Monitoring Stratospheric Winds with Concorde-Generated Infrasound[1]

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ABSTRACT

The relatively low frequency of the sonic boom generated by the Concorde SST permits propagation in the form of infrasound to long range with small attenuation. Signal characteristics at long range are a function of atmospheric propagation parameters. When the relationship of propagation to signal is understood, then propagation conditions can be determined by inversion with good accuracy. We show here how signal recorded at Palisades, New York, from the Dulles-bound SST reveals direction and speed of stratospheric wind variations diurnally and seasonally and also gives details of at least local circulation change at times of stratospheric warmings.

1. Principle of the study

Long-range infrasound from the Concorde shock wave serves as a novel and useful tool to probe both the stratosphere and lower thermosphere. At present there are several daily arrivals and departures at J. F. Kennedy and at Dulles Airports, the former having commenced at the end of November 1977 and the latter at the end of May 1976.

The basic frequency of the shock wave or N wave generated by the SST is 2.5 Hz. Because sound attenuation varies as the square of the frequency, such relatively low-frequency waves can propagate to large distances in which the spreading law is the dominant cause of signal decay. Also, because the plane travels in the region of the temperature minimum in the lower stratosphere, both the upgoing and downgoing shock waves, and the infrasound into which they degenerate, refract away from the normal as temperatures increase above and below the flight path. When the sound traveling to the upper stratosphere, whether directly or after reflection at the surface, reaches a stratospheric level where the sound velocity begins to exceed the velocity at the surface, refraction toward the surface occurs. The steeper the upward angle of the rays, the greater is the velocity necessary for total reflection.

Donn and Rind (1972) and Rind and Donn (1975) have already shown how natural infrasound of a few seconds period that is radiated into the atmosphere by interfering ocean waves can be used as a passive probe of both stratosphere and lower thermosphere. But the sources of natural infrasound are usually very broad and also quite variable in strength. However, infrasound from the SST can be considered coming from a nearly point source with a known time and place of origin and with a constant source strength. The magnitude of the long-range SST infrasound depends primarily on propagation conditions and hence has considerable quantitative significance. In this report we will restrict the discussion to the application of SST infrasound to stratospheric wind motion. The study is also restricted to signal from the inbound Dulles flight whose path relative to our station in Palisades, New York is shown in Fig. 1. By using data from our tripartite station, the dominant arrival direction of signal reflected from the stratosphere is 111° with the source being indicated by the arrow.

Normally the temperature in the stratosphere, and the related speed of sound, does not quite equal surface conditions as indicated in Fig. 2 in which the curve C shows the scalar speed of sound for two dates involved in this study. However, in summer (as on 17 August) the east wind component of the stratospheric easterlies, when added to the speed of sound ($C+w_e$) brings the effective speed of sound in the stratosphere for a source to the east well above the sound speed at the surface. The region between 40–60 km and the surface is thus a good sound channel for sound propagating from a source to the east, as in the case of the Concorde whose elevation at the time of signal generation is shown by the horizontal broken line. In the autumn, after stratospheric winds have reversed to westerly, the effective speed of sound ($C-w_w$) in the stratosphere for a source to the east is very low, and the sound channel disappears (Fig. 2B).

Figs. 3A and 3B show computer-drawn ray tracings for conditions corresponding to those in Figs. 2A and 2B, respectively. The importance of wind in maintaining a sound channel below the stratosphere for sources

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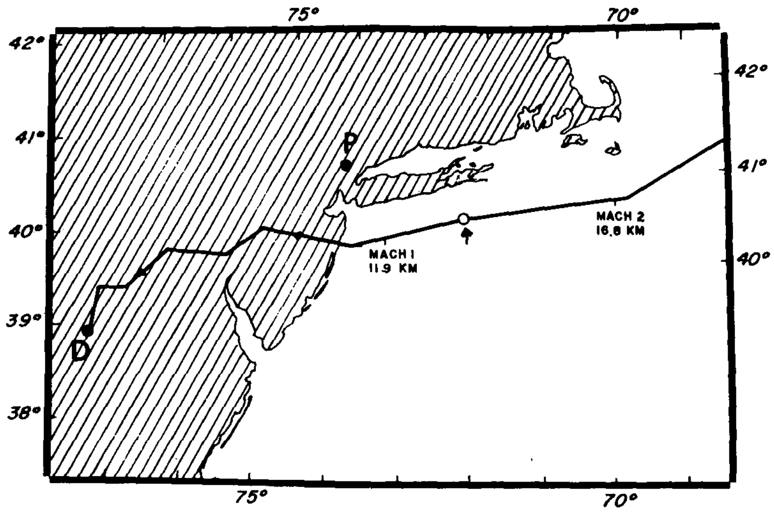

FIG. 1. Flight path and elevation data for the Dulles-bound Concorde. P is the recording site at Palisades, New York. The arrow indicates the mean source location for infrasound generated by the SST and recorded at P.

to the east in summer and in destroying the channel when winds reverse in early autumn is evident from the differing ray paths.

The data on which Figs. 2 and 3 are based were taken from the rocketsonde data for Wallops Island, Virginia (~325 km to our south) as given in monthly reports of the Meteorological Rocket Network. Data below 20 km come from normal tropospheric soundings and surface reports.

We emphasize that this is a new procedure to investigate winds in the upper atmosphere. Because no independent upper wind observations are available locally to calibrate our results we use Wallops Island observations as a guide to the interpretation of our data and for calibrating our results. Once the validity of the procedure is established, the infrasonic observation and analysis can be used as an independent source of upper air wind behavior particularly at either times or places of no direct observation.

2. Nature of the data

The primary data used in the present study are the amplitudes of the largest infrasound signal from the Concorde recorded on visual drum records. To better appreciate the procedure a copy of a typical summer

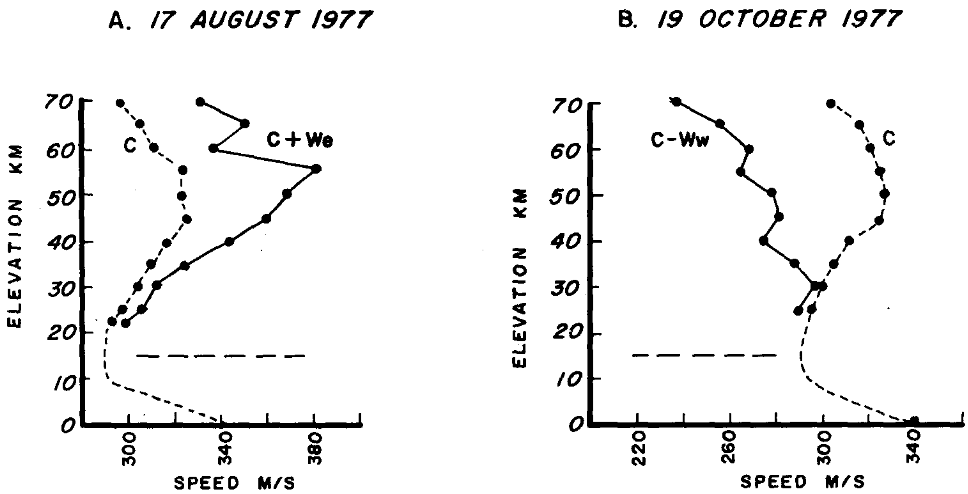

FIG. 2. Vertical profiles of sound speed C and sound speed plus the easterly component of the wind ($C+w_e$) as taken from the Wallops Island Meteorological Rocketsonde data for a typical summer day (A) and of sound speed and sound speed minus the westerly components of the wind for a typical autumn day (B). The profile for $C+w_e$ shows a good sound channel between 55 km and the surface for signal from the east. The $C-w_w$ profile shows no sound channel between the stratosphere and the surface.

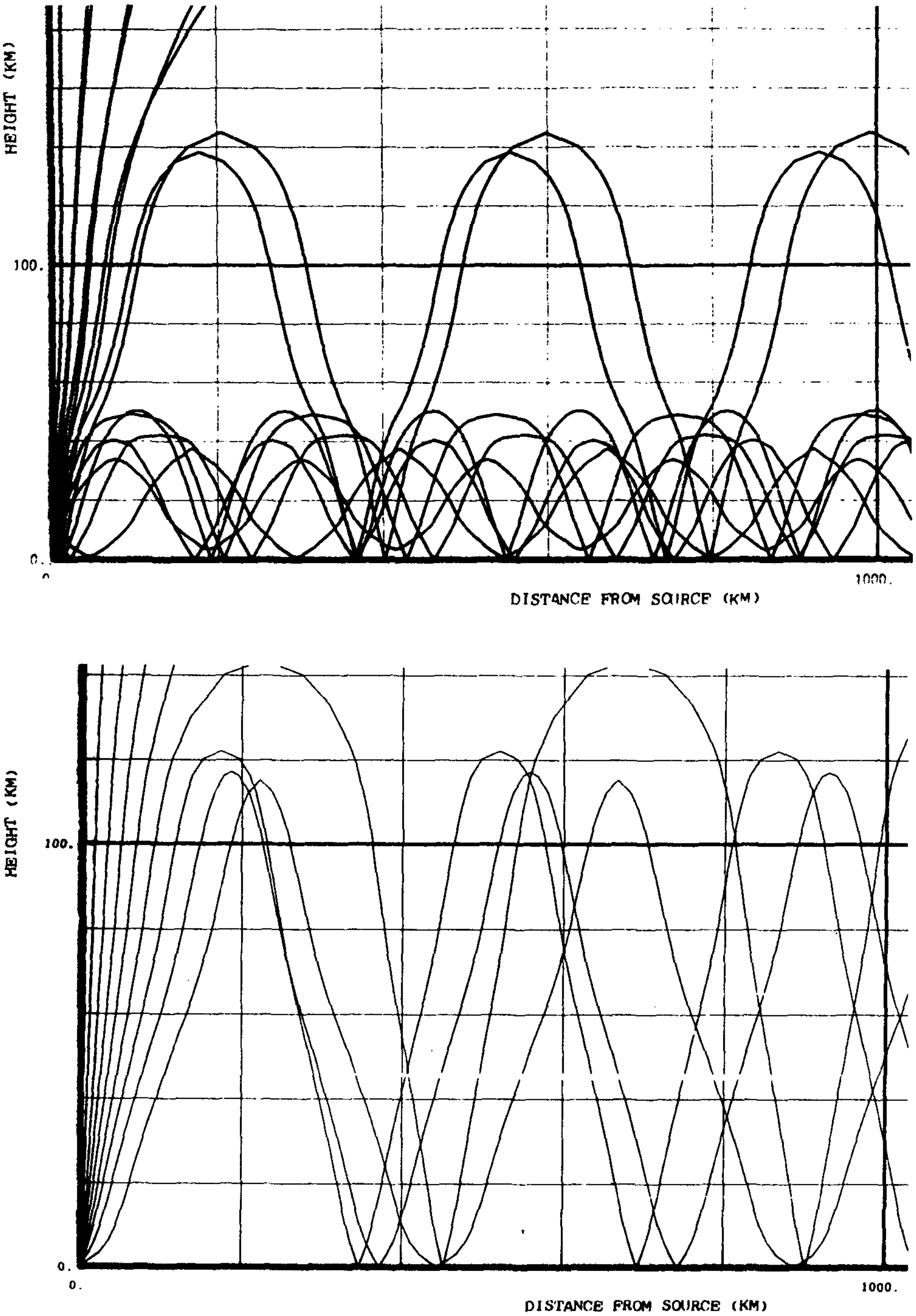

FIG. 3. Computer-drawn ray tracings for conditions resembling those in Fig. 2 showing strong reflection in the stratosphere for a source to the east (A) and where there is no reflection for a source to the east (B). Under both conditions signal is returned to the surface from some level in the lower thermosphere.

record showing two Concorde signals is reproduced in Fig. 4 in which waves of maximum amplitude are about 3 N m^{-2} (30 μb or d cm^{-2}). The two separate strong pulses in each signal develop from the initially upgoing and downgoing shock waves, respectively.

Before considering the actual sound and wind data it should be noted that strong impulsive long-range signals like those in Fig. 4 represent focussed energy in which waves arriving simultaneously at slightly different angles combine to give a strong impulse. This effect can

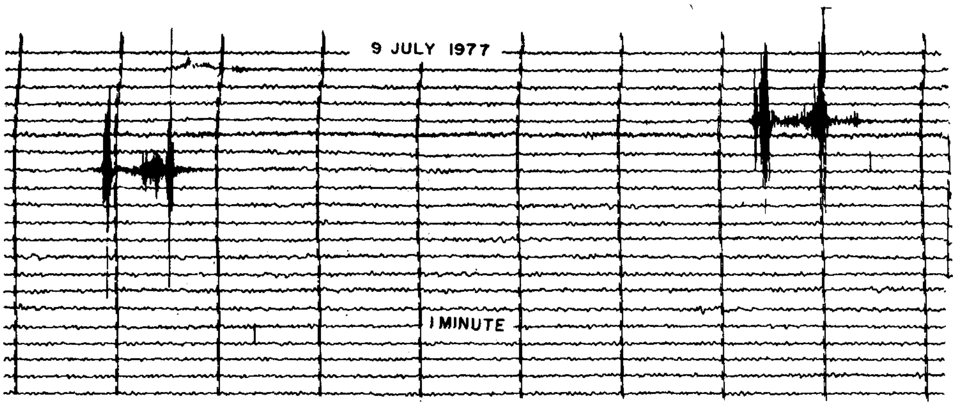

FIG. 4. Part of a drum recording showing two typical strong summer infrasound signals reflected from the stratosphere and recorded at Lamont from the Concorde near the position marked in Fig. 1. The strong double pulse in each signal represents the upgoing and downgoing waves, respectively. The signal amplitude is approximately 3 N m^{-2}.

be appreciated by reference to Fig. 3A in which even the rather coarse 10° interval between rays shows many surface impulses, an effect that would be greatly enhanced if the drawing of more intervening rays were programmed. Steep sound gradients in the region of reflection tend to concentrate rays and increase signal strength.

Amplitude data used in the arguments below will be supported by the data computed for the horizontal trace velocity of the signal. Because the signal arrives at some angle with the vertical, phase time lags across our horizontal array of detectors give an apparent horizontal or "trace velocity." The latter has been shown by Rind *et al.* (1973) to be equal to the sound velocity ($C+w$) in the direction of signal propagation in the stratosphere. In comparing local measured trace velocity with values of $C+w$ determined at Wallops Island, we note 1) Wallops Island observations are about 325 km south of our station and may not be quite comparable and 2). According to Schmidlin (1978) the determination of $C+w$ has a precision of a few meters per second.

Possible error in wind speed determinations may result from uncertainties in C, from inaccurate temperature knowledge and from errors inherent in the experimental procedure. Because of the nature of the procedure we depend on independent temperature observations made elsewhere and our results are influenced by the accuracy of these determinations. But C is proportional to the square root of the absolute temperature so that error effects are small. For example, an error of 5 K in the vicinity of the stratopause causes an error in C of only 3 m s^{-1}. We currently extrapolate temperature from Wallops Island but will use any improved local data as they become available.

The experimental error in determining trace velocities is a function of 1) the coherence of the waves; 2) the time resolution in cross correlation, and 3) the statistical error. By taking the ratio of the amplitudes of the autocorrelation and cross-correlation functions among the sensors, the coherence is found to be so close to 100% as to introduce no significant error. We can at present determine time lags to 0.05 s, giving a possible error for our array of a few meters per second, no worse than the Wallops Island determinations. A possible error difficult to estimate is related to the short signal duration and to the signal bandwidth. On the basis of internal consistency or results for different observations we consider this error source as small.

3. Stratospheric seasonal wind reversals

In Fig. 5, the lower section shows a time series of pressure amplitudes beginning 22 August 1977 (just after the time shown by the upper air data of Fig. 2A) and terminating on 10 October (just before the time of the observation of Fig. 2B). Above the amplitude curve are vertical profiles of the speed and direction of winds in the stratosphere taken from rocketsonde observations at Wallops Island, Virginia, at roughly one-week intervals. Although taken several degrees south of our observations these winds do serve as a guide to the interpretation of our data.

Sound pressure amplitudes show a precipitous plunge from 6 to 7 September that indicates the beginning of the seasonal wind reversal in the stratosphere. Also, the sound speed computed from trace velocity measurements of recorded infrasound is 365 m s^{-1} on 6 September and 351 m s^{-1} on 7 September. This drop in sound speed, matching the amplitude drop, indicates a decrease in wind speed in the reflection level and a resulting decrease in the efficiency of reflection. To compare these results with wind observations at Wallops Island we note that a distinct weakening of winds occurred between 31 August and 7 September. Amplitudes indicate a temporary partial return to the easterly regime for a few days centered on 12 September followed by a firm reversal to a strong westerly regime by 18 September. The 15 m s^{-1} easterly wind at Wallops Island on 14 September could not have provided a sound

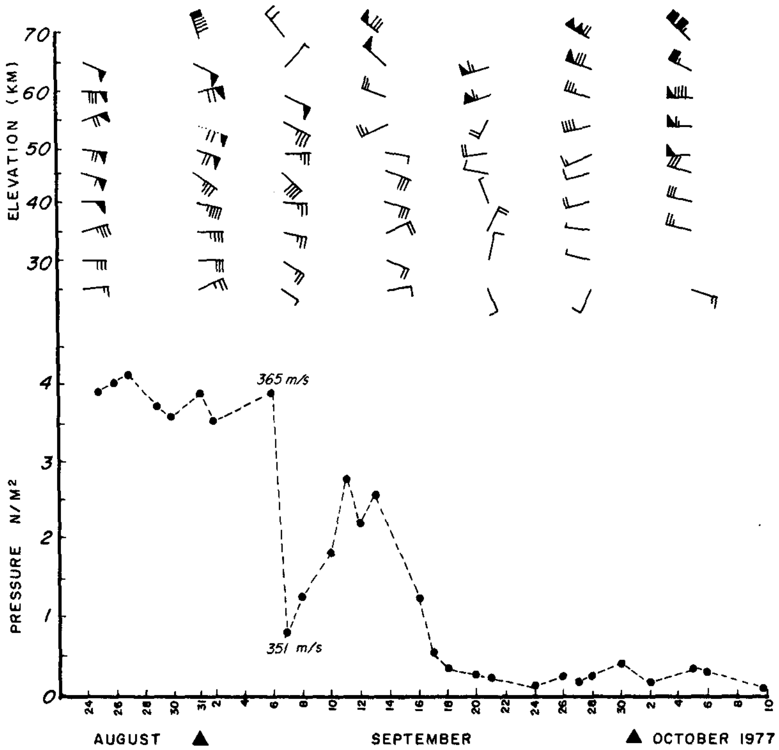

Fig. 5. Time series of pressure amplitudes of Concorde infrasound showing how signal strength indicates stratospheric wind changes from east to west in autumn. Wind observations from meteorological rocketsondes at Wallops Island are given in the upper half of the diagram. Wind arrows fly with the wind. Each full barb represents 5 m s^{-1}, a pennant 25 m s^{-1} and a flag 50 m s^{-1}. 360° of direction are shown with north to the top. Trace velocities computed for the signal September are given for 6 and 7 September.

channel (as in Fig. 2A) adequate for the observed signal strength. It is probable that the temporary increase in easterlies over our region did not extend far enough to the south to reach Wallops Island.

The more gradual change from strong winter westerlies to summer easterlies is also revealed with good detail by the Concorde signal strength. Pressure amplitudes in Fig. 6 show a gradual increase compared to the rather abrupt change in the autumn. Wallops Island winds show a month-long transition from strong west to strong east winds in the stratosphere. Both the variations in speed and direction that occur during the transition period modify the effective sound speed in the direction of signal propagation and consequently modulate signal amplitude. Hence, variations in amplitude during the transition show fine details of the wind fluctuations.

During the transition period when winds are vacillating it is likely that Wallops Island observations are not strictly applicable to local conditions in contrast to the situation in summer when steady easterlies prevail in the stratosphere. For example, it was shown by Rind *et al.* (1973) and Rind and Donn (in preparation) that excellent agreement is obtained between the trace velocities of infrasound radiated by ocean waves in the Atlantic and the Wallops Island sound velocities for long intervals of time in summer. In contrast, on 27 April Wallops Island data show that the highest effective sound velocity ($C+w$) along 111° is 342 m s^{-1} at 55 km whereas the measured trace velocity is 358 m s^{-1} (as described in Fig. 6). On 4 May the highest effective velocity is 343 m s^{-1} at 60 km while the measured trace velocity is 355 m s^{-1}. But on 11 May the highest effective velocity of 343 m s^{-1} at 60 km is nearly matched by a local trace velocity of 341 m s^{-1}. The low-amplitude signal at this time is explainable by this low trace velocity which indicates that the local sound channel was barely developed.

Following the time sequence shown here, both Wallops Island winds from the east and Concorde signal amplitudes reached and remained at high levels until the autumn reversal described with Fig. 5. Thus the results show that the variations in Concorde-generated infrasound wave amplitude and velocity generally matched variations in wind speed and direction at Wallops Island, and their daily observations allow the spring and fall reversal and associated wind vacillations to be ascertained.

4. Stratospheric warmings

Concorde pressure amplitudes also show an immediate response to reversals in regional wind direction asso-

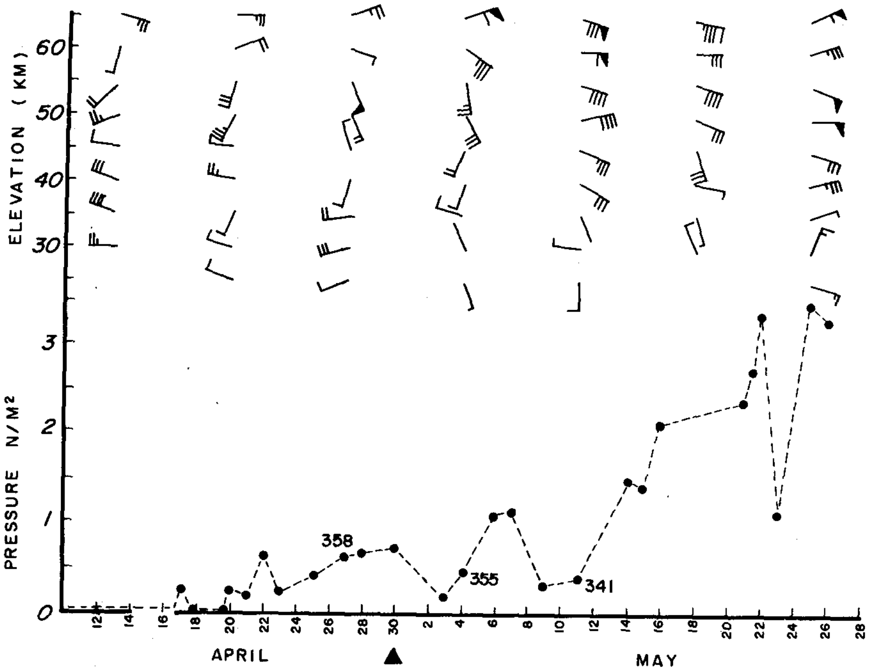

FIG. 6. Time series showing how Concorde-generated infrasound shows the reversal from west to east winds in the stratosphere in spring. The changes are not as abrupt in the autumn case. Numbers on the amplitude graph are the observed trace velocities of infrasound at the times indicated.

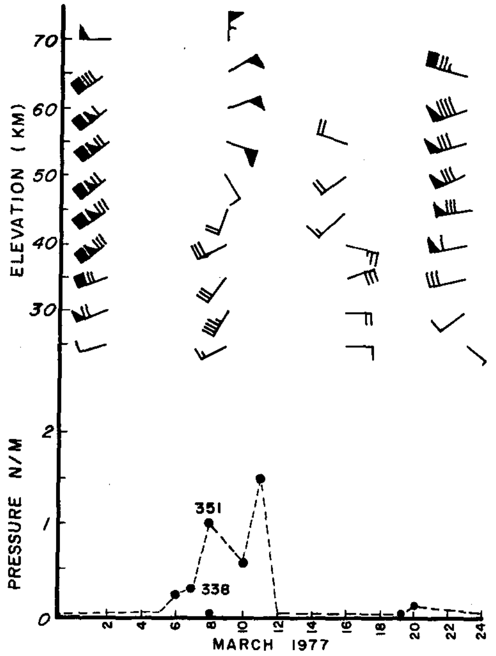

FIG. 7. A wintertime surge of Concorde infrasound reveals wind changes related to a stratospheric warming when a temporary reversal of winds from west to east occurred as observed at Wallops Island. The upper number on the amplitude graph is the observed infrasound trace velocity. The lower value is the local acoustic velocity determined by surface temperature and wind.

ciated with sudden stratospheric warmings. For example, during the winter, in March 1977, preceding the observations described above, Concorde infrasound increased suddenly beginning 6 March from a winter null level as shown in Fig. 7 and then decreased to zero between 11 and 12 March. Wallops Island winds for 9 March show strong easterlies from 55–65 km which provide the sound channel that accounts for the few days of high Concorde infrasound.

We can estimate as follows that the region of infrasound reflection in this particular case is the 5 km thick layer from 55 to 60 km. The horizontal trace velocity measured across our tripartite array of microphones is 351 m s^{-1} on 8 March. As noted above this is equal to the mean velocity $C+w$ at the reflection level. If we consider the Wallops Island sounding data for 9 March the sound speed C and the wind speed w along the 111° propagation direction for 50, 55, 60 and 65 km are as follows:

Height (km)	C (m s^{-1})	w (m s^{-1})	C+w (m s^{-1})
65	303	8	311
60	320	23	343
55	327	25	352
50	327	2	329

As the surface sound speed was 338 m s^{-1} at the time,

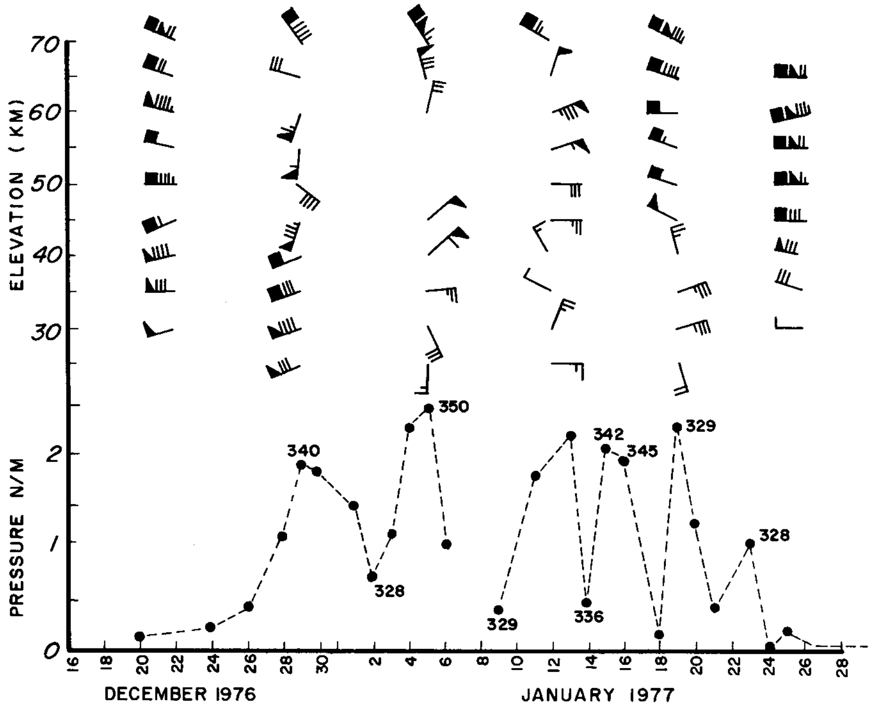

Fig. 8. Variations of infrasound amplitude during a prolonged stratospheric warming in the winter of 1976–77. Variations in amplitude and observed trace velocity indicate variability in the stratospheric easterlies during the warming.

only the 55–60 km layer would have provided a region of reflection, and the 351 m s^{-1} trace velocity suggests that most of the signal was returned from close to the 55 km level. The interpretation is, of course, based on the application of the Wallops Island to our locality. Infrasound amplitudes certainly establish the details of the event between 6 and 12 March as it affected wind motion between our station and Wallops Island, at least.

A longer but more irregular reversal to easterly winds began with a warming that occurred earlier in the winter of 76–77 and is again instructive in the application of Concorde pressure signal to the stratosphere. Signal amplitude (Fig. 8) rose slowly above zero beginning 20 December 1976 and more rapidly from 26 to 29 December. After maintaining high but variable amplitudes until 23 January 1977, the signal fell to zero on the 24th and remained so until the March warming described above.

The fluctuations in signal amplitude indicate strong fluctuations in the speed and/or direction of the easterly components (as well as temperature variations) and are very similar to fluctuation in amplitude of infrasound from ocean waves (microbaroms) reflected from the stratosphere at times of stratospheric warmings (Rind and Donn, 1978).

Although wind reversal at Wallops Island was restricted to a thin layer at about 50 km on 29 December, this effect was quickly revealed by the strong infrasound signal increase at this time when the combination $(C+w)$ for 50 km was 355 m s^{-1}. Our observed trace velocity of 340 m s^{-1} suggests that either the wind direction or speed or the temperature was locally sufficiently different to yield the lower velocity. It can be seen that during this period of fluctuation, the greater infrasound amplitudes are in general associated with higher trace velocities. As the higher trace velocities indicate a greater stratospheric sound velocity in the signal direction, the stronger sound channel would be expected to produce increased reflection and higher amplitudes at the surface. Thus, as indicated earlier, the amplitude alone is a good measure of the strength of the stratospheric sound channel. An interesting exception occurred on 19 January when high signal amplitude was associated with the relatively low sound velocity value of 329 m s^{-1}. This can be explained by the extremely cold surface temperature on that date which reduced the surface sound velocity to 320 m s^{-1}. As the magnitude of the energy reaching the ground from stratospheric reflection is determined by the difference betweeen the sound velocity at the reflection level and the sound velocity at the surface, this latter parameter must be kept in mind in the use of amplitude to evaluate the abruptness of wind reversals.

Following this date, as shown in Fig. 8, a weaker but distinctive signal was again present on 23 January indicating a temporary return to conditions favoring reflection. By 24 January our data show a return to regular winter conditions. Our results are supported by Wallops Island observations which show a complete restoration of westerlies along the entire column by 26 January.

5. The level of reflection

As noted previously, amplitudes and speeds of observed infrasound refer to the largest pulse or wave train. Note, however, that each stratospheric reflection normally consists of two pulses as is evident in Fig. 4. The first is the signal from that part of the shock cone traveling upward from the SST. The second pulse represents the signal from the downgoing part of the shock that is reflected first from the surface and then the stratosphere. Considerations of both the geometry of the shock cone and the ray paths indicate that the ray reflected from the surface should have a somewhat steeper path than that of the direct upgoing signal, hence a higher sound (wind) velocity is required for reflection. Thus, the trace velocities of each of the double pulses indicate the wind velocities in two regions of reflection. The mean values for 300 cases for which computations were performed give 362 m s^{-1} for the first pulse and 374 m s^{-1} for the second.

In most cases the higher speed second pulse represents a higher level of reflection. The major uncertainty in the wind velocity determinations is the exact level of reflection. As described with the cases given previously, we can approximate this by comparison with the nearest rocketsonde station although this destroys independence. An independent procedure is the use of the frequency change resulting from signal stretching in the upper atmosphere.

As noted in Balachandran *et al.* (1977) the frequency of the returning Concorde signal varies with reflection level due to the stretching of the sound wave resulting from its overpressure. This presents the possibility of determining the exact level of reflection by examining the frequency of the recorded waves. For example, infrasound reaching the surface directly from the plane (15 km) has the basic N wave-generated frequency of 2.5 Hz, while infrasound reflected from 50 km has a frequency closer to 1 Hz (and that from the thermosphere approaches 0.1 Hz). Thus, it should be possible to determine not only the stratospheric sound velocity but also the elevation of this velocity, which would be of additional importance during rapidly fluctuating periods in assessing upward or downward propagation of wind/temperature reversals. This effect is currently being investigated.

6. Conclusions

Infrasound recorded at long range from the Concorde sonic boom provides both qualitative and quantitative information on the behavior of winds in the stratosphere. Details of seasonal wind reversals and of circulation changes related to stratospheric warmings are immediately evident from our records.

At present the study is still in its infancy. We have reported here only information and interpretations gleaned from infrasound recorded from one station from the Dulles-bound Concorde. As noted previously, we also record very strong infrasound from JFK-bound Concordes. Because these planes are more frequent and have different flight path characteristics, signal approaches from a mean azimuth of 73° rather than 111°. A comparison of observed signal amplitudes and trace velocities from two different source directions several times a day will permit much greater resolution of stratospheric parameters. Of course data from several stations will give even greater resolution of conditions aloft. Stations in eastern New England will receive signal from the outbound as well as the inbound planes and will provide for observations of atmospheric west winds as well, because the source in the case of outbound flights would be to the west of such observing stations.

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