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Infrasound fluctuations during heavy fog event in the Arctic: A case study

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Abstract: Extremely dense fog event was studied on the 3rd December 2001, which occurred in the city of Apatity, the Kola Peninsula, northwestern Russia. Fog had low visibility (30–50 m) and lasted 17 h. Variations of atmospheric pressure and electric field before and during the fog event were measured. Multiple Taper Method (MTM) of spectral analysis has revealed pulsations of the atmospheric electric field in the frequency band of 0.007–0.05 Hz with a power-law turbulence spectrum. MTM and wavelet decomposition analysis results indicate the appearance of two types of atmospheric pressure oscillations under the fog conditions: low-frequency variations with periods of internal gravity waves and a substantial increase in pulsation intensity (more than an order of magnitude) in the high frequency (0.03–0.35 Hz) range. These results may help to improve the understanding of the microphysics of fog formation, development, and dissipation. High-frequency pulsations generation of atmospheric pressure under the fog conditions is also of interest because their period is close to the range of infrasonic oscillations, which can have negative consequences for human health.

Keywords: Arctic, Kola, infrasonic waves, atmospheric electric field oscillations.

Introduction

Fog can strongly affect some aspects of human activity directly and indirectly. Dense fog is very dangerous for air, marine, and road traffic (Pagowski *et al*. 2004; Gultepe *et al*. 2007; Van der Velde *et al*. 2010; Veljovic *et al*. 2015; Qian *et al*. 2019). Acid fog and smog caused by air pollution, can as well pose

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a health hazard (Tanaka *et al*. 1998). The financial losses related to fog can be comparable with that of some other extreme weather events like tornadoes and hurricanes (Gultepe *et al*. 2007). To better understand fog microphysics and improve its forecasting, a lot of field measurements and remote sensing observations, as well as laboratory experiments and numerical modelling of fog, has been carried out (Bott *et al*. 1990; Tanaka *et al*. 1998; Pagowski *et al*. 2004; Gultepe *et al*. 2007; Van der Velde *et al*. 2010; Bergot 2012; Schmitt *et al*. 2013; El-Madany *et al*. 2016; Qian *et al*. 2019).

Several fog investigations are devoted to quasi-periodic oscillations of atmospheric parameters, *i.e.* liquid water content, visibility, temperature, wind velocity, pressure, electric field, with periods of minutes and tens of minutes (Bott *et al*. 1990; Duynkerke 1991; Richiardone *et al*. 1995; Anisimov *et al*. 2001, 2013; Shumilov *et al*. 2005; Uematsu *et al*. 2007; Bergot 2012; Hang *et al*. 2016). Most studies associated these oscillations with internal gravity waves, including mountain lee waves, which were rather typical under very stable conditions (Duynkerke 1991; Richiardone *et al*. 1995; Uematsu *et al*. 2007; Hang *et al*. 2016). Bott *et al*. (1990) attributed the oscillations to the interaction between the radiatively induced droplet growth and their subsequent gravitational settling. Uematsu *et al*. (2007) concluded based on millimeter-wave scanning Doppler radar measurements that probably wind shear-induced Kelvin-Helmholtz instability (KHI) which may be one of the causes of gravity waves observed during the fog event. Bergot (2012) showed that KHI may influence the drop size distribution and development of cell structures inside the fog layer, and as a consequence, generation of waves at different scales.

To date, several works have been published, having got focus on the short-term spectra (1–100 s) fluctuations of the atmospheric electric field vertical component (Anisimov *et al*. 2001, 2013). These oscillations have power law spectra under fog conditions while their intensity is about an order of magnitude greater than the energy of fair-weather electric field pulsations (Anisimov *et al*. 2001, 2013).

In the present work, we analyzed a fog event that occurred in the city of Apatity on the Kola Peninsula, on the 3rd December 2001. Results of measurements and spectral analysis of pulsations of the electric field and pressure in the fog are presented.

Data and methods

The observations were made in the city of Apatity (65.6°N, 33.4°E) on the Kola Peninsula with the high-latitude automated system which contained three spaced, each of them is ~150 m, microbarographs, sensors to measure electric field intensity and conductivity, special telemetry system, an automated data collector, including the corresponding software (Shumilov *et al.* 2005). Measurements of atmospheric pressure fluctuations within the frequency range

(0.0001–5 Hz) were carried out utilizing liquid microbarographs with a sampling rate of 1 Hz (Bovsheverov *et al*. 1979). The Pole 2 electric field sensor was used to measure atmospheric electric field intensity and its variations. The instrument has got a collection frequency of 0.1 Hz and two limits of electric field measurements: ± 5000 V/m and ± 500 V/m (Shumilov *et al.* 2005).

The Multiple Taper Method (MTM) of spectral analysis (Thomson 1982) was applied to reveal the main periodicities in signal records. The MTM, being a non-parametric method, avoids some limitations associated with the use of an a priori model of the process (Thomson 1982). The significance of spectral peaks was assessed against a statistical red noise model (Mann and Lees 1996). To analyze the main periodicities of atmospheric pressure and their evolution in time-frequency modes we performed the spectrogram analysis using the windowed discrete-time Fourier transform of a signal with a sliding window.

To analyze a fine structure of pulsations and reveal main periodicities in high-frequency bands the discrete wavelet decomposition (Mann and Lees, 1996) of the original records of pressure variations was performed. It decomposes the signal in approximation (*A*) and in detail (*D*) containing the frequency sub-bands limited by 2^n and 2^{n+1} (where n is related to the time series step). Using the orthogonal discrete Meyer wavelet, we performed an n=5 level decomposition, which passes frequencies in a period range: *D1* (2–4 s, n=1), *D2* (4–8 s, n=2), *D3* (8–16 s, n=3), *D4* (16–32 s, n=4), and *D5* (32–64 s, n=5). The wavelet analysis was made for the standardized (zero mean, unit standard deviation) time series.

Results

Figure 1 shows the measured atmospheric pressure (Fig. 1A) and vertical electric field *E*z (Fig. 1B) variations during a fog on 3rd December 2001. The dynamical spectrum of atmospheric pressure variations for the event is also shown (Fig. 1C). On the day the air temperature was stable at ~ –5ºC, there is no precipitation and a weak wind flow (V<1 m/s) was observed. The heavy fog event began at around ~07:00 UT (the visibility was less than 50 m at the moment) and dissipated at ~22:30 UT. Overall, the fog event lasted more than 15h.

During the time of fog formation, a gradual increase in E_Z took place and lasted up to noon when the maximal electric field values reached ~1kV/m that exceed nearly by one order the background values (Fig. 1B). In the evening, when the fog scattered, the electric field decreased but still exceeded the background value by two-three times.

Together with the start of considerable variations in E_Z some changes in the atmospheric pressure, namely a decrease in the amplitude of low-frequency variations and the occurrence of a high-frequency component, were also detected (Fig. 1A). The dynamical spectrum of atmospheric pressure oscillations demonstrates a noise burst in a wide-frequency band at ~08:00 UT which disappeared after the fog vanished (Fig. 1C).

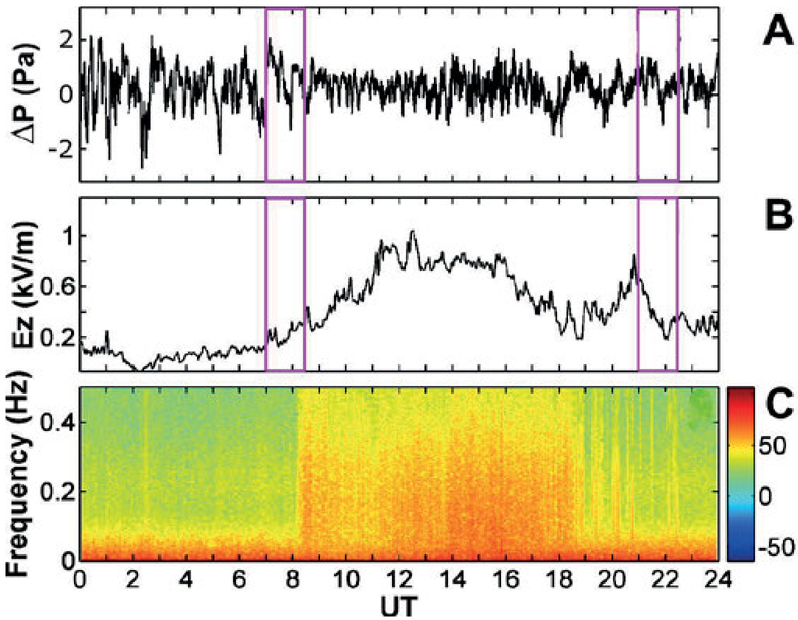

Fig. 1. Variations of atmospheric variables during the fog event of 3rd December 2001: **A** – atmospheric pressure (1s sampling), **B** – vertical electric field EZ (10s sampling), and **C** – spectrogram of atmospheric pressure variations. Rectangles show the intervals of fog formation and fog dissipation, respectively.

Figure 2 demonstrates the MTM spectra of the atmospheric electric field (Figs 2A and 2C) and pressure (Figs 2B and 2D) pulsations. Spectra were calculated for 3h time intervals: 01:00–04:00 UT (pre-fog stage) and 14:00–17:00 UT, fog occurrence. It is obvious that, under the both conditions, a remarkable change in the spectrum slope of E_Z pulsations takes place in the vicinity of 0.07 Hz (Figs 2A and). In the frequency band, 0.007–0.05 Hz, the spectra of E_Z pulsations reveal the power law behaviour under both fair weather ($S(f) \sim f^{-1.6}$) and fog ($S(f) \sim f^{-1.98}$) conditions (Fig. 2C). The difference in the exponent is not significant between fog and non-fog conditions. The both spectra at frequencies 0.001–0.007 Hz are characterized by the presence of low-frequency variations and deviations from the power law shape (Figs 2A and 2C).

Two spectra of atmospheric pressure oscillations are rather different from each other. It is clear that under pre-fog conditions, the spectral density in the frequency range 0.015–0.1 Hz can be fit with a high accuracy by the power law $S(f) \sim f^{-3.9}$ (Fig. 2B). Otherwise, under fog conditions, the spectrum in the same frequency range is characterized by deviations from the power law behaviour and saturation of the spectrum in some time intervals (Fig. 2D). A rather sharp change in the spectrum slope takes place in the vicinity of 0.15 Hz, where the spectrum

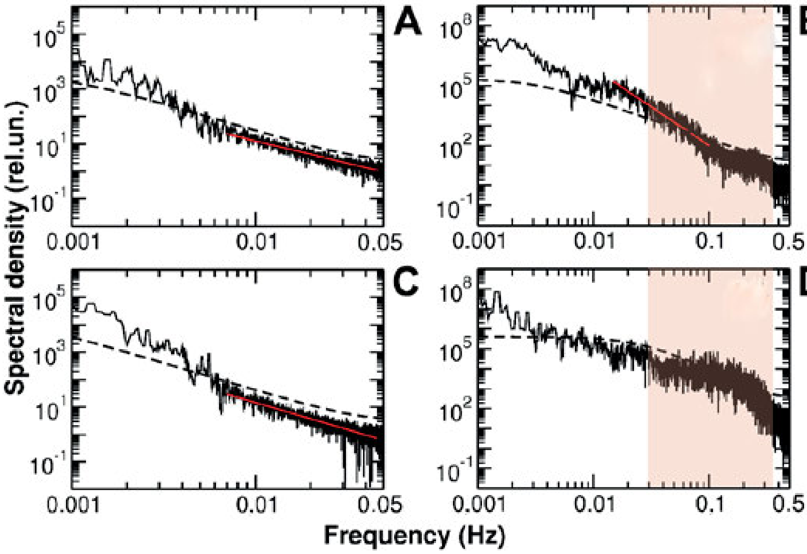

Fig. 2. MTM spectra of the atmospheric electric field (**A**) and atmospheric pressure (**B**) variations for stable conditions (01:00 to 04:00 UT of 3 December 2001) and during the fog event (14:00 to 17:00 UT of 3 December 2001) – **C** and **D**, respectively. Dashed black and solid red lines show 99% confidence levels against red noise and spectral approximations, respectively. Shaded areas show the frequency band of 0.03–0.35 Hz, in which a significant increase in pulsation intensity, more than an order of magnitude, was observed.

becomes steeper (Fig. 2D). Furthermore, under the fog conditions, one can observe a significant (>99% confidence level) increase in pulsation intensity (more than three orders of magnitude) in the frequency band of 0.03–0.35 Hz (Figs 2B and 2D). Again, similar to the spectra of E_Z pulsations, the both spectra at frequencies 0.001–0.015 Hz are characterized by the presence of low-frequency variations which lead to deviations from the power law behaviour (Figs 2B and 2D).

To investigate the evolution of atmospheric pressure oscillations in the time-frequency scale, we have applied the discrete wavelet decomposition of a signal. Figure 3 displays the atmospheric pressure and wavelet decomposition levels: *D1* (2–4 s), *D2* (4–8 s), *D3* (8–16 s), *D4* (16–32 s), and *D5* (32–64 s).

Strong signals are observed in the *D1*, *D2*, and *D3* decomposition levels under the fog conditions (~08:00–19:00 UT). After this time interval (until ~22:30 UT) the signals are still significant in amplitude, but intermittent (Figs 3B, 3C, and 3D). A signal with much weaker amplitude still exists in the *D4* frequency range, and it almost completely disappears in the next *D5* decomposition level (Figs 3E and , respectively). Thus, the wavelet decomposition results allowed us to identify a significant signal of atmospheric pressure variations in the period range (2–16 s) arising under the fog conditions, which does not contradict the data of MTM spectrum analysis.

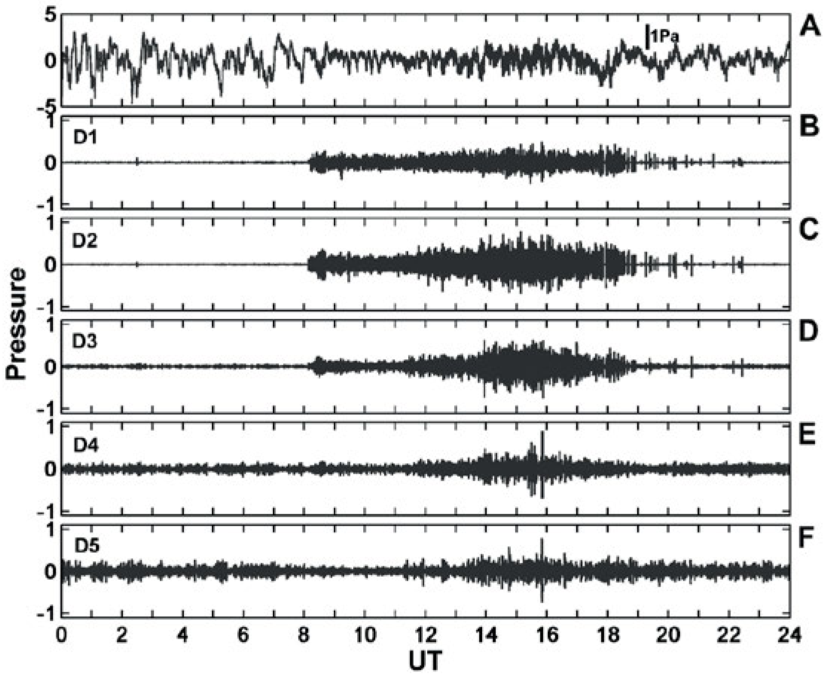

Fig. 3. Variations of atmospheric pressure (**A**) and wavelet decomposition levels on December 3, 2002: (**B**) *D1* (2–4 s), (**C**) *D2* (4–8 s), (**D**) *D3* (8–16 s), (**E**) *D4* (16–32 s), and (**F**) *D5* (32–64 s).

Discussion

Results of spectral and wavelet decomposition analysis demonstrate the existence of atmospheric pressure and electric field oscillations during the fog event. We showed that pulsations of E_Z in the 0.007–0.05 Hz frequency range had a power law spectrum under both fair-weather and fog conditions. The spectral shape under pre-fog conditions was similar to the Kolmogorov spectra of temperature, with the spectral index close to –5/3 in the inertial subrange, and wind velocity variations in a turbulent atmosphere (Anderson 1982; Anisimov *et al*. 2013; Nosov *et al*. 2019). One of possible mechanisms of coupling between electric field and temperature fluctuations is based on the light ion mobility variations induced by a temperature change (Anisimov *et al*. 2001, 2013). Otherwise, oscillations of the medium velocity during turbulence might lead to the electric-charge mixing, *i.e.*, to small-scale pulsations (Anisimov *et al*. 2001). The turbulent mixing of particles (droplets) with large charges under fog conditions should lead to a significant increase in the amplitude of small-scale fluctuations (Anisimov *et al*. 2001, 2013), as it is shown in our Fig. 2C. Nevertheless, the spectral indices under the both pre-fog and fog conditions do not differ significantly.

It should be noted that simultaneously with the onset of significant changes in the atmospheric electric field, changes were also observed in atmospheric pressure variations, namely, a decrease in the amplitude of low-frequency fluctuations and the appearance of a high-frequency component. The spectral slope of atmospheric pressure variations under stable conditions at frequencies 0.015–0.1 Hz (~–3.9 exponent) differs from the Kolmogorov turbulence spectrum (Fig. 2B). It is similar to the spectrum of so-called coherent turbulence or coherent structure with the spectrum decreasing by the 8/3-power law (Davies and Yule 1975; Nosov *et al*. 2019). These structures are large-scale energy-carrying vortices in the turbulent atmosphere (Barthlott *et al.* 2007; Nosov *et al.* 2019). The analysis of MTM spectra allowed us to reveal a substantial change in the spectrum behaviour of atmospheric pressure variations in the 0.015–0.1 Hz frequency range during fog conditions: it completely deviates from the power-law shape. Also, one can see that during the fog a rather sharp change in spectrum slope takes place in the vicinity of ~0.07 Hz (Fig. 2D).

Low-frequency variations of atmospheric parameters with periods of internal gravity waves have been earlier detected in fog and seemed to be caused by a wind-shear induced KHI instability (Richiardone *et al*. 1995; Uematsu *et al*. 2007; Bergot 2012) or by the mountain lee waves that can occur in mountain regions (Shumilov *et al*. 2002). Unfortunately, in our case, we have not got any information about the vertical profile of potential temperature and wind speed to make a more detailed conclusion. As to the high-frequency variations, it is interesting to highlight a significant, *i.e.* more than order of magnitude, growth of their amplitudes in the 0.03–0.35 Hz frequency band. This result is also interesting from the point of view that the fog may be considered as a non-equilibrium medium in which the wave buildup and amplification are theoretically possible. In support of this, there are some studies directly proving the possibility of the development of microdroplet self-oscillations with a period close to infrasound during condensation of water vapor in an external electric field (Gabyshev 2018; Fedorets *et al*. 2019).

Conclusions

The obtained results demonstrate the appearance of atmospheric pressure and electric field pulsations under the fog conditions. In the frequency band of 0.007–0.05 Hz, the spectrum of *Ez* pulsations revealed the power law behaviour of turbulence type under both fair weather ($S(f) \sim f^{-1.6}$) and fog ($S(f) \sim f^{-1.98}$) ($S(f) \sim f^{-1.6}$) conditions. As to the atmospheric pressure variations, there are two types: low-frequency oscillations with periods of internal gravity waves and high frequency (0.03–0.35 Hz) pulsations with amplitudes of more than order of magnitude compared to pre-fog stage. A substantial change in the spectrum shape in the 0.015–0.1 Hz frequency range occurred during fog conditions. The spectrum in this frequency range was characterized by deviations from the power law behaviour and saturation of the spectrum in some time intervals. Further research is needed to investigate the formation and microphysics of fog and fog-like structures (clouds, dust clouds) of natural and man-made origin at high latitudes with help of integrated methods measuring several atmospheric parameters simultaneously. Another important aspect of such studies is the possible negative effect of electromagnetic and infrasonic pulsations in the range of units and tenths of a hertz on human health.

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