Infrasonic signature of the 2009 major sudden stratospheric warming

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[1] The study of infrasound is experiencing a renaissance since it was chosen as a verification technique for the Comprehensive Nuclear-Test-Ban Treaty. The success of the verification technique strongly depends on knowledge of upper atmospheric processes. The ability of infrasound to probe the upper atmosphere starts to be exploited, taking the field beyond its monitoring application. Processes in the stratosphere couple to the troposphere and influence our daily weather and climate. Infrasound delivers actual observations of the state of the stratosphere with a high spatial and temporal resolution. Here we show the infrasonic signature, passively obtained, of a drastic change in the stratosphere due to the major sudden stratospheric warming (SSW) of January 2009. With this study, we infer the enormous capacity of infrasound in acoustic remote sensing of atmospheric processes on a global scale with surface based instruments. Citation: Evers, L. G., and P. Siegmund (2009), Infrasonic signature of the 2009 major sudden stratospheric warming, Geophys. Res. Lett., 36, L23808, doi:10.1029/2009GL041323.

1. Introduction

[2] Infrasound was first detected on barographs after the eruption of the Krakatao in Indonesia (1883) when low frequency acoustic waves were observed to travel around the earth four times [Symons, 1888]. Scientific and societal interest in infrasound gradually increased [Whipple, 1939], especially during World War I, and later on in the nuclear testing era [Posey and Pierce, 1971]. During the latter period, the potential of infrasound as a passive atmospheric probe started to be recognized [Donn and Rind, 1971]. As nuclear tests were confined to the subsurface, under the Limited Test Ban Treaty (1963), only a few studies could be maintained [Balachandran et al., 1977; Liszka, 1978]. Interest recently increased again with the signing of the Comprehensive Nuclear-Test-Ban Treaty (CTBT) in 1996 [Dahlman et al., 2009]. Currently, a worldwide network of 60 infrasound arrays is being established for Treaty verification. Infrasound reaches thermospheric altitudes and information on the whole atmosphere is recorded by the surface based microbarometers [Drob et al., 2003]. Interacting oceanic waves almost continually radiate infrasound (so-called microbaroms); the amplitude of the microbaroms, the distance to the source and the atmospheric wind and temperature structure determines their detectability [Posmentier, 1967]. Actual observations of basic physical parameters, like wind and temperature, are sparse for stratospheric altitudes, but the stratospheric winds and temperatures leave a signature in the passively obtained infrasound recordings. Infrasonic observations of a sudden stratospheric warming event were first described by [Rind and Donn, 1978]. Processes in the stratosphere are no longer considered to be isolated from the troposphere by an assumed impermeable tropopause, instead their importance for weather and climate has recently been firmly established [Limpasuvan et al., 2004; Shaw and Shepherd, 2008].

2. IMS Infrasound Measurements

[3] The 60-station infrasound component of the International Monitoring System (IMS) for the CTBT is used to detect and locate nuclear explosions in the atmosphere. The arrays in this global network consist of array elements, based on microbarometers, that are capable of measuring infrasound in the range of at least 0.02 to 4 Hz with amplitudes of mPa up to tens of pascals. Not only acoustic waves, like infrasound, are sensed in this pass-band, but also waves with gravity as restoring force, i.e., gravity waves [Gossard and Hooke, 1975]. Figure 1 shows the infrasound arrays of the IMS in the Northern Hemisphere. These arrays have a wide range of array elements (four to eight) and apertures (1200 to 2500 meters). Each microbarometer is connected to a wind noise reducing system which enhances the signal-to-noise ratio by reducing the negative effect of wind on the micro-pressure measurements. Such noise reducers can consist of pipes with discrete inlets which spatially integrate the pressure field [Hedlin et al., 2003]. The incoherent pressure disturbances due to wind are partially canceled out through summation, while the infrasonic waves remain unaffected because of their much larger coherency lengths.

3. Signal Detection

[4] A coherent infrasonic wave can be detected by evaluating the Fisher statistics [Melton and Bailey, 1957], in an array processing scheme. In essence, the Fisher (F) detector evaluates the signal-to-noise power ratio (SNR\textsuperscript{2}) of the coherent wave traveling over the array at each element. The parameters that can be estimated for a certain detection, i.e., an event, are the back azimuth and apparent sound speed. The back azimuth is the angle, measured clockwise in degrees, between the North and the line connecting the receiver to the source. The apparent sound speed is the propagation velocity of the wave over the array and can range from the local sound speed to infinity, for a vertically incident wave. All data in this study have been filtered with a second order Butterworth band-pass filter with corner frequencies of 0.1 and 1.0 Hz, as microbaroms typically occur around 0.2 Hz. This frequency band is also of utmost importance for the CTBT, since small-
sized nuclear tests, of around 1 kT TNT equivalent, are expected to occur within this frequency range [Evers and Haak, 2001].

[5] Figure 2a shows the results of such a detection and processing approach for the IMS infrasound array IS18 on Greenland (see Figure 1). Results illustrated in Figure 2b correspond to IS53 located in Alaska. Shown are several measurements, processing results and models for the period of 2009, January 1 up to February 15. The microbarometer recordings show some periods of high amplitude. Most of these are related to strong surface wind conditions at the array. The increased noise levels, resulting from these strong winds, degrade the detection capabilities of the arrays as the coherency of the infrasonic signals is altered. This effect is also notable in the three processing frames. The detected $SNR^2$ strongly vary as function of time and are in principle determined by the source activity and the state of the boundary layer and the upper atmosphere. Considering IS18, there is a period of increased signal coherency also notable in the resolved apparent sound speeds between January 15 and 29. A drastic change is also visible in the direction where the infrasonic waves come from. A source to the southeast, around 140 deg, seems to intensify or atmospheric circumstances make its detection more favorable. At IS53, changes in apparent sound speed and back azimuth are also visible. A source to the east is suddenly detected while activity to the west becomes less well defined. From these observations the question arises: what is the cause of these abrupt changes in the detection characteristics, except for the local noise conditions due to boundary layer winds?

4. Propagation of Microbaroms

[6] Infrasound propagation is mainly controlled by the effective sound speed, i.e., the propagation velocity as function of the temperature and wind along the source-
receiver trajectory. At long ranges, say 200 km and more, there are two regions in the atmosphere which lead to the refraction of waves due to an increase in effective velocity. If the gradient in the effective sound profile is strong enough, waves are refracted back to the earth’s surface. This is the case in the stratosphere around 50 km altitude and the thermosphere from 100 km and upwards. Stratospheric refractions are caused by the increase in temperature with altitude due to the absorption of solar radiation by ozone and the presence of the polar vortex. The latter makes the refractivity of the medium seasonal dependent, as the vortex wind is directed eastwards in the Northern Hemisphere winter and westwards in summer. The direct influence of solar radiation on the molecules in the thermosphere leads to an increase of their average kinetic energy, i.e., a temperature increase, which enables refractions back to the earth’s surface from this region. Attenuation seriously alters infrasonic energy in the strongly rarefied gases at thermospheric altitudes [Sutherland and Bass, 2004]. Therefore, stratospheric returns are dominant over long ranges of more than 1000 km.

Figure 2. The observations, array processing results and source characteristics for (a) IS18 and (b) IS53. From bottom to top are shown, a single microbarometer trace band-pass filtered between 0.1 and 1.0 Hz with a second order Butterworth filter. The next observation is the wind measured at the array site, low-pass filtered with a period of six hours. The array processing results consist of the maximum signal-to-noise power ratio ($SNR^2$) as derived from the $F$-detector, the resolved apparent sound speed and the back azimuth (0 degrees means a source to the north, 90 degrees is to the east). The parameters are determined in segments of 256 samples (12.8 seconds) on a $100 \times 100$ points slowness (in s/m) grid for beam-forming, with 50% overlapping segments. A common threshold criterion is set by only allowing for events with $SNR^2 > 1$, which enhances the dominant characteristics by reducing the influence of noise. The number of events per hour are color coded, five or more events are indicated by red colors. The source characteristics follow from ECMWF ocean wave analyses with a resolution of $0.5^\circ \times 0.5^\circ$ each 12 hours. The direction with respect to the array of the Pacific Ocean microbarom maximum (MBPO) is denoted with the black dashed line, the Atlantic maximum (MBAO) is given by the solid line. The green line represents the wind direction at 50 km altitude at the nearest ECMWF model gridpoint to the array. The top frame shows the approximated source intensity, the squared multiplication of the ocean wave height and radial frequency, and their averages as horizontal lines.
frequency of the oceanic waves. The amplitude of the microbaroms is proportional to the squared multiplication of the wave height and radial frequency [Posmentier, 1967]. In Figure 1, an approximation of the source location and intensity \(I_S\) is given by evaluating these microbaroms amplitudes for 2009, January 19 at 12 UT from ocean-wave analyses provided by the European Centre for Medium-Range Weather Forecasts (ECMWF). Strictly, the directional spectra of oceanic waves at specific frequencies should be evaluated to identify oppositely traveling waves and to accurately characterize the source [Kedar et al., 2008]. For this study, it is sufficient to have an indication where the activity is likely to occur and to have an estimate of the intensity [Evers and Haak, 2001]. The directions from the Atlantic and Pacific maxima are superimposed on the resolved back azimuths in Figure 2, by a solid and dashed black line, respectively. \(I_S\) is given in the top frame following the same convention where the straight lines are the averages. Clearly, both arrays detect microbaroms from the Atlantic (MBAO) and Pacific Ocean (MBPO). The sudden loss of MBPO and increase of MBAO detections can not be explained by changes in \(I_S\), which are fluctuating around their average values up to January 29.

5. Anomalous Propagation Due to the SSW

The drastic change in the microbarom’s detectability, in terms of back azimuth, can be understood by considering the atmosphere. Changes in the direction and intensity of the polar vortex determine the sensitivity of the arrays for sources located in specific directions. The reduction in detections from MBPO indicates the lack of a component directed to the southeast in the polar vortex [Rind and Donn, 1978]. The increased sensitivity to MBAO is also in line with a direction change of the polar vortex from eastward to westward, i.e., from a normal Northern Hemisphere winter to summer state. Such a reversal during winter implies the occurrence of a major sudden stratospheric warming (SSW) [Holton, 1979]. ECMWF analysis shows that a major SSW started around January 15. At an altitude of 30 km, the average temperature to the north of 65°N increased in one week by more than 50°C, leading to exceptionally high
temperatures of about $-20^\circ C$. Simultaneously, the polar vortex reversed direction from eastward to westward. The warming was accompanied by a split-up of the polar vortex and an increased amplitude of the zonal wavenumber number 2 planetary waves.

[9] Although clear signatures are visible in the back azimuths, the drastic change in SNR$^2$'s at IS18 is not observed in IS53 (see Figure 2). Two effects are of importance: (1) the source-receiver distance and (2) the presence of multiple microbarom sources. During the SSW, IS18 only detects MBAO which occur close to the array. MBAO and MBPO are measured before and after the SSW, causing one signal to become noise for the other leading to a smaller SNR$^2$'s. Microbaroms from MBAO and MBPO are hardly detected simultaneously at IS53 and both sources are located at similar distances. Therefore, no pronounced effect in the SNR$^2$ is visible during the SSW at IS53. However, the wind at 50 km altitude nearby the stations shows the coincidence between the SSW and changes in the observed back azimuths (see Figure 2).

[10] The processing results of all operational IMS arrays north of $15^\circ N$ show that all arrays detect a large amount of coherent infrasound as long as the local wind speeds are lower than 5 m/s (Figure S1 of the auxiliary material). The detection capability is significantly reduced for stronger wind conditions (see IS11 and IS51). Clear infrasonic signatures of the SSW, like those observed in IS18 and IS53, are also visible over the western US (IS56) and central Canada (IS10). Even slight changes, in the retrieved back azimuths, are notable in Kazakhstan (IS31). At the Russian arrays (IS44, IS45 and IS46) no pronounced changes in the observed back azimuths are visible. Similar results are also found for the German (IS26), Japanese (IS30), Mongolian (IS34) and Tunesian (IS48) arrays.

[11] The winds and temperatures at 50 km altitude are given in Figure 3, and are derived from ECMWF analyses. Prior to the SSW, an easterly flow is present from $15^\circ N$ and northwards and temperatures below $-20^\circ C$ prevail. A disturbed flow and temperatures of up to $15^\circ C$ occur during the SSW. Arrays that sensed the SSW are near regions of strong winds and high temperatures, which are both favorable for refraction. However, the analyzed wind direction does not always confirm the observations. For example, an easterly flow is predicted above IS10 and IS56, while the observations of MBAO, at these arrays, are indicative for a westerly flow. At the more northern arrays, i.e., IS18 and IS53, the wind direction agrees with the infrasonic observations (see also Figure 2).

6. Discussion and Conclusions

[12] In this study, we concentrated on the observed back azimuths at the arrays. Further studies will include other signal characteristics such as: apparent sound speed and amplitude. Combined with propagation modeling, such an analysis will unravel how all these observations quantitatively relate to the wind and temperature structure of the stratosphere. However, it has been shown that the passively obtained infrasonic records provide detailed information on upper atmospheric processes, for the first time on a global scale. These surface based observations of oceanic noise thus enable a characterization of the wind and temperature structure of the upper atmosphere. Actual observations of the upper atmosphere are sparse. Meteorological balloons reach an altitude of roughly 30 km. Rocket sondes are capable of probing the stratosphere and mesosphere but lack temporal and spatial coverage. Satellite observations have a limited vertical resolution and are difficult to validate for these altitudes. Therefore, current atmospheric analyses for these altitudes strongly depend on model characteristics. Here, we present the technique of infrasound which has the capacity of validating such models. Additional knowledge on an even finer spatial and temporal scale might be obtained in near-future studies. The influence of the stratosphere on our daily weather and climate has conclusively been resolved [Baldwin and Dunkerton, 2001; Thompson and Solomon, 2002; Ineson and Scaife, 2009]. Therefore, high resolution and actual observations of the upper atmosphere would be a welcome addition for future atmospheric research and could come from inverse modeling of infrasound observations [Le Pichon et al., 2005; Antier et al., 2007] and correlation techniques with ambient noise [Godin, 2006; Wapenaar, 2006]. Understanding the detectability of infrasound and its dependencies is also crucial for successfully applying infrasound as a verification technique. The mission capability of IMS infrasound arrays is determined by the state of the stratosphere, considering the long range propagation aspect. Weak stratospheric winds reduce the detectability of infrasound during equinox periods [Le Pichon et al., 2009]. Similarly, unforeseen changes in the upper atmospheric wind and temperature structure strongly influence the system’s sensitivity, as we have shown for this SSW. Future investigations will focus on how signal characteristics other than the back azimuth are altered by such drastic changes in the stratosphere. This will provide additional information on the infrasonic signature of a major SSW.

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References


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