces the uncertainty in r (for the considered dataset, it is ~10%) and increases the statistics for $D_T(r)$ estimates.

[7] A relatively rapid growth of the variance of temperature difference (note the logarithmic scale) with increasing separation is observed. The smallest rms of temperature difference, which corresponds to the smallest spatio-temporal separation, is ~0.3 K. This is in agreement with the estimates of the precision of temperature measurements with the Vaisala RS92 radiosonde [*Nash et al.*, 2006]. The values of $D_T(r)$ exhibit a rather large scattering. This is not surprising: the data correspond to different seasons and meteorological conditions. The red line in Figure 2 (top) represents the median values $\langle D_T(r)\rangle$ in the bins, whose mid-points are indicated by open circles.

[8] The black line in Figure 2 (top) shows the fit of $D_T(r)$ values corresponding to separation smaller than 300 km by a power law (performed as a robust linear fit in logarithmic scale). Analyses of aircraft measurements of temperature and wind have shown that horizontal spectra of temperature and horizontal wind fluctuations have a slope close to −5/3 in the wavenumber range from $\sim 3 \cdot 10^{-6}$ cy/m to $\sim 8 \cdot 10^{-4}$ cy/m [*Nastrom and Gage*, 1985]. However, the corresponding horizontal structure function of the form $r^{2/3}$ covers a significantly smaller interval of scales [*Lindborg*, 1999]. Our estimate of the slope of the structure function 0.56 is not so far from the value 2/3. In fitting, we used only the points corresponding to a separation <300 km, in order to exclude temporal dependence in the data to some extent. However, changes in the structure function at $r > 300$ km are not clearly visible (note that there are not so many data with large spatial separation).

[9] Figure 2 (middle) shows rms of temperature difference obtained using the collocated radiosonde profiles in original resolution (~10 m), and for profiles smoothed down to 200 m and 1 km vertical resolution, on a linear scale. Solid lines denote the median value and dashed lines indicate the inter-quartile range. The rms of temperature difference is smaller for coarser vertical resolution, as expected, but the general behavior of the experimental structure function estimates is similar.

[10] An analogous study based on collocated Formosat-3/COSMIC radio occultation data (RO) has shown a similar dependence of rms of temperature and refractivity deviations on horizontal separation distance [*Anthes et al.*, 2008]. *Anthes et al.* [2008, Figure 9] shows the mean standard deviation of refractivity difference (in %) for profile pairs with tangent point separation smaller than $d_{\max}$, presented as a function of $d_{\max}$. Hence, the corresponding variance is the integral of the structure function weighted by the separation distance. Figure 2 (bottom) shows the same characteristic computed using the collocated radiosonde data smoothed down to 1 km resolution (approximate vertical resolution of radio-occultation measurements). We take that the variance of relative temperature fluctuations is equal to that of relative refractivity fluctuations, if pressure fluctuations are ignored. The integrated structure functions are in very good agreement for separations <100 km, consistent up to 250 km within variability intervals, and they diverge slowly at large separations. Seasonal difference, longitudinal and sampling effects might contribute to this divergence. Both integrated structure functions, which were estimated using collocated radiosonde profiles and collocated radio-occultation data, grow non-uniformly with increasing separation distance. They have intervals of rapid nearly linear growth for separations smaller than 30 km (seen especially well in RO data because of the significantly smaller rms corresponding to $r \approx 0$ km), and nearly flat

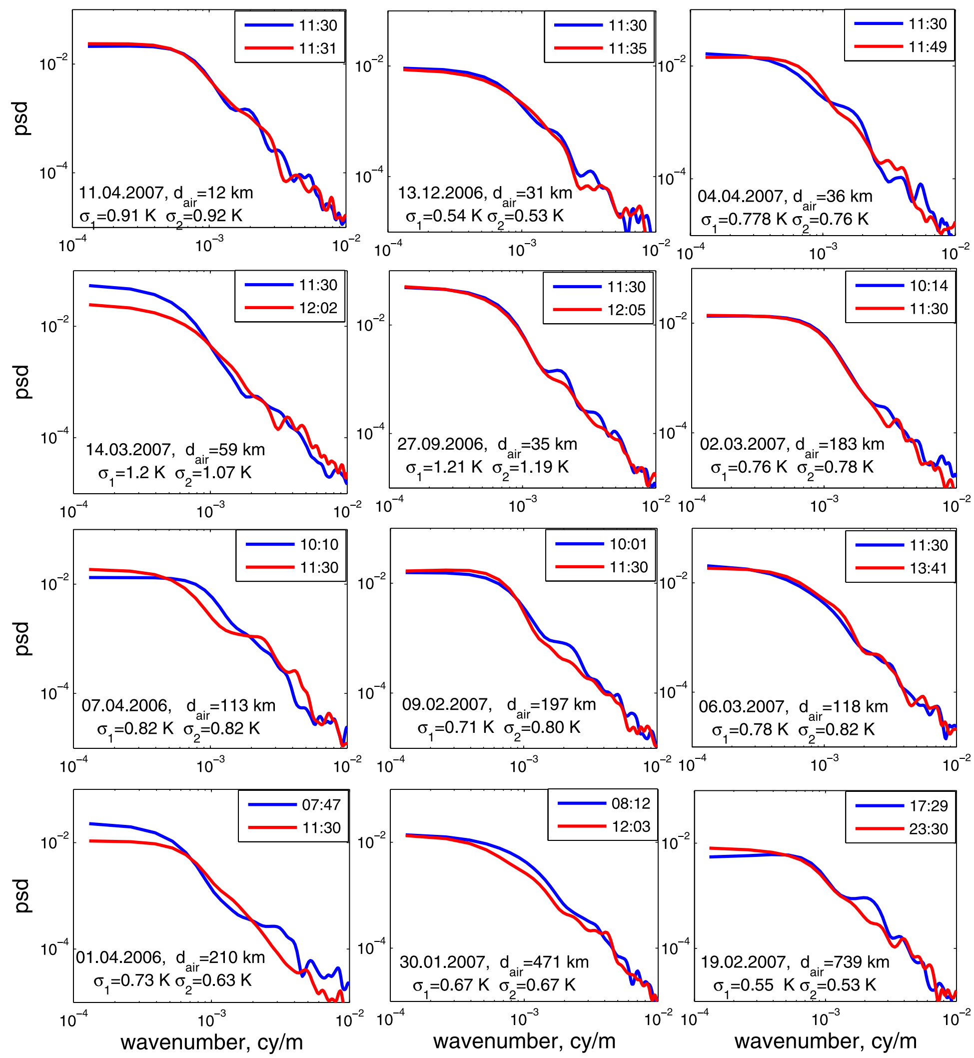

Figure 3. Examples of 1D vertical wavenumber spectra of relative temperature fluctuations in collocated radiosonde profiles.

intervals for separations of 30–70 km, followed by a steady increase for separations >100 km.

3.2. Comparison of Spectra

[11] Although the small-scale structure in temperature profiles becomes visually different when the spatial separation exceeds 20–30 km, the spectral properties of temperature fluctuations are very similar even for profiles separated by few hundred kilometers (as expected). This is illustrated in Figure 3, which shows examples of the vertical wavenumber spectra of relative temperature fluctuations $\delta T = \frac{T-\overline{T}}{\overline{T}}$ in time-collocated radiosonde temperature profiles. The altitude range above 10 km (the stratospheric part) was used for the analysis. The reference temperature profile $\overline{T}$ was obtained by smoothing the original profiles by the Hanning window with a cut-off scale of 4 km. The information about the time differences and the mean distance with respect to air d_{air} is provided in legends. The rms of temperature fluctuations σ_1 and σ_2 in the collocated profiles (σ_1 corresponds to the first profile, while σ_2 corresponds to the second one) are also indicated. As seen in Figure 3, the spectra of temperature fluctuations look similar even for profiles significantly separated in time and space (a few hundreds of kilometers, several hours).

[12] Figure 4 compares rms of temperature fluctuations in the collocated radiosonde profiles (σ_1 versus σ_2) in the original resolution (Figure 4 (left)) and smoothed down to 200 m vertical resolution (Figure 4 (right)), for the whole dataset. The rms of temperature fluctuations in the collocated profiles are found to be very close to each other: the smaller the distance, the smaller the difference in rms of fluctuations, despite relatively large overall variability of σ.

[13] For temperature profiles separated in the stratosphere by up to 500 km, the rms of temperature fluctuations are within the ±40% interval in the majority (>95%) of cases.

4. Discussion: Implications for Validation

[14] The first and obvious conclusion from the performed analysis is that taking into account advection of air masses

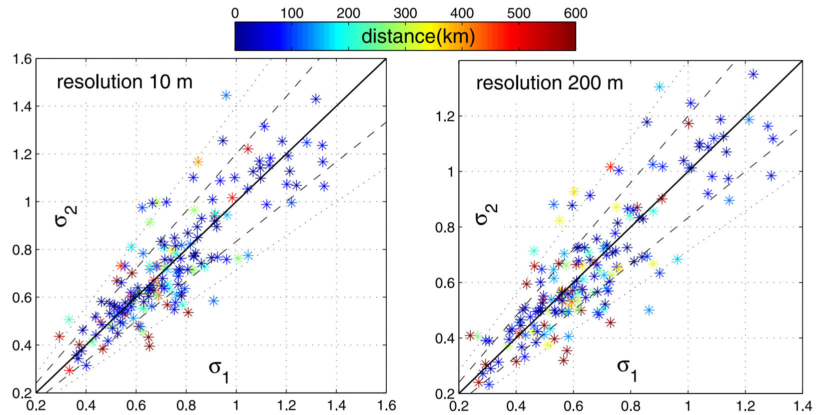

Figure 4. Scatter plot of rms of relative temperature fluctuations (in K) in collocated radiosonde profile pairs. The color denotes horizontal separation (distance with respect to air d_{air}) of measurements. (left) Profiles are in original resolution; (right) profiles are smoothed down to 200 m vertical resolution. Solid line, $y=x$; dashed lines, $y=1.2x$ and $y=(1/1.2)x$; dotted lines, $y=1.4x$ and $y=(1/1.4)x$.

is important for computing the separation of measurements in the atmosphere and thus for defining collocation criteria.

[15] The analysis of collocated radiosonde temperature profiles has shown that their small-scale structures become different if the spatial separation of measurements exceeds 20–30 km. This implies a rather pessimistic conclusion for direct comparison (direct validation) of high-resolution profiles: for similarity of small-scale structure, the profiles should be almost exactly collocated in time and in space. For profiles located at a larger distance from each other, the natural variability can contribute significantly to the observed temperature difference. Our analysis has shown that the rms of temperature difference rapidly grows with increasing distance: for high-resolution profiles (vertical resolution <200 m), the rms of temperature difference is ~0.5 K for 40 km horizontal separation, ~0.7 K for 80 km separation and it is ~1–1.5 K for separations 200–1000 km. These natural variation values are comparable with the accuracy of the best ground-based and remote sensing measurements having relatively high vertical resolution, such as lidars, stellar occultation satellite instruments using star scintillation for temperature profiling [*Dalaudier et al.*, 2006], and GPS radio occultation temperature profiling [*Schreiner et al.*, 2007; *Schmidt et al.*, 2005].

[16] Let us consider how much information can be obtained by estimating statistical parameters of differences between temperature profiles T_{val} that are to be validated and reference ones T_{ref}. By computing the mean of profile deviations, it is possible, of course, to detect a bias $b = \langle T_{val} - T_{ref}\rangle$ (we assume hereafter that T_{ref} and T_{val} have the same vertical resolution). The variance of the observed temperature differences between validated and reference profiles $\sigma^2 = \langle (T_{val} - T_{ref})^2 \rangle - b^2$ is defined not only by the measurement precision, but also by the natural variability of the temperature field. In validation experiments, the natural variability is often assumed to be small within the time-space collocation window and is therefore ignored. Our analysis has shown that the natural variability is small (much smaller than the measurement precision) only within a very narrow time-space window. Therefore, σ^2 should be compared with $\sigma^2_{ref} + \sigma^2_{val} + \sigma^2_{nat}$, where σ^2_{ref} and σ^2_{val} characterize measurement accuracies and σ^2_{nat} characterizes the natural variability in the chosen collocation window. The analysis presented in the current paper provides estimates of σ^2_{nat} at Sodankylä, which can be also used for locations at Northern Hemisphere high latitudes. Provided the accuracy of reference profiles is known, it is possible, in principle, to get also experimental estimates of accuracy of validated profiles as $\sigma^2_{val,est} = \sigma^2 - \sigma^2_{ref} - \sigma^2_{nat}$. In practice, such an approach should work if there are sufficiently many collocated pairs of validated and reference measurements and if the expected uncertainty, σ_{val}, is not negligible compared to σ_{ref} and σ_{nat}. Variations in σ_{nat} should also be taken into account.

[17] The spectral analysis of collocated radiosonde temperature profiles have shown that the spectral properties of temperature fluctuations remain similar even for profiles significantly separated in space and in time (a few hundreds of kilometers, a few hours). This gives an opportunity for checking whether small-scale fluctuations have realistic amplitude and spectral shape. For the spectral validation, the time-space collocation window can be significantly broader than for direct comparisons. This approach is attractive for spectral validation of small-scale structure in temperature profiles retrieved from satellite stellar scintillation measurements [*Dalaudier et al.*, 2006] (resolution ~150–200 m) and retrieved from GPS radio-occultation measurements using wave-optics inversion [e.g., *Jensen et al.*, 2003] (resolution better than 300 m). However, the comparison of vertical wavenumber spectra of temperature fluctuations from nearly instantaneous (e.g., satellite) measurements and balloon ones, advected by wind, should be performed with care. The vertical wavenumber spectra of temperature fluctuations in the ground-based and gravity wave intrinsic reference frames can be different, as a result of a wind-shifting effect [e.g., *Eckermann*, 1995]. *Gardner and Gardner* [1993] estimated the influence of horizontal winds on vertical wavenumber spectra from balloon soundings and found that the distortion is only significant in case of very strong horizontal winds. The cases where very strong spatial inhomogeneities (e.g., above regions of intense deep convection) are expected should also be excluded from validation.

[18] **Acknowledgments.** The authors thank the Sodankylä team for the radiosonde data. The work of V.F. Sofieva was supported by the Academy of Finland. The authors thank two anonymous reviewers for their very valuable comments.

References

Anthes, R. A., et al. (2008), The COSMIC/FORMOSAT-3 mission: Early results, *Bull. Am. Meteorol. Soc.*, *89*(3), 313–333, doi:10.1175/BAMS-89-3-313.

Dalaudier, F., A. Hauchecorne, V. Sofieva, and E. Kyrölä (2006), High-resolution density and temperature profiling in the stratosphere using bi-chromatic scintillation measurements by GOMOS, paper presented at the Atmospheric Science Conference, Eur. Space Agency, Frascati, Italy.

Eckermann, S. D. (1995), Effect of background winds on vertical wavenumber spectra of atmospheric gravity waves, *J. Geophys. Res.*, *100*(D7), 14,097–14,112.

Gardner, C., and N. Gardner (1993), Measurement distortion in aircraft, space shuttle, and balloon observations of atmospheric density and temperature perturbation spectra, *J. Geophys. Res.*, *98*(D1), 1023–1033.

Jensen, A. S., M. S. Lohmann, H. Benzon, and A. S. Nielsen (2003), Full Spectrum Inversion of radio occultation signals, *Radio Sci.*, *38*(3), 1040, doi:10.1029/2002RS002763.

Lindborg, E. (1999), Can the atmospheric kinetic energy spectrum be explained by two-dimensional turbulence?, *J. Fluid Mech.*, *388*, 259–288.

Nash, J., R. Smout, T. Oakley, and B. Pathack (2006), WMO intercomparison of high quality radiosonde systems, in *Instrum. Observ. Methods Rep. 83/TD-1303*, World Meteorol. Organ., Vacoas, Mauritius.

Nastrom, G. D., and K. S. Gage (1985), A climatology of atmospheric wavenumber spectra of wind and temperature observed by commercial aircraft, *J. Atmos. Sci.*, *42*(9), 950–960.

Schmidt, T., S. Heise, J. Wickert, G. Beyerle, and C. Reigber (2005), GPS radio occultation with CHAMP and SAC-C: Global monitoring of thermal tropopause parameters, *Atmos. Chem. Phys.*, *5*, 1473–1488.

Schreiner, W., C. Rocken, S. Sokolovskiy, S. Syndergaard, and D. Hunt (2007), Estimates of the precision of GPS radio occultations from the COSMIC/FORMOSAT-3 mission, *Geophys. Res. Lett.*, *34*, L04808, doi:10.1029/2006GL027557.

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