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# 1 ECMWF SSW forecast evaluation using infrasound

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**Key Points.**

- A novel method for forecast evaluation in the middle atmosphere is proposed
- Infrasound provides independent measurements to improve the middle/upper atmospheric coverage
- SSW onset is better predicted by the ten day forecast, duration by the nowcast

2 **Abstract.** Accurate prediction of Sudden Stratospheric Warming (SSW)  
3 events is important for the performance of numerical weather prediction due  
4 to significant stratosphere–troposphere coupling. In this study, for the first  
5 time middle atmospheric numerical weather forecasts are evaluated using in-  
6 frasound. A year of near continuous infrasound from the volcano Mt. Tol-  
7 bachik (Kamchatka, Russian Federation) is compared with simulations us-  
8 ing high resolution deterministic forecasts of the European Centre for Medium-  
9 range Weather Forecasts (ECMWF). For the entire timespan the nowcast  
10 generally performs best, indicated by a higher continuity of the predicted wave-  
11 front characteristics with a minimal back azimuth difference. Best perfor-  
12 mance for all forecasts is obtained in summer. The difference between the  
13 infrasound observations and the predictions based on the forecasts is signif-  
14 icantly larger during the 2013 SSW period for all forecasts. Simulations show  
15 that the SSW onset is better captured by the ten day forecast while the re-  
16 covery is better captured by the nowcast.

## 1. Introduction

17 The middle atmosphere has gained more and more importance for the purpose of  
18 weather and climate prediction, since increasing evidence indicates that the troposphere  
19 and stratosphere are more closely coupled than assumed before [*Baldwin and Dunker-*  
20 *ton, 2001; Charlton et al., 2004; Shaw and Shepherd, 2008*]. Significant effort has been  
21 made towards a more comprehensive representation of the atmosphere to better capture  
22 the stratospheric variability as well as the stratospheric-tropospheric interactions [*Randel*  
23 *et al., 2004; Charlton-Perez et al., 2013*].

24 The strongest manifestations of this stratosphere-troposphere coupling are Sudden  
25 Stratospheric Warmings (SSW) [*Charlton and Polvani, 2007; Gerber et al., 2009*]. SSWs  
26 are regularly occurring features of the winter stratosphere on the Northern hemisphere,  
27 characterized by dramatic changes in the stratospheric wind and temperature. The impor-  
28 tance of accurately predicting SSWs is justified by the delayed impact up to two months  
29 that such events have on the weather as experienced on the Earth's surface [*Sigmond*  
30 *et al., 2013*]. However, significant discrepancies between numerical weather prediction  
31 models and the observations they assimilate, may lead to rejection of good data by the  
32 data assimilation system which means that both the forecasts and analyses of SSWs will  
33 likely be inadequate. Recently, the European Centre for Medium-range Weather Fore-  
34 casts (ECMWF) has adapted its numerical scheme that reduces this problem, leading to  
35 an improved characterization of SSWs [*Diamantakis, 2014*]. Besides such numerical adap-  
36 tions, further improvements in SSW predictions can be obtained from better resolving the  
37 stratosphere [*Gerber et al., 2009; Roff et al., 2011*] and mesosphere [*Coy et al., 2011*] as

38 well as assimilating data from these regions, which have been notoriously difficult to  
39 monitor [*Ramaswamy et al.*, 2001]. Only temperature can be resolved by satellites, dom-  
40 inated by Advanced Microwave Sounding Unit type A (AMSU-A) observations, available  
41 by more than a dozen satellites, and are directly assimilated in the European Centre for  
42 MediumRange Weather Forecasts (ECMWF) models. In a recent study [*Le Pichon et al.*,  
43 2015], co-located independent ground-based middle-atmospheric wind and temperature  
44 measurements have been compared to both the ECMWF operational analyses as well as  
45 NASA’s Modern Era Retrospective analysis for Research and Applications (MERRA) re-  
46 analyses. Significant discrepancies were identified in the region above 40 km in winter as  
47 well as for variability on shorter timescales (2-15 day period) above 30 km. Thus, SSWs  
48 are a good starting point to apply novel techniques based on infrasonic analysis.

49 Since the pioneering work of *Donn and Rind* [1972], there has been much development  
50 in the use of ground-based infrasound arrays for upper atmospheric remote sensing [*Le*  
51 *Pichon et al.*, 2005; *Lalande et al.*, 2012; *Assink et al.*, 2013; *Fricke et al.*, 2014; *Chunchuzov*  
52 *et al.*, 2015]. An important application of this technique is the evaluation of atmospheric  
53 analyses [*Assink et al.*, 2014a] and ensemble members [*Smets et al.*, 2015]. Recently,  
54 various passive acoustic remote sensing studies have focused on SSW events [*Evers and*  
55 *Siegmund*, 2009; *Evers et al.*, 2012; *Assink et al.*, 2014b; *Smets and Evers*, 2014].

56 Volcanoes represent valuable sources for passive acoustic remote sensing of the atmo-  
57 sphere, as the source location is fixed and the source is relatively well-understood [*Fee*  
58 *et al.*, 2010; *Matoza et al.*, 2011; *Marchetti et al.*, 2013]. Here, a novel method for the  
59 evaluation of middle atmospheric weather forecasts is introduced, using near continuous  
60 infrasound detections from Mt. Tolbachik on the Kamchatka peninsula in Russian Feder-

61 ation ( $55.8^\circ$  N,  $160.3^\circ$  E). The relative small wavelength and near-continuous character  
62 of the source leads to high spatio-temporal resolution evaluations and improved insight in  
63 the forecast capabilities in the middle atmosphere, in particular during SSW events. In  
64 addition, it is demonstrated that infrasound can provide useful additional information on  
65 SSW onset and duration.

66 The article is organized as follows. Section 2 sets out the fundamentals of infrasound  
67 as an atmospheric remote sensing technique, including the signature of SSW events on  
68 infrasound recordings. Section 3 explains the methods in more detail, covering infrasound  
69 observations, propagation modeling, and the atmospheric specifications. Section 4 de-  
70 scribes the observations, followed by the evaluation of ECMWF forecasts in Section 5  
71 with distinction between the entire observation period and the 2013 SSW. Discussion and  
72 conclusions are stated in Section 6.

## 2. Background

### 2.1. The relationship between wind, temperature and infrasound

73 Infrasound, or low-frequency acoustic waves, are generated by movement of large vol-  
74 umes of air. Such movements can be created by natural or anthropogenic sources. Exam-  
75 ples include interfering ocean-waves, volcanic eruptions, (nuclear) explosions and meteor  
76 explosions [*Brachet et al.*, 2010]. Infrasound can propagate efficiently over long ranges,  
77 since attenuation is relatively low. Moreover, several wave guides exist between the Earth's  
78 surface and the (upper) atmosphere that channel infrasonic energy.

79 One can distinguish between tropospheric, stratospheric and thermospheric waveguides.  
80 The tropospheric waveguide is bound by the jet stream around the tropopause ( $\sim 10$  km).  
81 The stratospheric waveguide is formed by the temperature increase due to the presence

of ozone and the circumpolar vortex. Generally, the stratospheric waveguide extends to  $\sim 50$  km during the boreal summer. During SSWs, the top of the waveguide may descend into the lower stratosphere and may even extend into the lower mesosphere. The thermospheric waveguide exists due to the strong temperature gradient above the mesopause. However, infrasound is much attenuated at thermospheric altitudes [Assink *et al.*, 2012].

Sound propagation in the atmosphere is a function of wind  $\mathbf{w}$  and temperature  $T$ , which may vary strongly as a function of location and time. For a fixed source-receiver pair, changes in the mode of propagation (i.e. stratospheric to thermospheric) can be observed as horizontal wind and temperature change seasonally. Ray tracing (Figure 1) can be used to model the influence of 3D temperature and three component wind fields on infrasound propagation [Brekhovskikh and Godin, 1999].

It is instructive to consider a horizontally layered atmosphere to review basic concepts of infrasound propagation. The effective sound speed  $c_{\text{eff}}$  can be used to approximate to first order [Godin, 2002] the effects of temperature  $T$  and horizontal wind  $\mathbf{w}_{uv}$  in the direction of propagation  $\phi$ :

$$\begin{aligned} c_{\text{eff}}(z) &= \sqrt{\gamma RT(z)} + |\mathbf{w}_{uv}(z)| \cos(\phi - \phi_{\mathbf{w}_{uv}}(z)) \\ &= c_T(z) + w_a(z) \end{aligned} \tag{1}$$

Here,  $\gamma = 1.4$  and  $R = 286.9 \text{ J kg}^{-1} \text{ K}^{-1}$  are the ratio of specific heats and the specific gas constant for dry air, respectively. Note, that both propagation azimuth  $\phi$  and wind direction  $\phi_{\mathbf{w}_{uv}}$  are clockwise relative to the North. From Snell's law, it follows that positive vertical gradients of the effective sound speed lead to downward refraction, and vice versa. Acoustic waveguides are combinations of these gradients. The orientation of the source and receiver locations determine the propagation azimuth  $\phi$ . This angle is used to estimate

105 the along-track wind ( $w_a$ ) and cross-wind ( $w_c$ ) components, by rotating the zonal ( $w_u$ )  
 106 and meridional ( $w_v$ ) components of the horizontal wind vector  $\mathbf{w}_{uv}$  (see Figure 1d)

$$107 \quad \begin{pmatrix} w_a \\ w_c \end{pmatrix} = \begin{pmatrix} \sin \phi & \cos \phi \\ -\cos \phi & \sin \phi \end{pmatrix} \begin{pmatrix} w_u \\ w_v \end{pmatrix} \quad (2)$$

108 The quantities  $w_a$  and  $w_c$  each have a specific influence on infrasound propagation.

109 Infrasound is often measured with arrays of microbarometers (Figure 1b). Beamforming  
 110 techniques allow for the detection of coherent infrasound and the estimation of the *slow-*  
 111 *ness vector*  $\mathbf{s} = \{s_x, s_y, s_z\}$ . The slowness vector describes the direction of propagation of  
 112 a wavefront in three dimensions. The magnitude of slowness corresponds to the reciprocal  
 113 of wave propagation speed. The slowness vector can be converted into azimuth  $\phi$  and  
 114 trace velocity  $c_{\text{trc}}$  as:

$$115 \quad \phi = \arctan \frac{s_x}{s_y} \quad (3)$$

$$116 \quad c_{\text{trc}} = \frac{1}{|\mathbf{s}_{xy}|} = \frac{1}{|\mathbf{s}| \cos \theta} = \frac{c_{\text{rcv}}}{\cos \theta} \quad (4)$$

117 In observational studies, *back azimuth* is used instead of azimuth (Equation 3), taking the  
 118 array as the point of reference. It is often found that significant deviations exist between  
 119 the observed and theoretical back azimuth. Such deviations exist due to the influence of  
 120 cross-winds  $w_c$ , and are like the crabbing of an airplane needed to fly along a constant  
 121 bearing in a crosswind. Back azimuth deviation is illustrated in Figure 1c, as the angle  
 122 between the true azimuth (gray line) and the propagation azimuth (purple line) needed to  
 123 arrive at the receiver location. Note that the propagation path is denoted by the dashed  
 124 red line. At the receiver location, the observed back azimuth (orange line) does not point  
 125 towards the source. Only in the case of zero cross-wind, all four mentioned lines would  
 126 align.



127 Trace velocity (Equation 4) is the horizontal projection of the propagation velocity vec-  
128 tor, and describes the horizontal propagation speed of an wavefront with grazing angle  $\theta$ .  
129 This quantity is of interest observationally, as infrasound arrays are typically constructed  
130 horizontally. For a layered medium, trace velocity is an invariant [*Pierce*, 1981].

131 Finally, return height  $z_R$  is defined as an altitude at which sound refracts down from  
132 the upper atmosphere towards the Earth's surface. From the definition of trace velocity  
133 and its invariance, it follows that the trace velocity equals the effective sound speed at  
134 the return height. This relationship allows one to identify return heights from an effective  
135 sound speed profile. A range of return heights may exist, but  $z_R$  is necessarily smaller  
136 or equal to the top of the acoustic waveguide. For the ray shown in Figure 1a,  $z_R$  is  
137 estimated to be around 37.5 km.

138 In summary, ignoring vertical wind, in-plane atmospheric specifications (temperature,  
139 along-track wind) determine effective sound speed and therefore trace velocity, while the  
140 cross-track winds determine the back azimuth deviation. Thus, a complementary set of  
141 infrasound observations exist that is sensitive to temperature and horizontal wind.

## 2.2. Signature of SSW events on infrasound recordings

142 Infrasound has a long history as method to monitor changes in the stratospheric polar  
143 vortex wind direction dedicated to SSWs. Already in the early seventies, various pio-  
144 neering studies of Donn and Rind describe the infrasonic signature of a SSW [*Donn and*  
145 *Rind*, 1971, 1972; *Rind and Donn*, 1975; *Rind*, 1978]. Using ambient coherent noise,  
146 microbaroms, as a continuously natural mechanism for probing the upper atmosphere,  
147 they relate abnormal winter amplitude intensities to SSW events. However, these studies  
148 came to a stop when nuclear tests were diverted to the subsurface under the Limited or

149 Partial Test Ban Treaty. Recently, with the signature of the Comprehensive Nuclear-  
150 Test-Ban Treaty, the use of infrasound as a passive atmospheric probe gained renewed  
151 attention. More recently, *Evers and Siegmund* [2009] used coherent ambient noise to  
152 identify signals arriving from the opposite direction than expected under regular winter  
153 conditions to characterize the infrasonic signature of the 2009 major SSW, whereas *Assink*  
154 *et al.* [2014b] identified simultaneous arrivals from two stratospheric ducts due to the 2011  
155 minor SSW. The temperature effect of a hot stratosphere during a SSW on infrasound  
156 propagation is studied by *Evers et al.* [2012]. During the 2010 SSW, the extent of the  
157 classical stratospheric shadow zone ( $\sim 200$  km) reduces by a factor of 2, leading to ex-  
158 tremely small shadow zones. *Smets and Evers* [2014] demonstrated the use of ambient  
159 noise amplitude variations to describe the life cycle of the 2009 major SSW. Similar to the  
160 earlier study of *Donn and Rind* [1972], amplitudes variations allow to estimate the return  
161 height. In addition, *Smets and Evers* [2014] demonstrate that the combined signature of  
162 the change in back azimuth direction, solar tidal signature type, and/or phase variation of  
163 the amplitude variation of the observed microbaroms reveals type of vortex disturbance,  
164 either split or reversal.

### 3. Methods

165 In this work, simulated and observed infrasound wavefront parameters are compared,  
166 i.e. back azimuth and trace velocity. The theoretical basis of this method relies on the  
167 assertion that sound propagates through a particular atmospheric state. The atmospheric  
168 state that is closest to reality will then lead to simulated values that are closest to the  
169 observed values.

170 Experimental evidence for the validity of this method has been provided by various  
171 earlier studies (e.g. *Le Pichon et al.* [2005]; *Assink et al.* [2014a]; *Smets et al.* [2015]).

172 For this study, infrasound propagation is simulated from volcano Mt. Tolbachik to a  
173 regional infrasound station at 347 km distance (Figure 1), for comparison with observa-  
174 tions. The remainder of this section describes the observations, the propagation method  
175 and the atmospheric specifications that are used.

### 3.1. Infrasound observations

176 Observations from infrasound station IS44 (Kamchatka, Russian Federation) are used.  
177 IS44 is part of the International Monitoring System (IMS). The IMS is a global network  
178 of infrasound, seismic, hydroacoustic and radionuclide stations for the verification of the  
179 Comprehensive Nuclear-Test-Ban Treaty (CTBT) [*Dahlman et al.*, 2009]. Today, 45 out of  
180 60 infrasound stations have been installed and certified, providing continuous recordings  
181 of infrasound worldwide.

182 IS44 consists of four MB2000 microbarometers [*Ponceau and Bosca*, 2010] that measure  
183 small pressure fluctuations on the order of mPa up to tens of pascals. The microbarometers  
184 have a flat response over the frequency band spanning from 0.08 to 4 Hz and are sampled  
185 at 20 Hz. Wind noise filters are used to reduce noise levels over the infrasonic frequency  
186 band, by spatially averaging the pressure field in the vicinity of an infrasound sensor.  
187 Infrasound detection bulletins are provided by the International Data Centre (IDC) of the  
188 CTBT-Organization (CTBTO). The bulletins include infrasound waveform parameters  
189 (including their uncertainties) as a function of time, such as back azimuth, trace velocity  
190 and dominant frequency. The bulletins correspond to average values of grouped detections

191 in time-frequency space [*Brachet et al.*, 2010]. The parameters used to filter the relevant  
192 detections from the raw IDC bulletins are given in Table 1.

### 3.2. Propagation modeling

193 For the evaluation, an in-house developed ray-tracing algorithm (cast in spherical co-  
194 ordinates) is used that takes into account the full effect of the 3D inhomogeneous wind  
195 and temperature fields, see for example, *Brekhovskikh and Godin* [1999]. See Figure 2 for  
196 an example of stratospheric infrasound propagation using 3D ray theory. For every atmo-  
197 spheric model, eigenrays (connecting source and receiver, see Figure 1a) are considered  
198 for further analysis. Given the aperture of IS44, rays that pass within 1 km of the center  
199 of the array are counted as eigenrays. For every eigenray, trace velocity and back azimuth  
200 deviation values are stored, for comparison with the observed values.

201 Except for the limitations that are inherent to the ray theory approximation  
202 [*Brekhovskikh and Godin*, 1999], namely that the variations in atmospheric wind and  
203 temperature are small over an acoustic wavelength, the theory is exact. Thus, the prop-  
204 agation effects such as diffraction and scattering from small-scale structure (e.g. from  
205 gravity waves; *Chunchuzov et al.* [2015]) are neglected. These effects are included in full-  
206 wave modeling, e.g., [*Assink et al.*, 2014a]. Typically, such computations are limited to  
207 in-plane effects, because of the additional high computational load for out-of-plane effects.

### 3.3. Atmospheric specifications

208 In this study, ECMWF’s operational high spatial resolution forecasts (HRES), part of  
209 the Integrated Forecast System (IFS) cycle 38r1 (June 2012) and cycle 38r2 (June 2013)  
210 are used. The IFS consists of a general circulation model and assimilates radiosonde,

211 ground, and satellite based atmospheric observations by four-dimensional variational as-  
212 simulation (4D-Var). HRES is the deterministic and highest spatial resolution member of  
213 the IFS with a resolution of  $T_L1279L91$  (horizontal resolution of  $\sim 16$  km or  $0.125^\circ$  and 91  
214 vertical levels up to 0.01 hPa, increased to 137 levels in June 2013. See *ECMWF* [2016]  
215 for the evolution of the IFS. Forecasts are available every 12 hours with a forecast step up  
216 to 10 days. For this study, 3D atmospheric specifications of wind, temperature, humidity,  
217 and pressure are used every 12 hours for the 0 (nowcast), 5 and 10 day forecasts. All  
218 specifications are vertically resampled to 500 m levels from ground up to 70 km. Conse-  
219 quentially, infrasound propagation above 70 km cannot be simulated using the ECMWF  
220 IFS. To obtain mesospheric and thermospheric returns the ECMWF forecasts are ex-  
221 tended above 70 km by splining a 1D wind and temperature profile obtained from the  
222 Horizontal Wind Model (HWM) and Mass Spectrometer and Incoherent Radar Model  
223 (MSIS) semi-empirical models [*Drob et al.*, 2008; *Picone et al.*, 2002], for the midpoint  
224 between source and receiver.

#### 4. Observations

225 Figure 3 shows four states of the analysis temperature and wind field in the Northern  
226 hemisphere at 5.0 hPa (about 36 km altitude), prior to the 2013 major SSW (left), during  
227 the SSW (two middle) and during the summer of 2013 (right).

228 Prior to the SSW, the circumpolar vortex flows eastward around the Arctic region,  
229 thereby sustaining a cold Arctic stratosphere. This typical winter situation is disturbed  
230 during the first week of January 2013. As a result of upward propagating planetary waves,  
231 e.g., *Matsuno* [1971]; *Baldwin and Dunkerton* [2001], the circumpolar vortex weakens and  
232 destabilizes, migrates south of  $65^\circ$  N and finally is split into two daughter vortices. As

233 a result, the vortex direction is reversed for various regions. Additionally, the Arctic  
234 stratosphere warms up to 50 °C within a few days, classifying the warming as major. After  
235 18 January 2013, the stratosphere on the Northern hemisphere returns to its more common  
236 winter state until the final warming (March), after which the stratosphere transforms into  
237 its summer state, featuring a westward circumpolar vortex.

238 Nearly 36 years after its last eruption, Mt. Tolbachik began erupting again on 27  
239 November 2012, leading to the largest basaltic eruption in Kamchatka during historic  
240 times. The volcanic activity remained high for nine months, and finally weakened at the  
241 end of August 2013 [*Albert et al.*, 2015]. Infrasound detections at IS44, at 347 km distance  
242 from Mt. Tolbachik, provide a near continuous record of the eruption sequence (Figures  
243 4a and 5a). The relative position of Mt. Tolbachik to IS44 as well as the stratospheric  
244 dynamics are paramount in understanding the observations. While more volcanoes are  
245 present in the area, we assume that infrasound detections for the parameters given in  
246 Table 1 correspond to Mt. Tolbachik. This seems justified based on activity reports  
247 [*Smithsonian Institution*, 2013]. Moreover, we assume that the source has a constant  
248 spectral content.

249 During the winter period, not including the warming period, infrasound is detected with  
250 a relatively large back azimuth offset of +5°, when compared to the summer observations  
251 (Figure 4a). Taking into account the direction of the winter circumpolar vortex, this  
252 suggests that these signals have likely returned from the lower thermosphere instead of  
253 the stratopause. After the transition to the summer stratosphere, the back azimuth offset  
254 is small and of opposite sign, due to the presence of a westward circumpolar vortex, that  
255 creates a stratospheric waveguide. Trace velocities show the expected seasonal signature

(Figure 5a) on the basis of higher boundary layer temperatures in summer than in winter, with lower velocities in winter and higher in during summer. During the SSW, a strong westward vortex is present above the region (Figure 3). As a result, three particularities can be noted. First, the back azimuth deviation rapidly reverses, and reaches a much higher value than during the summer. This is in accord with the much stronger westward vortex, i.e., the cross wind causing the back azimuth deviation. Second, the trace velocities are higher than usual and even reach values of  $400 \text{ m s}^{-1}$ , likely due to the increased temperature and along-track wind. Third, the dominant frequency is significantly higher during the warming period, when compared to the summer. This may be explained by the lower return height during the warming period (30 km as opposed to 45 km; see Figure 6), important for propagation efficiency, resulting in reduced geometrical spreading in combination with reduced absorption of higher frequencies [Lonzaga *et al.*, 2015].

## 5. Evaluating ECMWF forecasts

Figure 2 shows an example of stratospheric infrasound propagation, using 3D ray theory, for three different ECMWF forecasts for 6 January 2013. Typically, IS44 is reached after one bounce. Figure 2a shows the effective sound speed (combining the effect of wind and temperature on infrasound propagation) profiles for the different forecast steps. The largest variability between the different forecasts is found in the upper stratosphere, except for the ten day forecast, which is different throughout the troposphere and lower stratosphere as well. The sensitivity of infrasound propagation to the variations in forecast steps is essential in this evaluation work.

ECMWF forecasts are evaluated by forward modeling the propagation of infrasound from Mt Tolbachik towards IS44 every 12 hours for the entire observation period by 3D

278 ray theory using the various forecast steps. These wavefront simulations are compared to  
279 the array observations in order to validate the atmospheric specifications of each forecast  
280 step. Significant inconsistencies or lack of simulated returns indicates a possible difference  
281 between the true state of the atmosphere and the consulted forecast in the vicinity of the  
282 return height.

283 As mesospheric and thermospheric specifications are missing using the ECMWF IFS,  
284 comparison of predictions and observations can be misleading. To explain mesospheric  
285 and thermospheric returns, all forecasts are extended with semi-empirical wind and tem-  
286 perature profiles (see Subsection 3.3). In general, observations from mesospheric and ther-  
287 mospheric return heights correspond to observations within the lower frequency range of  
288 0.5–1.5 Hz (see Figures 4 and 5). For these arrivals, there appears to be a near-constant  
289 offset of  $\pm 2.5^\circ$  (Figures 4), similar to earlier findings by *Le Pichon et al.* [2005]. In their  
290 study, the bias between the measurements and the results of simulation is explained by  
291 undervalued wind speeds by HWM in the upper atmosphere. Trace velocity values are  
292 generally overestimated by 10 to 20  $\text{m s}^{-1}$  (Figure 5).

293 Comparisons of the observed and simulated wavefront characteristics for the entire  
294 period of observation, using different forecast steps, are shown in Figures 4 and 5, for  
295 back azimuth and trace velocity, respectively. Figures 7 and 8 zoom in on the period  
296 of the SSW. For sake of brevity, the discussion here is mainly focused on back azimuth  
297 deviations although most conclusions hold for the trace velocity observations as well.

298 The estimated difference between the observed and predicted back azimuth, an indi-  
299 cation of the forecast uncertainty, is shown in Figure 9. For each forecast the difference  
300 is calculated between the observations (black dots) and predictions (red dots) of Figures



301 4b–d. All observations are averaged using 12 hour time bins and contain at least 6 de-  
302 tections (on average, every bin contains 50 detections). In general, uncertainty values of  
303 observed back azimuth (horizontal dashed black line in Figure 9) and trace velocity are  
304 dependent on the detection slowness, the planarity of the waveform and the signal-to-noise  
305 level [Szuberla and Olson, 2004]. For IS44 95% uncertainty values up to  $2^\circ$  and  $10 \text{ m s}^{-1}$   
306 are possible. In this paper we estimate typical uncertainty values for IS44  $1^\circ$  and  $5 \text{ m s}^{-1}$ .

### 5.1. Entire observation period

307 For the entire observation timespan the nowcast performs best out of all forecast steps  
308 (see Figures 4, 5 and 9a), indicated by a higher continuity of the simulated characteristics  
309 and smaller back azimuth differences. The estimated average back azimuth difference  
310 shows a clear seasonal variation with a minimum in summer and differences frequently  
311 below the  $1^\circ$  estimated observational uncertainty.

312 Summer observations, related to the stable summer stratospheric waveguide, are in  
313 general well simulated by all forecasts up to approximately 10 July 2013. After 10 July  
314 2013, only the nowcast is able to provide continuous predictions (see Figure 9a). Smaller  
315 deviations are occasionally obtained using the five or ten day forecasts, though these  
316 forecasts do not adequately predict continuous values after 10 July 2013. Despite that  
317 the ten day forecast yields the worst performance, based on the density and continuity of  
318 the simulations, it still does provide some sparse predictions until the end of August.

319 In winter, the stratospheric waveguide is rather unstable, resulting in an increased back  
320 azimuth difference almost consistently above the  $1^\circ$  estimated observational uncertainty  
321 for all forecasts (see Figure 9a).

## 5.2. 2013 SSW

322 Zooming in on the period of the SSW, see Figures 7 and 8, midwinter stratospheric pre-  
323 dictions of back azimuth and trace velocity can only occur due the dramatic changes in the  
324 stratospheric wind and temperature of a SSW. For these unusual winter stratospheric pre-  
325 dictions (and during equinox periods), the prediction performance is significantly smaller  
326 and clearly different for all three forecast steps when compared to the summer predictions  
327 (Figure 9a). The local infrasonic signature of the 2013 SSW observed at IS44 is highlighted  
328 in Figures 7 and 8 by the gray rectangle and in Figure 9a by the green rectangle. The  
329 rectangle points to the continuous high-frequency infrasound observations interpreted as  
330 low stratospheric altitude returns ( $<40$  km return altitude). In addition, these low strato-  
331 spheric returns are characterized by a sudden reversal in the back azimuth deviation and  
332 an increase in trace velocity. Therefore, these low stratospheric returns are interpreted  
333 to be due to the SSW indicating the assumed warming onset (28 December 2012) and  
334 recovery (16 January 2013).

335 All forecasts are able to reproduce the general SSW characteristics, including the sudden  
336 reversal of the back azimuth deviation (Figures 4 and 7) as well as the sudden increase  
337 in trace velocity (Figures 5 and 8). Nevertheless, the performance skill during the SSW  
338 is much more variable when compared to the summer predictions.

339 • The warming onset (28 December 2012) is well predicted by all three forecasts, both  
340 the nowcast and five day forecast predict the same warming onset followed twelve hours  
341 later by the ten day forecast. Though, the ten day appears to be more accurate in  
342 predicting the larger back azimuth deviations and corresponding trace velocities during

343 the first days of the warming. The resemblance in timing of the predicted and observed  
344 stratospheric returns using the ten day forecast is better as well.

345 • During the vortex displacement phase of the major warming (before 7 January 2013),  
346 the ten day forecast most accurately predicts the varying back azimuth deviation, includ-  
347 ing a sudden wind direction change around 2 January 2013 with corresponding increase  
348 in trace velocity (Figure 8). Note, that the difference in back azimuth prediction of both  
349 the nowcast and ten day forecast is below the array uncertainty. Yet, the large difference  
350 of the five day forecast when compared to the nowcast and ten day forecast is remarkable.

351 • When the vortex splits (around 7 January 2013) the ten day forecast does no longer  
352 predict stratospheric returns, while the five day forecast and nowcast continue respectively  
353 two and four days with a quasi similar back azimuth difference.

354 • All forecasts have difficulties to predict the stratospheric observations up to the  
355 expected warming recovery (16 January 2013). Predictions for all forecast steps indicate  
356 a too early recovery. The ten day forecast predicts a difference of about nine days with  
357 respect to the moment that no stratospheric arrivals are expected anymore (8 January  
358 2016). The recovery is best captured by the nowcast model, continuously predicting up  
359 to 11 January 2013.

360 This relative performance is illustrated in Figure 9b, presenting a minimal mean differ-  
361 ence between the observed and modelled back azimuth. All forecasts indicate a reduction  
362 in back azimuth difference when the vortex migration evolves. Minimal back azimuth  
363 differences are obtained using the ten day forecast, while the nowcast yields the highest  
364 continuity of the predictions. Least performance is obtained by the five day forecast.

## 6. Discussion and Conclusions

365 For the discussion of our results it is important to establish that the nowcast is most  
366 constrained by the data assimilation whereas the ten day forecast tends to be quasi free  
367 running, with the five day forecast positioned somewhere in between. For a typical fore-  
368 cast, more forecast skill is expected for a shorter forecast step, as it is closer to the data  
369 assimilation. This is observed during summer (Figure 9), where the nowcast performs  
370 best. Surprisingly, in winter the ten day forecast appears to be most accurate in predict-  
371 ing the first phase of the warming. For validation, comparison of the nowcast with the  
372 subsequent analysis, often applied in NWP, reveals only a small improvement in absolute  
373 deviation compared to the nowcast (see Supplemental Figure S1). Our interpretation is  
374 that the ten day forecast is able to obtain sufficient information from the small a priori  
375 warming signatures with enough time to propagate through the atmosphere, to predict  
376 the warming including the sudden recovery around 2 January 2013. Once data has to be  
377 assimilated during the warming, the ten day forecast loses a lot of forecast skill. At this  
378 stage, data gets most likely rejected or modified by the data assimilation system leading  
379 to inaccurate initialization as addressed by *Diamantakis* [2014]. The nowcast is affected  
380 similarly, but recovers approximately at once with the data assimilation system such that  
381 it predicts best the SSW duration and recovery.

382 An ECMWF IFS cycle update has been implemented to address spurious data assim-  
383 ilation issues that occur during SSW events *Diamantakis* [2014]. For future research, it  
384 would be useful to evaluate the effects of this cycle update (Cy41r1, May 2015), includ-  
385 ing the consideration of the ensemble forecasts [*Smets et al.*, 2015], using our technique.  
386 Moreover, it would be of interest to study the uncertainties due to unresolved small-

387 scale structure, involving 3D full-wave modeling. Detailed analyses between the various  
388 forecasts are needed, for example, by considering differences in polar-cap averaged strato-  
389 spheric zonal wind and temperature.

390 For the first time, weather forecasts for different forecast steps are evaluated using  
391 infrasound. The high spatio-temporal resolution of infrasound is explained by the relative  
392 small wavelength of infrasound ( $< 500$  m) compared with the characteristic length scales  
393 of atmospheric features ( $> 500$  m). The high temporal resolution is due to the use of a  
394 near-continuous infrasound source (typical resolution of minutes; compared with 6-hourly  
395 atmospheric specifications). The proposed method in this study for the evaluation of  
396 middle atmospheric weather forecasts using near continuous infrasound detections can  
397 directly be applied to similar setups, making use of other IMS or even national infrasound  
398 arrays. The method presented here relies on an active source like the volcano used.  
399 However, source-independent techniques are being developed based on interferometry of  
400 the ambient noise field [*Fricke et al.*, 2013, 2014].

401 This study demonstrates that infrasound can provide useful additional information in  
402 regions where data coverage is sparse, such as in the upper stratosphere. The frequency  
403 content of the observed infrasound suggests a six day longer duration of the 2013 SSW  
404 than predicted by the ECMWF nowcast.

405 Validation of atmospheric analysis and forecast products, in particular in regions above  
406 30 km altitude, are important for numerical weather prediction applications, as the in-  
407 teraction between the stratosphere and the troposphere cannot be neglected. Due to  
408 the delayed impact of a warming on the weather at the ground, evaluating the forecast  
409 in the middle atmospheric can act as an early indicator of a possible upcoming loss of

410 forecast skill in the troposphere. As atmospheric specifications in the lower and middle  
411 atmosphere are routinely used in a wide variety of atmospheric sciences and applications,  
412 the validation is relevant to a broad community and a wide variety of applications, such  
413 as the verification of the Comprehensive Nuclear-Test-Ban Treaty, in which infrasound is  
414 used as a verification technique.

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422 CTBTO and ECMWF is available to member states, but can be requested for academic  
423 purposes. Infrasound data can be requested at the CTBTO International Data Centre  
424 (IDC) in Vienna, via the virtual Data Exploration Centre (vDEC). Atmospheric data  
425 can be requested at the ECMWF via the Meteorological Archival and Retrieval System  
426 (MARS). Figures 1 to 3 in this article are made with the Generic Mapping Tools [*Wessel*  
427 *and Smith*, 1991].

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**Table 1.** Parameters used to filter the relevant detections of Mt. Tolbachik from the raw IDC bulletins [*Brachet et al.*, 2010]

Parameter	Range
Mean frequency	0.5 – 3.5 Hz
Back azimuth $\psi$	$28.11 \pm 12^\circ$
$\sigma_\psi$	$< 2.0^\circ$
Trace velocity $c_{trc}$	310 – 450 m s <sup>-1</sup>
$\sigma_{c_{trc}}$	$< 25.0 \text{ m s}^{-1}$
Consistency	$< 0.15 \text{ s}$

**Figure 1.** (a) 3D map of the Kamchatka peninsula in Russian Federation ( $55.8^\circ \text{ N}$ ,  $160.3^\circ \text{ E}$ ), showing source (star) and receiver array (triangle) locations interconnected with an example eigenray (solid red line) and its horizontal projection (dashed red line). The purple, orange, and gray lines represent the azimuth, back azimuth, and theoretical back azimuth angles, respectively. (b) IS44 array elements layout (triangles) with theoretical, observed and ray simulated back azimuth angles, all with respect to the array central element. The thin red line perpendicular to the observed back azimuth indicates the incoming planar wavefront. (c) Horizontal projection (top-view) of (a) with the gray circle indicating the reflection at the ground. (d) Zoom in on (c), showing the receiver area with the observed and theoretical back azimuth angles. The black vectors indicate the zonal and meridional wind unit vectors  $\hat{\mathbf{e}}_u$  and  $\hat{\mathbf{e}}_v$  and the horizontal wind vector  $\mathbf{w}_{uv}$  at 37.5 km altitude. Its projection along the theoretical back azimuth, approximating the propagation direction, is given by the gray vectors resulting in the along-track  $w_a$  and cross-wind  $w_c$  components. The purple and orange lines change due to variations in the atmosphere while the solid gray line is constant.

**Figure 2.** (a) Sound speed profiles derived from ECMWF HRES forecasts for 6 January 2013 at 00 UTC indicating the (dashed) adiabatic and (solid) effective sound speed at the source. While the largest variability between the forecasts is found in the upper stratosphere, the 10 day forecast is different throughout the troposphere and lower stratosphere as well. The three panels on the right show 3D ray trace infrasound propagation over 400 km using three different ECMWF HRES forecasts: (b) nowcast, (c) 5 day forecast and (d) 10 day forecast. The background corresponds to the effective sound speed and the white triangle indicates the array distance. The temperature and wind variability in the profiles is reflected in the far-field infrasound predictions.

**Figure 3.** Temperature (top) and horizontal wind specifications (bottom) from ECMWF analysis at 5.0 hPa (around 36 km altitude) before, during and after the SSW, which directly influence the detectability of Mt. Tolbachik on IS44 (white rectangle).

**Figure 4.** (a) back azimuth deviation values from Mt. Tolbachik infrasound detections, for which trace velocity values are shown in Figure 5a. (b, c, d) Comparisons between observations (black dots) and 3D ray tracing results (red dots) as a function of time, using three different ECMWF HRES forecasts: (b) nowcast, (c) 5 day forecast and (d) 10 day forecast. The blue dots correspond to simulated arrivals that have propagated through the mesosphere and lower thermosphere, for which the MSIS and HWM climatologies have been used.

**Figure 5.** (a) Trace velocity values from Mt. Tolbachik infrasound detections. (b, c, d) Comparisons between observations (black dots) and 3D ray tracing results (red dots) as a function of time, using three different ECMWF HRES forecasts: (b) nowcast, (c) 5 day forecast and (d) 10 day forecast. The blue dots correspond to simulated arrivals that have propagated through the mesosphere and lower thermosphere, for which the MSIS and HWM climatologies have been used.

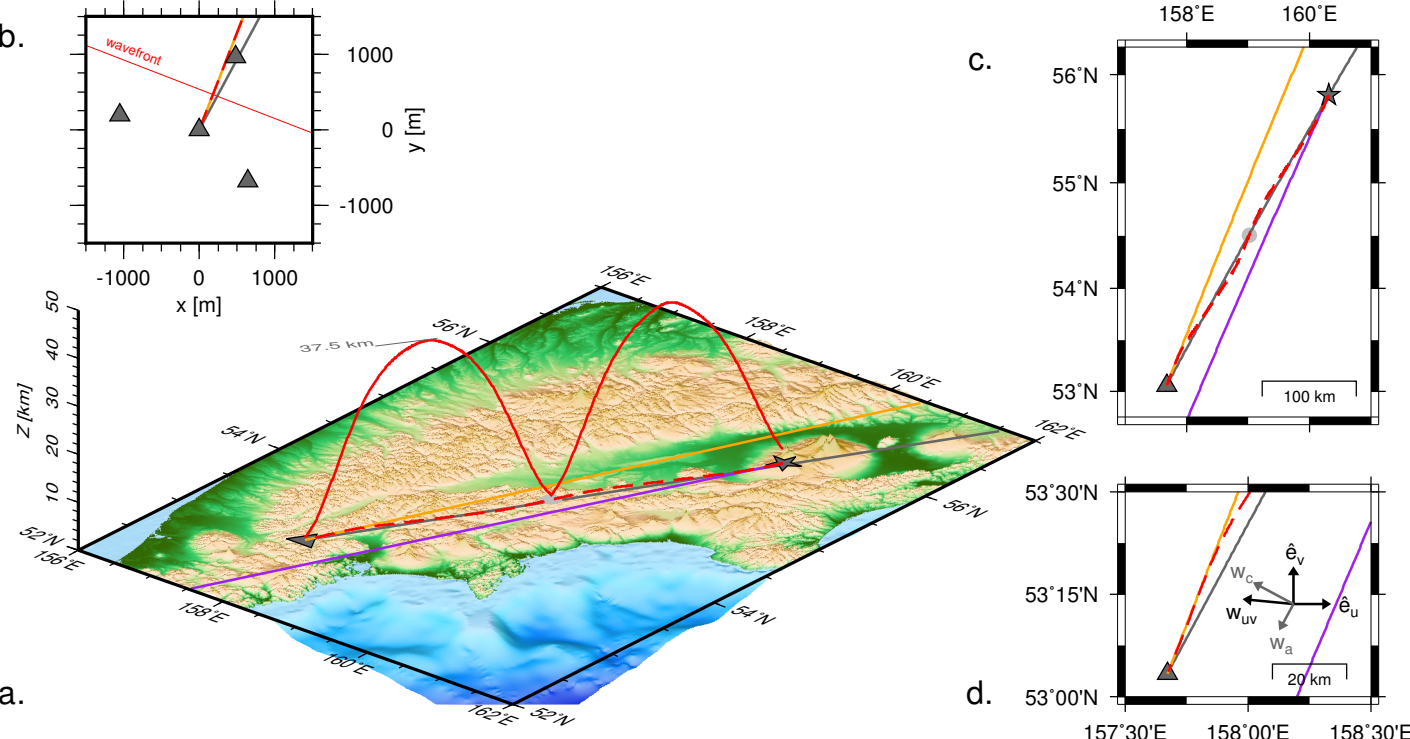
**Figure 6.** Return height range computed from vertical wind and temperature profiles over IS44 ( $53^{\circ}$  N,  $158^{\circ}$  E), for propagation from Mt. Tolbachik to IS44. During the SSW period, the return heights are lower when compared to the summer (30 km vs. 45 km). Lower return height correlates with the higher frequencies observed during the SSW period.

**Figure 7.** Zooms in on Figure 4, focusing on the SSW period. The gray rectangle points to the continuous high-frequency infrasound observations interpreted as low stratospheric altitude returns ( $<40$  km return altitude). These low stratospheric returns with sudden reversal in back azimuth are interpreted to be due to the SSW.

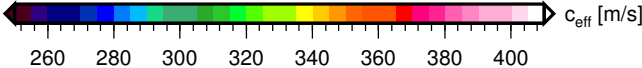
**Figure 8.** Zooms in on Figure 5, focusing on the SSW period.

**Figure 9.** (a) Estimated difference between the observed and predicted back azimuth of all returns over the full timespan of observation. Observations are averaged for 12 hour time bins and contain at least 6 detections. The different colors correspond to the different ECMWF forecasts that are used in the simulations. The lines connecting the dots indicate the continuity of the predictions. The horizontal dashed black line is indicative of the uncertainty of the infrasound array. (b) Similar as (a), but focusing on the midwinter with the SSW period (green rectangle).





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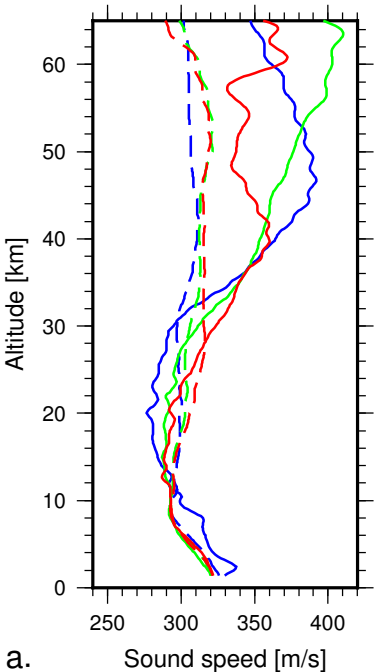
Nowcast

5 day forecast

10 day forecast

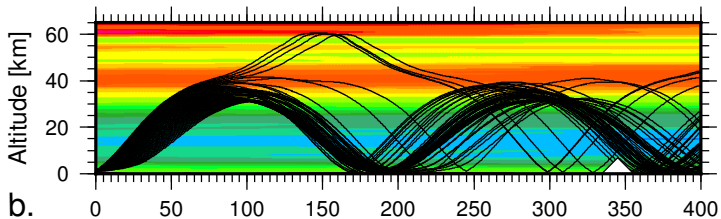
— effective sound speed

- - - adiabatic sound speed



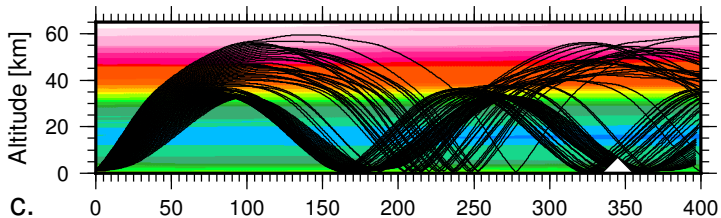
a.

Nowcast



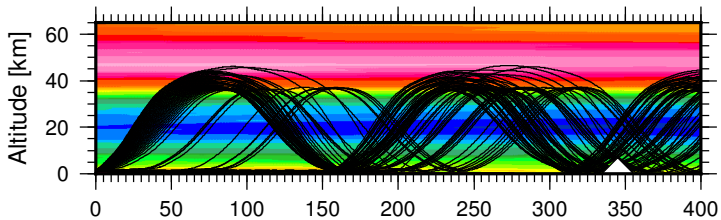
b.

5 day forecast



c.

10 day forecast

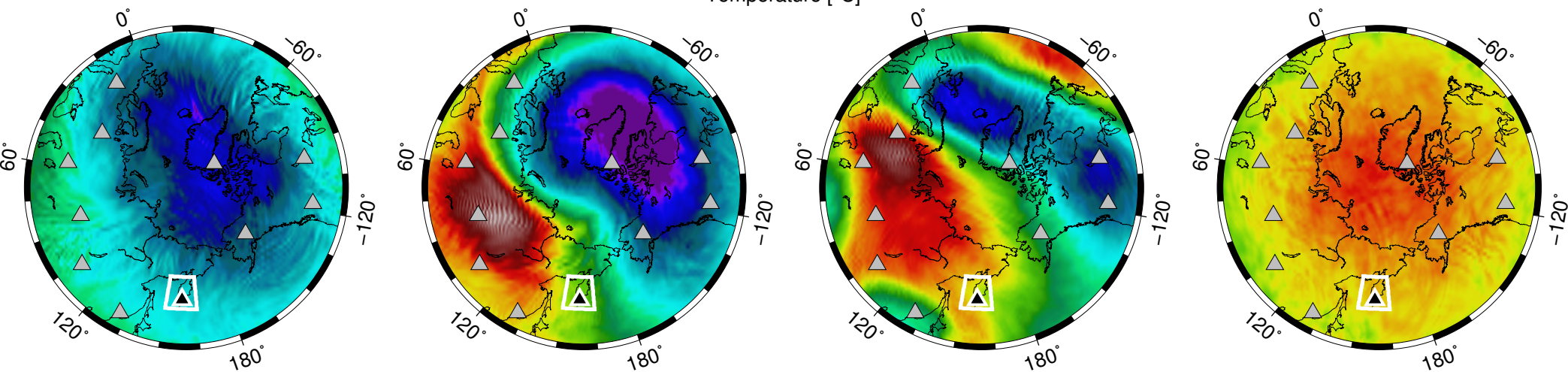


d.

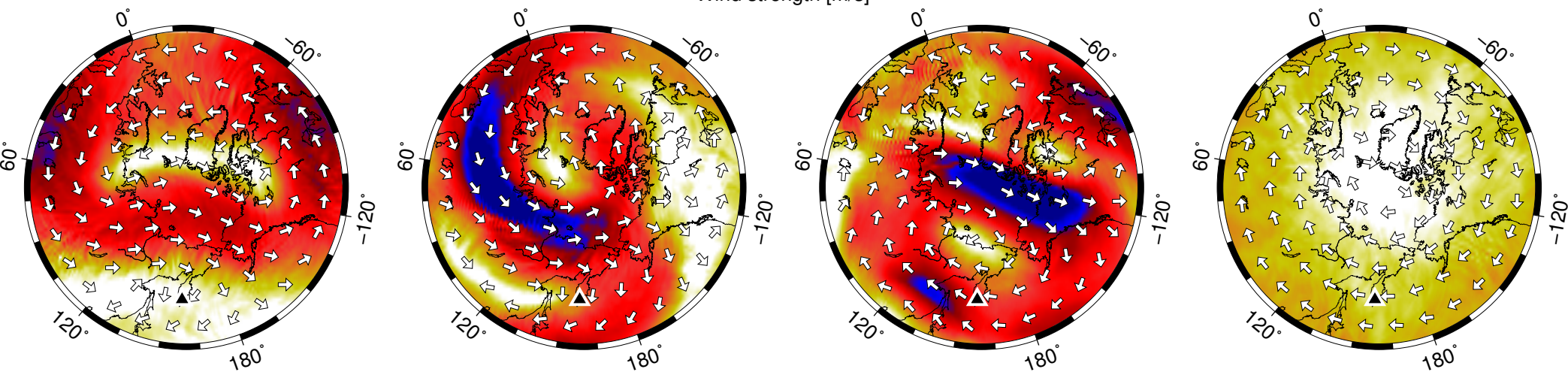
Distance [km]



Temperature [°C]



Wind strength [m/s]



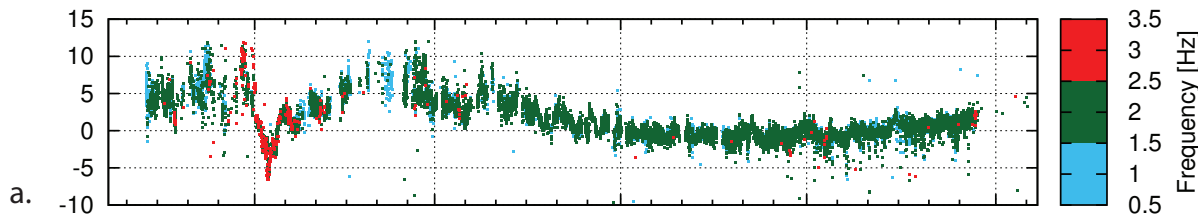
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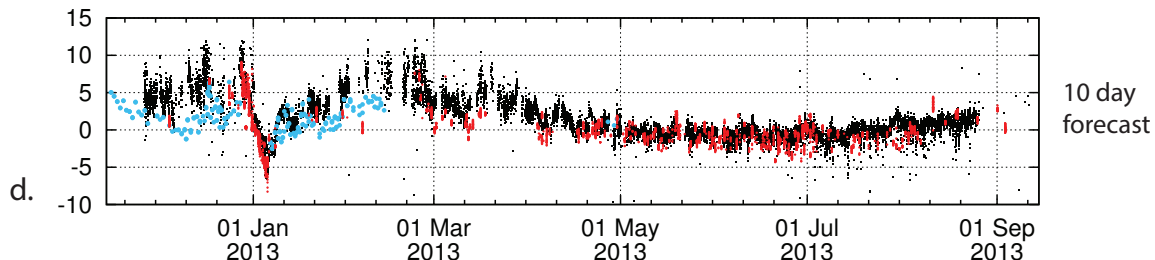
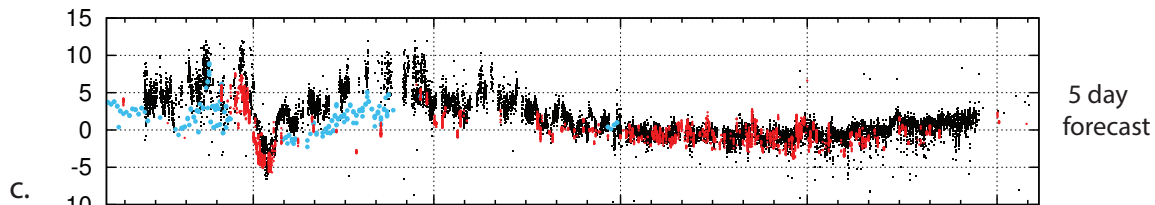
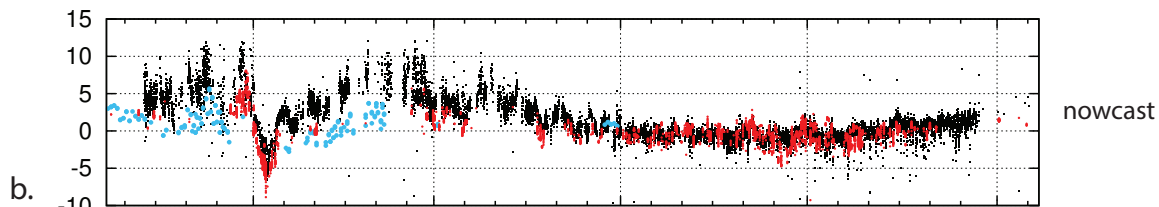
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# Observations only

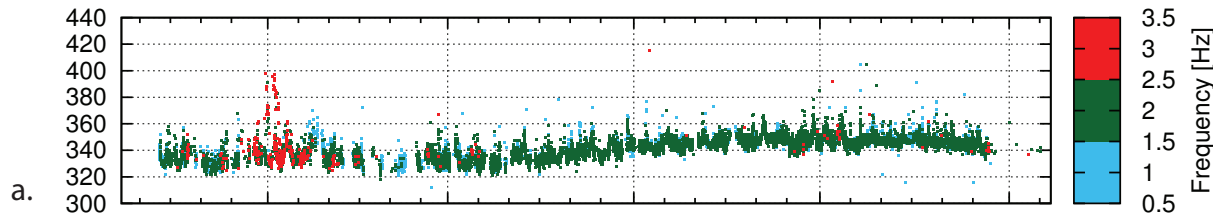


■ observations    ■ stratospheric predictions    ■ thermospheric predictions

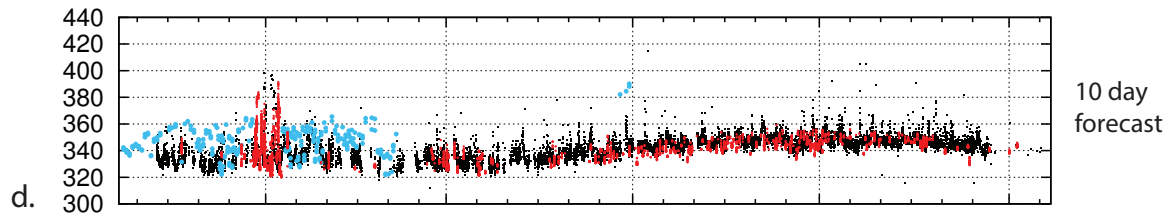
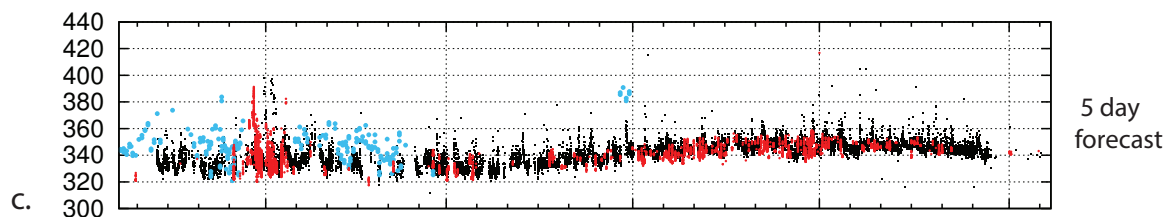
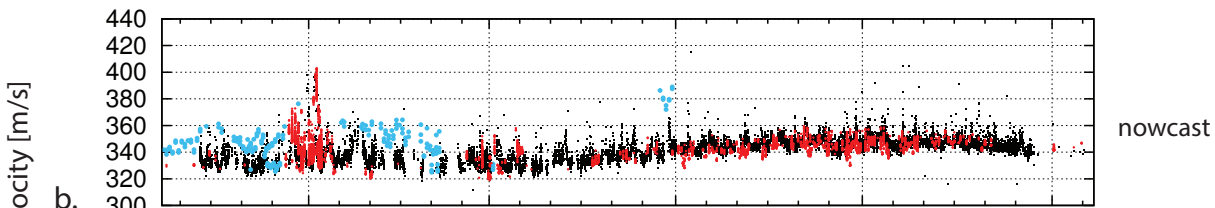
Back azimuth deviation [deg]



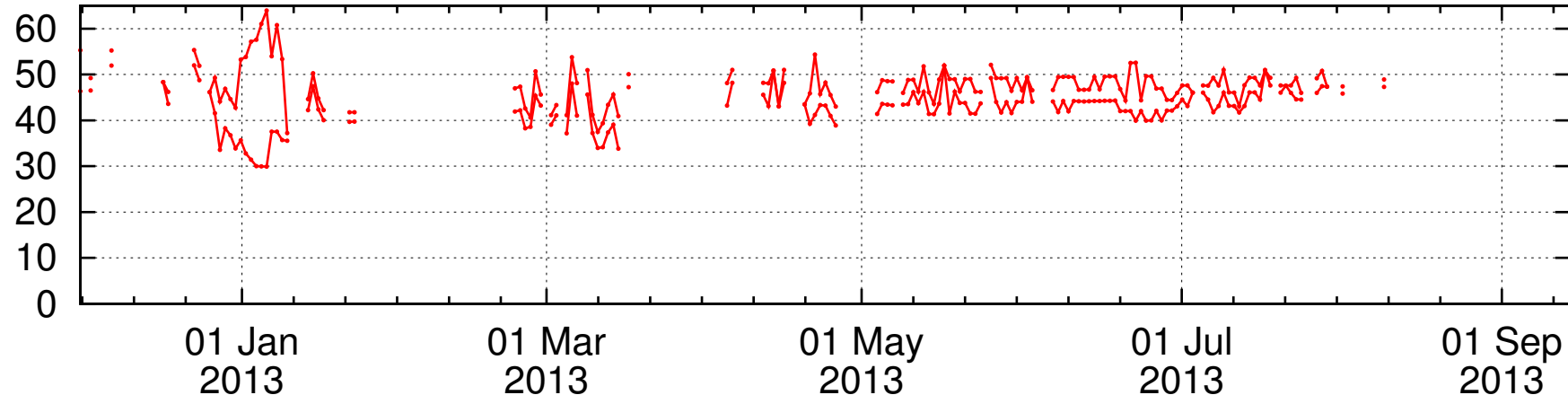
# Observations only



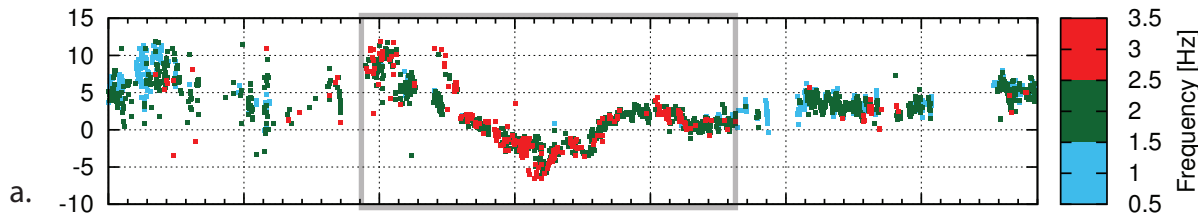
■ observations ■ stratospheric predictions ■ thermospheric predictions



Return height [km]

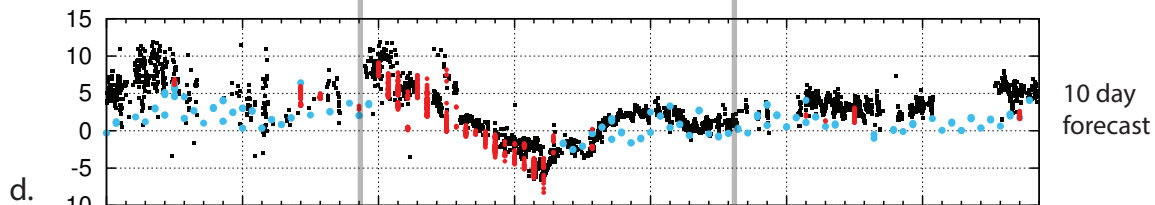
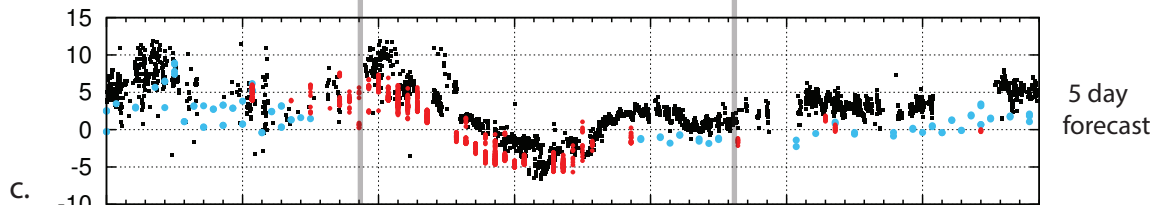
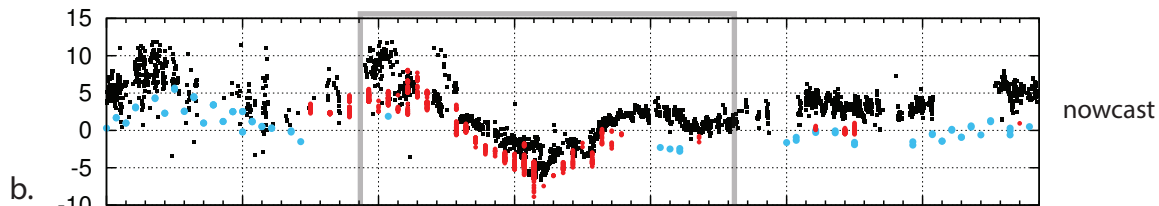


# Observations only



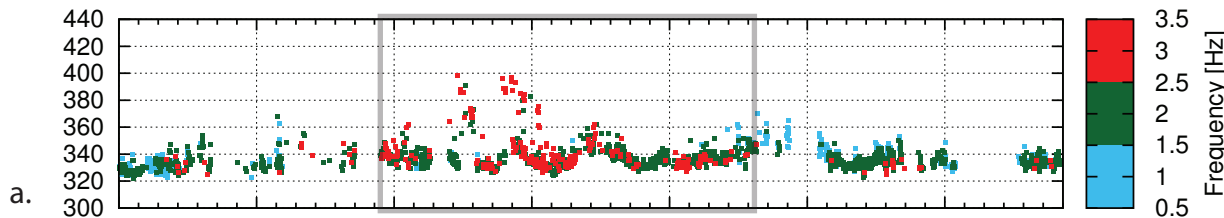
■ observations   ■ stratospheric predictions   ■ thermospheric predictions

Back azimuth deviation [deg]

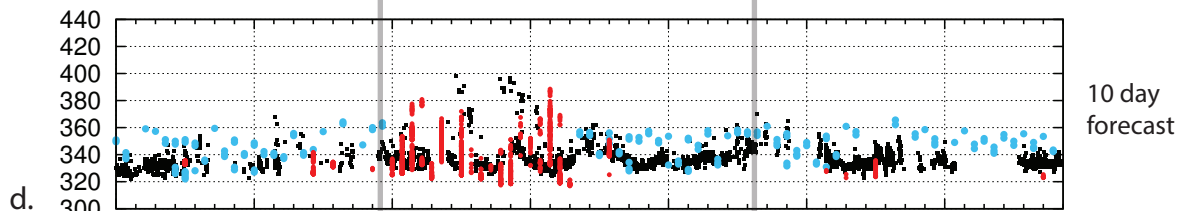
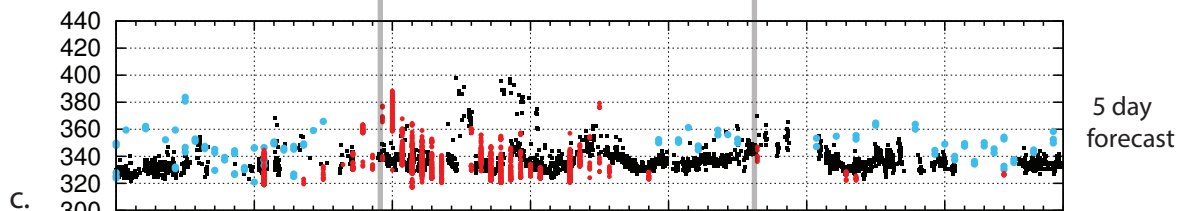
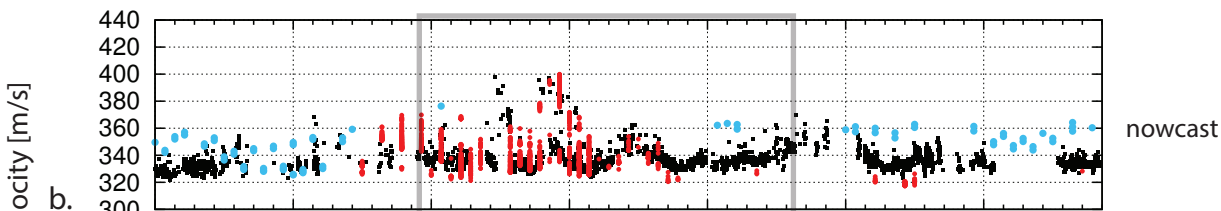


15 Dec 2012   22 Dec 2012   29 Dec 2012   05 Jan 2013   12 Jan 2013   19 Jan 2013   26 Jan 2013

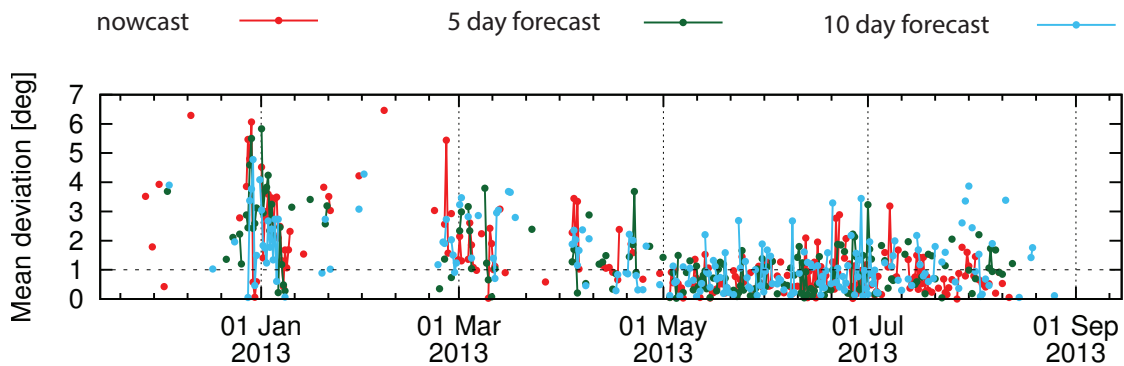
# Observations only



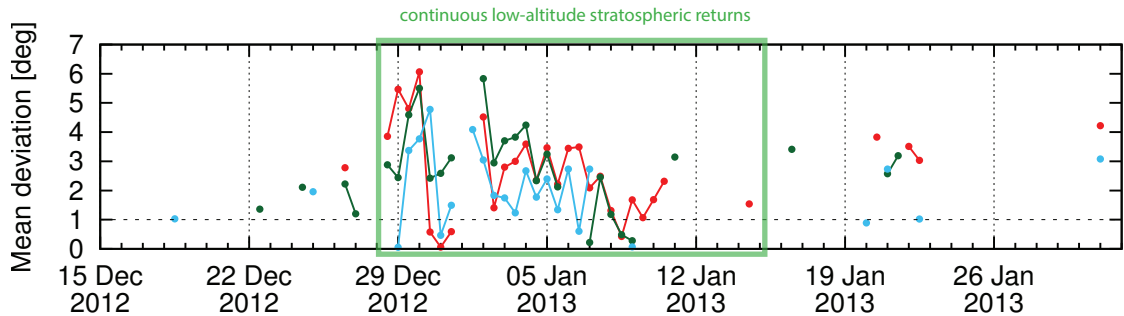
■ observations    ■ stratospheric predictions    ■ thermospheric predictions







a.



b.