# Thermistor Measurements of Temperature Oscillations During the Arctic Summer: Potential Coupling Between Severe Convective Thunderstorms and the Surface Prandtl Layer

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## Abstract

Thermistor observations taken at Jämtön, Sweden and at other IRF (Swedish Institute of Space Physics) stations exhibit two basic types of temperature oscillations. One type is observed in the summer and forms in association with severe convective thunderstorms. This is the subject of this paper. The other type forms primarily during stable surface boundary layer conditions in winter following the arrival of infrasonic pressure waves from the Concorde supersonic transport (Liszka, 1974, Liszka and Waldemark, 1995). The observed summer temperature oscillations as recorded on vertical masts of thermistors (at heights of 0, 1, 2, 3, 4, and at 5 m) are very large in amplitude (about 5 - 10 K).and appear coupled in some way to the presence of severe convective thunderstorms. In order to predict future conditions, we have used a one-dimensional boundary layer model (BLMARC), properly initialized, to examine the surface and planetary boundary layer behavior during this type of event. The model predicts a bursting type event (ReVelle, 1993) about 1 hour after the model initialization, in very good agreement with the onset of the observed temperature oscillations. It also predicts an amplitude envelope for the mean temperature field that encompasses the full range of the temperature oscillation amplitudes that are found in the thermistor data. Possible causes of this behavior are examined.

## I. Introduction

### A. Severe Convective Thunderstorms

Convective thunderstorms are meteorological regions that contain extensive turbulence that occurs in association with regions of significant buoyancy and of vertical shear of the horizontal winds. They are also regions with significant vertical and horizontal components of fluid vorticity. Their development and overall strength depends to a large degree on the presence of a supporting Tropospheric Polar jet stream in the air aloft, i.e., air mass versus frontal thunderstorms (Holton, 1992).

Meteorologists have subdivided the horizontal scales of motion into various regimes in order to categorize their detailed behavior, i.e., gust front outflow from an individual storm to squall line outflows from an active line of thunderstorms or to supercell thunderstorm outflow, etc. The latter storm and its development by low level jet moisture tongue conveyor belt dynamics has been widely studied as well. In our current case, we appear to have an isolated air mass convective thunderstorm so that the large-scale dynamical interaction with the Polar jet is not nearly as important as a source of energy for the storm development or for determining its path. These storms can also radiate acoustic-gravity waves as a result of the large amount of turbulence present ( Gossard and Hooke, 1975). As discussed later, this may also play a role in our understanding of the temperature oscillations seen in the thermistor data as well.

### B. Convective Planetary Boundary Layers

The atmospheric planetary boundary layer (PBL) has also been studied extensively for many years. A brief summary of the stable boundary layer ($z/L > 0$, with L the Monin-Obukhov-Lettau length) is given in ReVelle (1993). Unstable, convective boundary layers ($z/L < 0$) can be contrasted with stable boundary layers because potentially severe convective turbulence is active, i.e., a combination of wind shear and buoyancy forces are available to support convection currents. In some cases water vapor is also very important to the dynamics and thermodynamics of the predicted motion as well. In general in stable boundary layers, turbulence is intermittent and quite weak in comparison and gravity wave activity is also quite probable. For the current case of interest (see below), convection is initially relatively weak near the surface, but the winds are quite strong in the upper part of the PBL. This will discussed further below.

## II. Theoretical Modeling of the Boundary Layer

### A. The BLMARC Model

ReVelle, Nilsson and Kulmala (1997) have developed a very flexible 1-D computer code, BLMARC (Boundary layer mixing, aerosols, radiation and clouds) in support of the IAOE-96 (International Arctic Ocean Expedition-1996) to the North Pole on the icebreaker ODEN. This code is an very flexible adaptation of an earlier code developed by ReVelle (1993) that calculates the detailed dynamical behavior of the planetary boundary layer through time after being suitably initialized. The full thermodynamics of water in the gaseous and liquid phase are included in the model as well. A detailed surface energy budget is also evaluated at the interface between the lower boundary (soil, ice, etc.) and the atmosphere, i.e., at the level where $z=0$. Many of the details of the calculations are discussed in ReVelle (1993), in ReVelle and Coulter, 1995 and in ReVelle, Nilsson and Kulmala, (1997). Parameters predicted include temperature, mean winds, eddy diffusion coefficients, i.e., turbulence levels, etc. This model was chosen because of its relative simplicity and because of its predictive ability to forecast the surface boundary layer bursting phenomena (ReVelle, 1993). In the application of this code to the Jämtön data, we have turned off the aerosol scheme.

We have also not allowed for water and its thermodynamic effects at all in these initial runs since the necessary soil moisture properties are not known for this event. Dew point temperatures are available from the standard rawinsonde sounding profile, but we initially chose to run BLMARC in its “dry” mode. We will make additional runs soon that will allow the moisture availability to be a free parameter and will determine how large a value

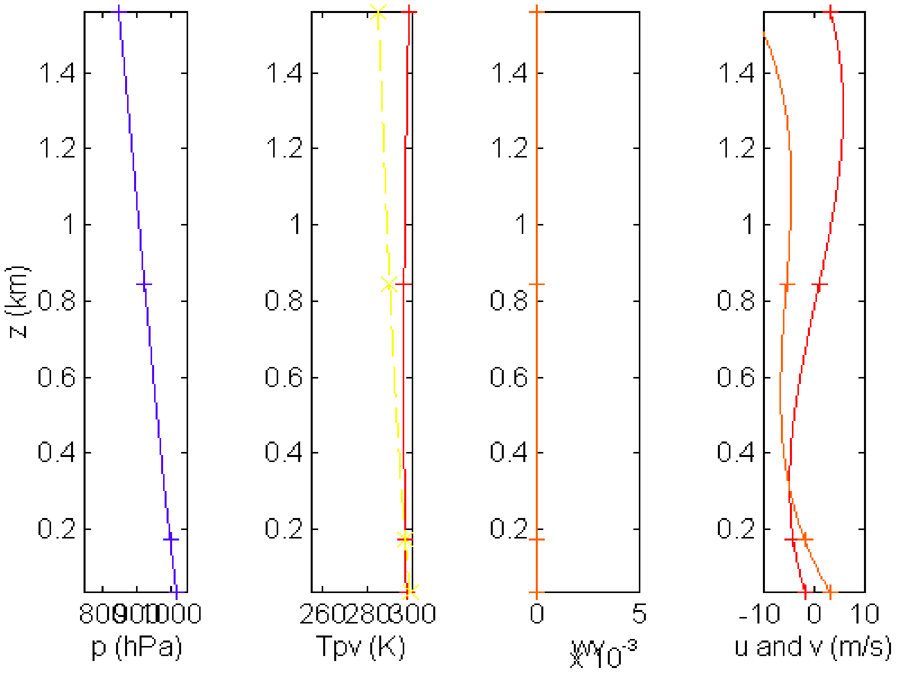

Figure 1. Initial vertical profile of hydrostatic pressure, potential temperature (K) and the dry adiabatic lapse rate, water vapor mixing ratio and zonal (u) and meridional (v) wind components (in m/s). All data were provided by rawinsondes from the Swedish Meteorological and Hydrological Institute at Luleå, 7/23/1997 at 1200 UTC for heights below 1560 gpm.

can be tolerated so that our initial “dry” results are essentially unchanged. As argued later the thunderstorm probably passed the area after the onset of the temperature oscillations so that the “dry” results are probably very reliable for this case.

Finally, we have also utilized a simple, empirical infrared radiation transfer scheme, rather than the full semi-empirical scheme, to calculate the planetary boundary layer and surface layer dynamical properties. Additional details of the BLMARC calculation are discussed below.

## B. Jämtön: July 1997-Severe Summer Thunderstorm Case

On July 23, 1997 one of many examples of the behavior described earlier was observed at the Jämtön IRF array. Temperature oscillations were observed on the thermistors. The thunderstorm was found to be a source of infrasound in the frequency range 1-2Hz arriving from the directions of 340-360° (see Fig. 11) corresponding to the central part of the thunderstorm region (see satellite images of Fig. 10). Temperature oscillations were observed on the thermistors starting at about 1300 UTC. Contours of constant temperature as a function of the height above ground and of the time are shown in Fig. 2.

A vertical sounding of the atmosphere was obtained from the SMHI (Swedish Meteorological and Hydrological Institute in Norrköping) for the rawinsonde station in Luleå some 30 km from Jämtön. A plot of the initial hydrostatic pressure, the potential temperature, the water vapor mixing ratio and of the zonal and meridional wind components for the lowest

1.56 km of the atmosphere at 1200 UTC as observed by the SMHI rawinsonde is presented in Figure 1. The potential temperature is characterized by a

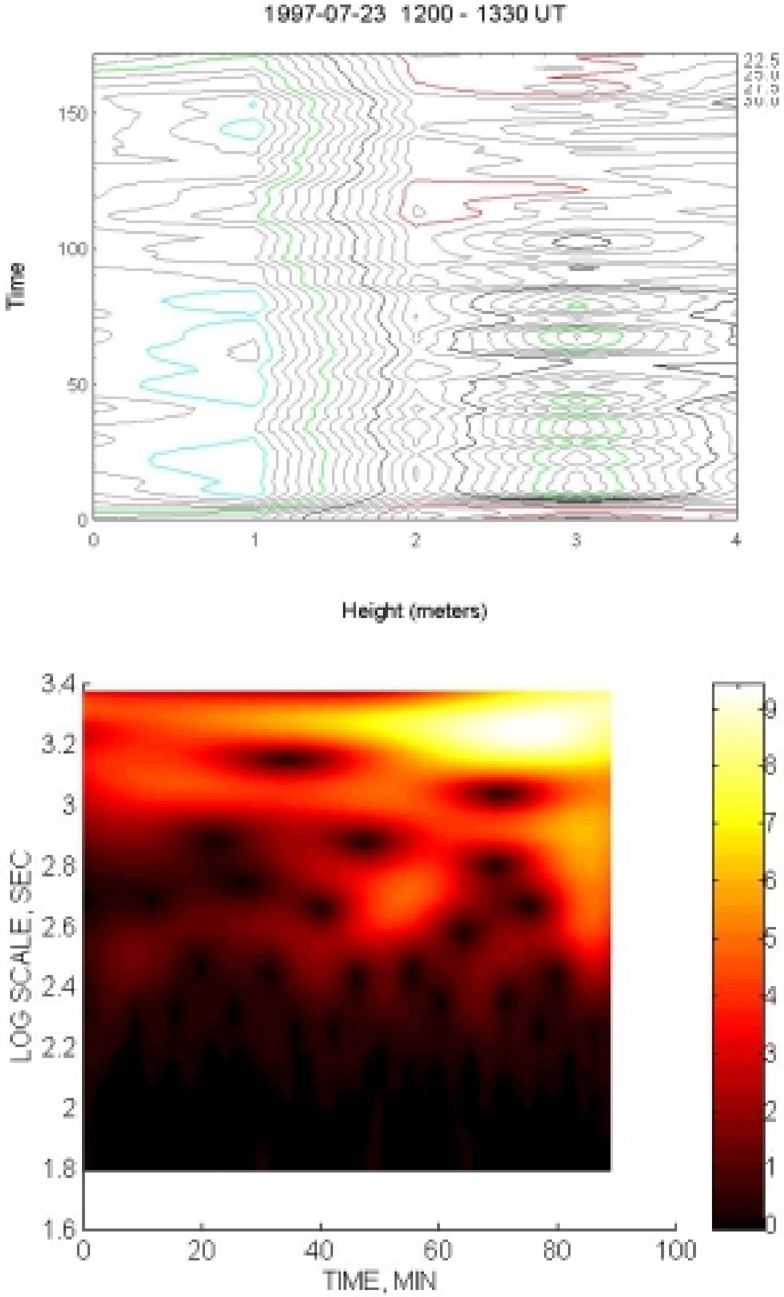

Figure 2. Temperature oscillation data at Jämtön as a function of height (a) and the wavelet scalogram of temperature variations at 3 m height(b).

decrease of about 1.2 degrees Kelvin over the lowest 500 m followed by an increase of almost 5 degrees Kelvin above that level. Thus at the lowest levels the atmosphere was slightly convective, but was capped by a strong stable layer aloft at about 2900 gpm (geopotential meters). The total vector winds aloft were characterized by the presence of at least two jet maxima in the lowest 3200 gpm. In addition there were also strong winds at the surface of almost 5 m/s. The jets aloft were at about 500 and 2400 gpm at speeds of about 7 and 17 m/s respectively. The region was rapidly developing areas of quite active thunderstorms. Satellite photos showed the presence of these developing regions of convective activity quite well. This case was chosen for study because it was typical of other observations from thermistors and the associated temperature oscillations that have been observed to develop in association with summer thunderstorms.

C. BLMARC Modeling for the specific case: 7/23/1997

BLMARC was initialized using the rawinsonde at Luleå at 1200 UTC. For the initial tests we have set up some parameter values that were not directly observed. This includes for example the temperature of the ground-air interface and that of the “deep” ground, i.e., the diurnal penetration depth of the temperature wave, the moisture availability, etc. A cubic spline interpolation program (GASINIT, a MATLAB script written by Dr. E.D. Nilsson) was also used to create a smoothed rawinsonde profile for insertion into BLMARC at all the appropriate height levels needed. The values used for the key parameters evaluated in BLMARC is listed in Table 1.

Table 1. Key values in BLMARC for 7/23/1997 Jämtön event.

| Key Parameter | Value |
|---|---|
| Aerodynamic roughness length | 0.02 m |
| Latitude and Longitude | 65.55 deg, 22.13 deg |
| Degree of cloudiness | None (from initial sounding) |
| Geostrophic wind speed, u | 3.1 m/s |
| Geostrophic wind speed, v | -11.8 m/s |
| Critical transition Richardson numbers | 1.0- surface<br>0.25- aloft (with no hysteresis) |
| Uniform vertical layer | 20 m |
| Initial time and time step | 1200 UTC, 1.0 s |
| Nonlinear advection terms | Turned off |
| Total boundary layer depth | 1.56 km |
| Assumed surface layer height | 10 m |
| Surface emissivity/albedo | 0.95/0.20 |
| Air temperature at z= 1m | 299.5 K |
| Air-Ground temperature (z=0) | 301.0 K |
| “Deep” Ground temperature | 297.0 K |
| Moisture availability | 0 |
| Soil thermal diffusivity | 2.4*10(-7) MKS (dry clay) |
| Soil heat capacity | 1.28*10(6) MKS (dry clay) |

The geostrophic winds specified in Table 1. have been determined at the top of the boundary layer, i.e., at about 1.56 km for this data. In addition, the degree of baroclinicity within the boundary layer have also not been currently addressed, but will be evaluated when further simulations are carried out with BLMARC.

## III. Data Analysis

In our experiments, we have used thermistors manufactured by National Semiconductor (LM35 series of precision centigrade temperature sensors).
00-03-06 10:40:21[1] These sensors have the following properties:

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[1]

a) Temperature range from –55 to +150 C
b) Typical accuracy, 0.25 C  (0.75 C over the entire temperature range quoted above)
c) Linear 10 mV/C scale factor, with direct calibration in C.
d) Low self heating: 0.08 C in still air

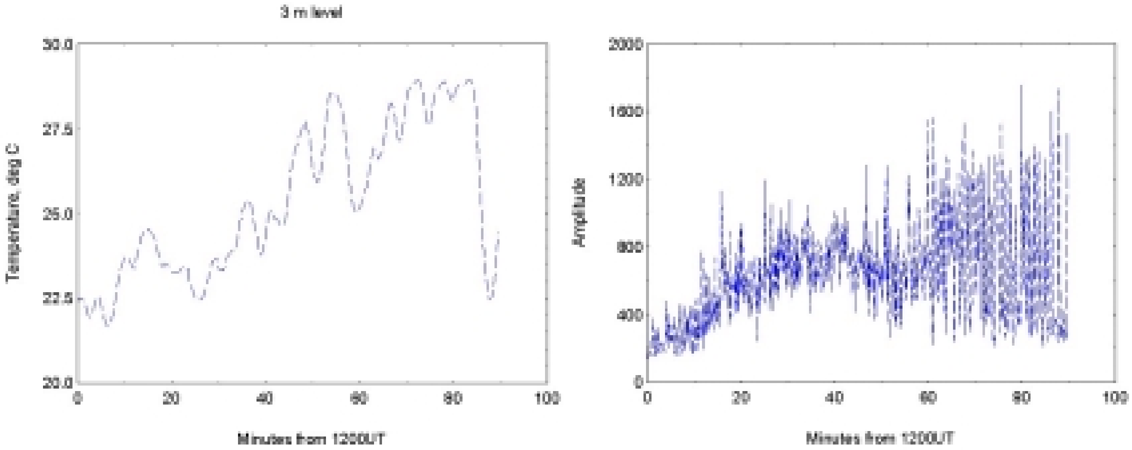

Figure 3. Comparison of the temperature recorded at 3 meter level (a) and the relative amplitude of 2Hz infrasound from the thunderstorm (b). The full scale on the amplitude diagram corresponds to 94 dB re 20 μPa.

The data from the thermistors during the 7/23/1997 1200-1330 UTC period are presented in Figure 2a as contours of equal temperature on the time - height plane. The results have been filtered to enhance the appearance of the oscillations in detail. Both wavelet analyses as well as the method of principal components have been used to gain an understanding of the oscillations during this period. Amplitudes and periods during this time period are about 5-10 K and 6 minutes respectively. A wavelet scalogram for this period is shown in Fig. 2b. Fig. 3 shows a comparison of the temperature recorded at 3 meter level (a) and the relative amplitude of 2Hz infrasound from the thunderstorm (b). The full scale on the amplitude diagram corresponds to 94 dB re 20 μPa. It may be seen that the temperature variations at 3 meter level corresponds to simultaneous amplitude variations of 2Hz infrasound. It is a remarkable observation

## IV. Discussion and Implications of Current Results.

### A. Discussion

The initial geostrophic winds for this case are quite large, but are certainly not untypical for summertime air-mass type, thunderstorm convection. The very short time-step used was a direct function of the large amount of turbulence predicted for the geostrophic wind speeds during the period (expressed in terms of an eddy diffusion coefficient below). It was necessary to choose such short values so that the linear CFL numerical instability limit was not exceeded. The time-step is actually a variable throughout the computer runs as the amount of turbulence changes during the integration, but it was not allowed to exceed 1 second during this specific integration.

The BLMARC runs indicate the presence of a surface layer, bursting event about 1 hr after the initialization of the code. Such bursting type events are not vary common during daytime however, but they certainly do occur (ReVelle, 1993). Clearly, more summertime type cases need to be examined to establish a definite connection between the observed temperature oscillations and severe convective thunderstorms, since meteorological conditions can also very widely when flow transitions are predicted for widely varying flow conditions.

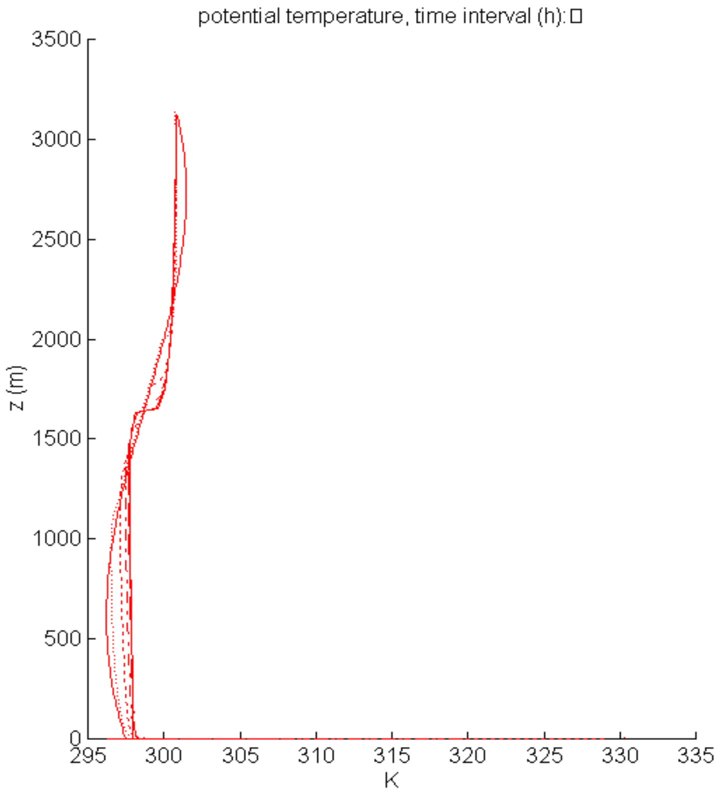

Figure 4. Predicted temperature versus height and time during the simulations for 7/23/1997 using BLMARC.

In Figures 4. -9., we have plotted the predicted BLMARC boundary layer behavior of the potential temperature, of the horizontal winds throughout the PBL, of winds in the surface layer and finally of the near surface temperature during this time period on July 23, 1997. The potential temperature as plotted in Figure 4. Is seen to initially decrease with height, but as time passes a well-mixed layer develops over the region up to heights of some 1500 gpm. Also, as seen in Figure 4., a region of very active low level winds exceeding 17 m/s developed at heights from about 1000-1500 gpm. These winds subsequently decay to values only half as large at later times in the simulation. As seen in Figure 6., during the first hour of the simulation the winds at heights below 50 m rapidly decreased from 4-5 m/s down to speeds < 0.2 m/s just as the winds aloft were predicted to greatly increase. Subsequently as the winds aloft dropped in strength the corresponding winds near the surface increased tremendously to values of almost 12 m/s after about 5 1/2 hours of simulated model time. Thus, a region of greatly enhanced vertical mixing was predicted to develop in the model. The eddy diffusion coefficients begin at 35 m2/s at heights of about 400-1000 m, but drop to 13 m2/s as time passes. At the lowest levels the eddy diffusion coefficients can even exceed 2-7 m2/s. Minimum low level winds also occurred when the surface layer bursting type event was predicted. In Figure 6., it is observed that this period of rapidly decreasing low-level winds occurred as a flow transition took place from turbulent to laminar flow. Normally in the stable, surface layer

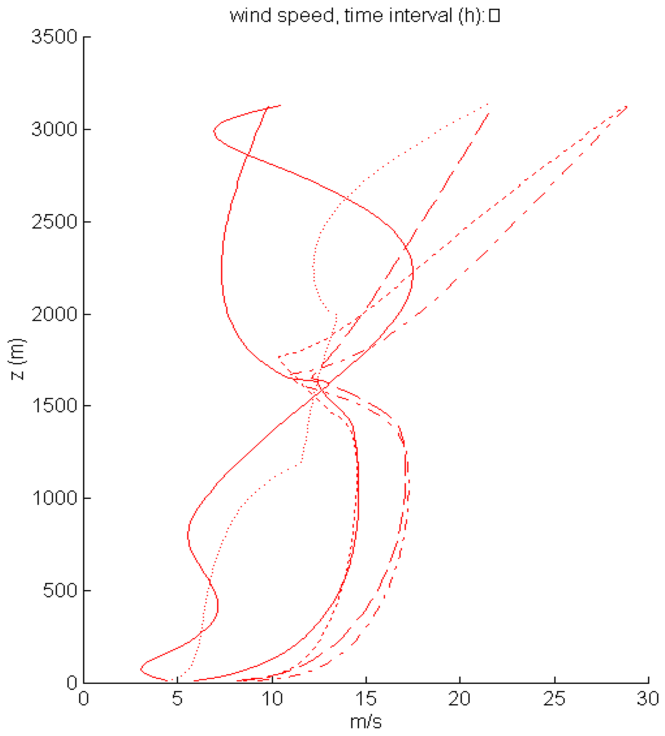

Figure 5. Predicted horizontal winds versus height and time during the simulations for 7/23/1997 using BLMARC.

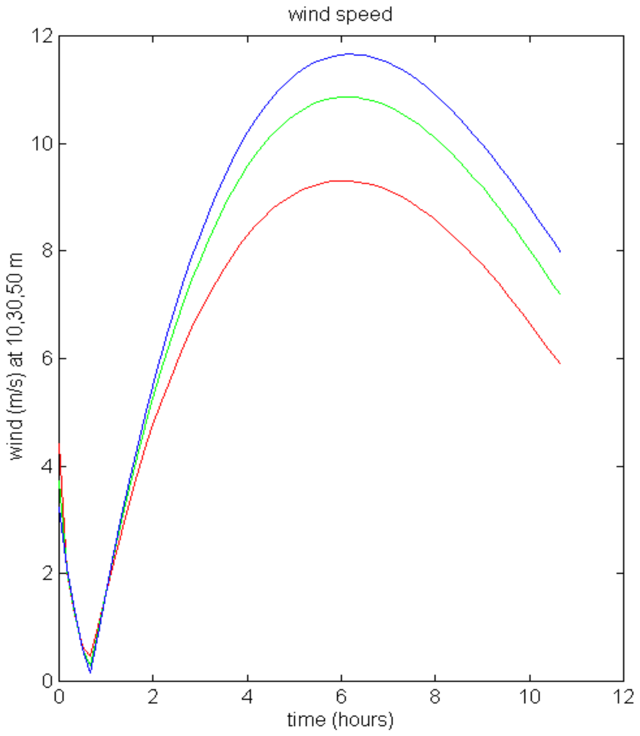

Figure 6. Predicted winds at the lowest model level heights versus height and time during the simulations for 7/23/1997 using BLMARC.

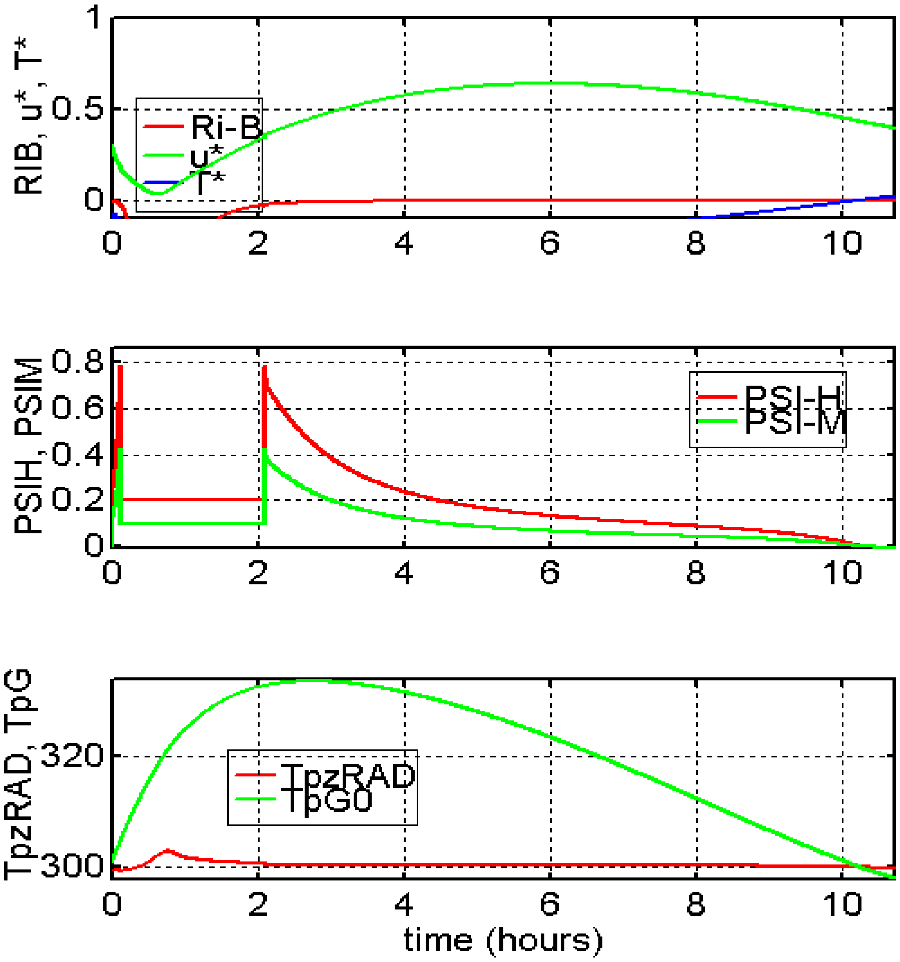

Figure 7. Predicted temperatures at the lowest model level heights versus height and time during the simulations for 7/23/1997 using BLMARC.

boundary layer the onset of bursting occurs as a region of laminar flow becomes turbulent. The Richardson number (a dynamic stability parameter of the flow- see discussions in Holton, 1992 for example) at such heights falls below a critical transitional value as this process develops. As seen in Figure 7., the Richardson number is actually < 0 for a brief period during this transition process and the friction velocity (a measure of the degree to which the air is turbulent) is very nearly zero just before the burst occurs.

In Figures 8 and 9, we have also plotted contours of the potential temperature and of the mean horizontal winds in a vertical cross-section (height in m versus time in hr) for simulations made using BLMARC for the Jämtön temperature oscillation data on 7/23/1997. These graphs clearly show the predicted temperature activity during the first hour after the start of the integration, but also shows that the temperature changes at very low heights essentially stopped after this initial period of rapid change. In contrast, the development of the winds into a low altitude jet region is rather remarkable following this initial period. Thus, Figure 9 delimits the lower boundary of the jet that was discussed previously in Figure 5. It clearly shows that the maximum low level winds occurred about 6 hours after the strat of the integration.

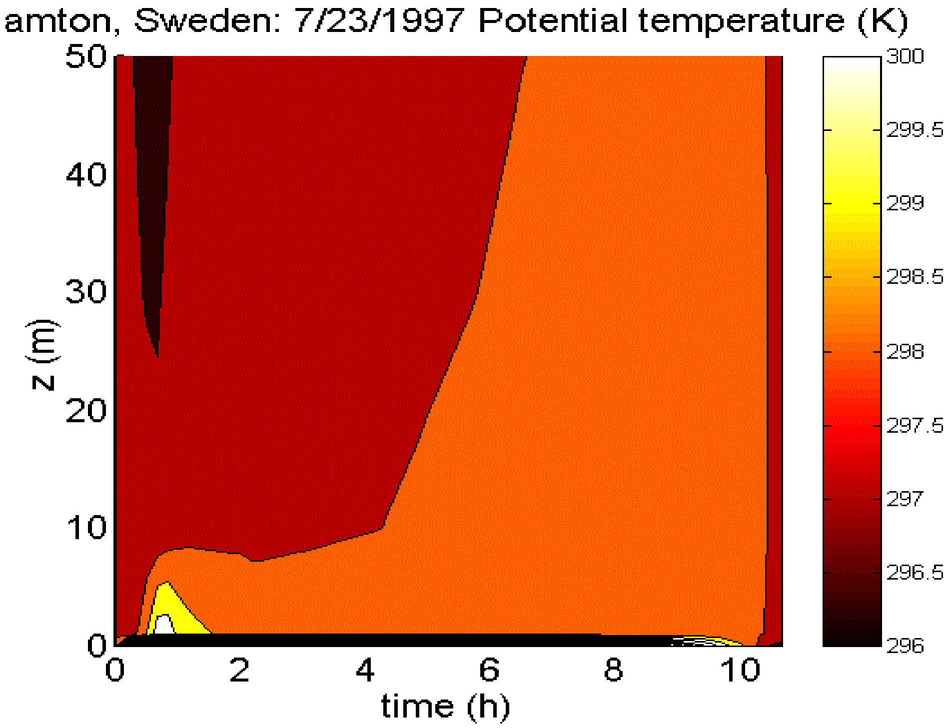

Figure 8. Vertical cross-section of height (m) versus time (hr). Contoured values of the potential temperature (K) for simulations using BLMARC for the Jämtön temperature oscillation observations on 7/23/1997.

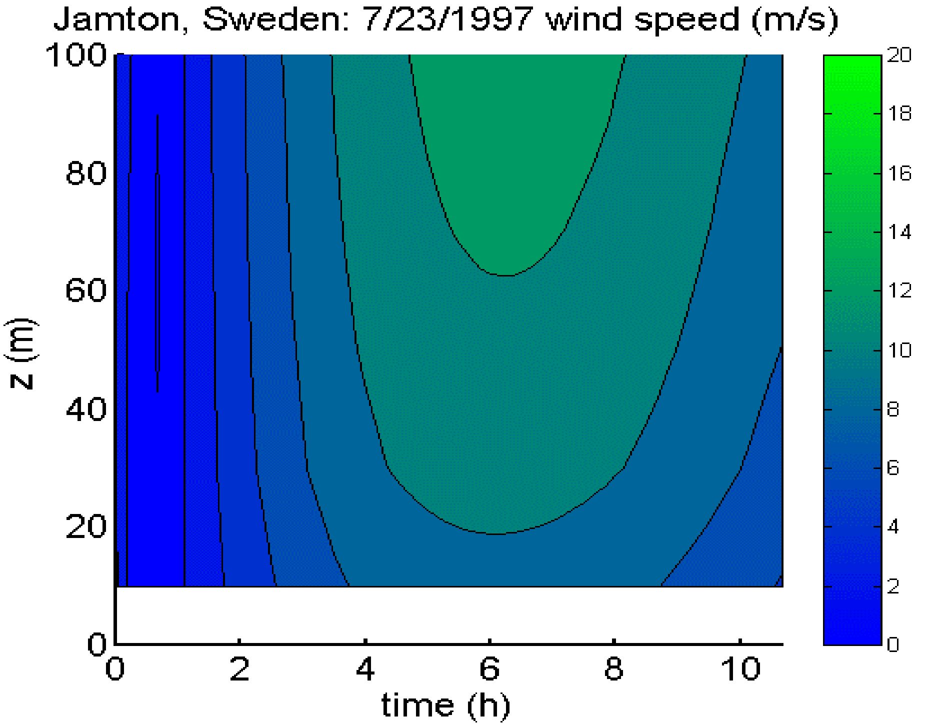

Figure 9. Vertical cross-section of height (m) versus time (hr). Contoured values of the mean wind speed (m/s) for simulations using BLMARC for the period during the Jämtön temperature oscillation observations on 7/23/1997.

In Figure 10., an infrared satellite photograph taken during this period has been included. A large region of very active air-mass type thunderstorms appears to be moving from south to north during the time of the onset of our thermistor observations.

Note timing/direction and positions of storms relative to Jämtön!

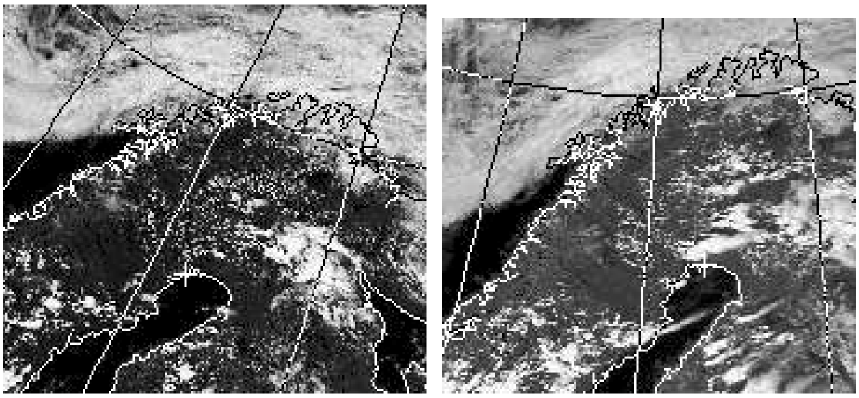

Figure 10. Infrared images of Northern Sweden taken by NOAA14 showing the presence of regions of very active thunderstorms in the vicinity of Jämtön on at 1121 UTC and at 1301 UTC on 7/23/1997. Position of the infrasonic station is indicated by a white cross.

### A. Implications of the Results

We have attempted to establish a causal relationship between the observed temperature oscillations and the dynamical behavior of the planetary boundary layer. To do this we have run the detailed boundary layer code, BLMARC , initialized using a vertical sounding taken very near the site of the thermistor measurements and only a hour earlier in time. The computer output directly confirms that something very interesting happens in the time interval within a few hours after the initialization in the surface layer regime. It also predicts changes in the temperature at the lowest levels with numerical values comparable to those observed in the thermistor data. It still remains for these facts to be connected to the thunderstorm dynamics that is occurring near the time of the thermistor measurements however.

Like in many other cases, perhaps it is not the phenomenon itself, but its associated characteristics that control the behavior of the temperature oscillations observed in the thermistor data. What is observed in the BLMARC output is that as the winds aloft increase (progressively smaller Richardson number), the winds near the surface drop (progressively larger Richardson number) and this process repeats itself in reverse at later times during the model simulation. This process thus maintains the presence of a well-mixed layer during the late morning hours. Thus, in order to have the surface layer behave the way it does, we also need the upper model levels to have the reverse behavior during the same time interval for these initial conditions. Perhaps the single most important dynamic property of thunderstorms is the presence of divergent and convergent winds and the associated vertical wind shear of the horizontal winds aloft. Thus, without the presence of such strong vertical wind shear, a comparable reduction of the surface layer winds may not be able to be sustained. Since low level convergence and upper level divergent flow are necessary indicators for the presence of thunderstorms, it is clear from the BLMARC results that the thunderstorm may have acted as a trigger for the onset of the temperature oscillations. The high wind speeds near the surface associated with strongly convergent boundary layer winds did not occur until after the temperature oscillations onset with concomitant weaker winds aloft acting in association with upper level divergence. This also helps to explain why the completely “dry” simulations worked so well in modeling the processes that occurred on 7/23/1997 near Jämtön. From previous work it is also known that adding moisture to the ground will tend to weaken the observed amplitude of the bursts that are predicted (ReVelle and Coulter, 1995). This will certainly put real limits as to how large the moisture availability was at the time of the thermistor measurements It will also decrease the rate of of increase of the ground temperature (at z=0) during this period as well.

Normally bursting type events occur at night during a time of strong static stability or in the Arctic regions when the sun is low in the sky for many months at a time, etc. It is quite unusual for bursting to occur during daytime, but it has been documented observationally to occur on occasion.

In addition to the vertical shear of winds as an agent for initiating the observed temperature oscillations in the manner described above, we also note that a shear layer aloft can generate a region of forced acoustic-gravity waves (Gossard and Hooke, 1975; Greene and Hooke, 1979; Holton, 1992) directly. Our current set-up of single thermistors will not allow us to determine if these oscillations are waves or not. We are currently in the process of adding a system of three masts separated by tens of meters horizontally. Each mast will have several thermistors at low heights so that this latter question can be definitively answered and so if they are waves, we can determine the arrival direction for these signals.

There are at least two choices for this process if it is wave driven. It can develop far away and propagate into the local region or it can build up locally and any delay can then be designated as the development time. This process is discussed in some detail in McIntosh and ReVelle (1984). It remains to be seen if these temperature oscillations are a direct manifestation of this latter process or are produced as described earlier above. We need to perform further studies to determine if there is a minimum level of vertical shear needed for the onset of the temperature oscillations. Thus, we need to see if there is a minimum level of severity before these oscillations develop or determine if summer thunderstorms in the Arctic will always produce such oscillations, which is certainly unlikely.

A final point should be made regarding waves and turbulence in the context being discussed here. BLMARC cannot currently handle wave processes directly, i.e., additional stress due to wave drag and the reinsertion of this energy at critical levels within and above the boundary layer. However, it is well known that large amplitude turbulence can radiate waves and that waves can grow to large amplitudes and break and generate turbulence (Gossard and Hooke, 1975). In the former sense waves are implicitly included in the BLMARC results, but there is no information provided regarding the properties of the waves, i.e., wave period(s), amplitude, power spectrum, etc. Once we have established an array of thermistors, we will be in a position to be able to understand some of these wave/turbulence processes much better than we can currently.

## V. Summary and Conclusions

### A. Surface Boundary Layer Temperature Oscillations

As we have demonstrated earlier, a dynamic PBL model, BLMARC , has indicated the correct behavior at the same heights and in the correct time frame to be consistent with the temperature oscillations and the mean temperature envelop that encompasses the oscillation amplitudes as observed on the IRF thermistors at Jämtön on July 23, 1997. The temperature oscillations are much too large in amplitude to be explained as free acoustic waves at Jämtön, but could possibly be forced gravity waves. The presence of a bursting type event in BLMARC during the daytime, at almost the same time as observed in the thermistor data is strongly supportive of this former interpretation of the data.

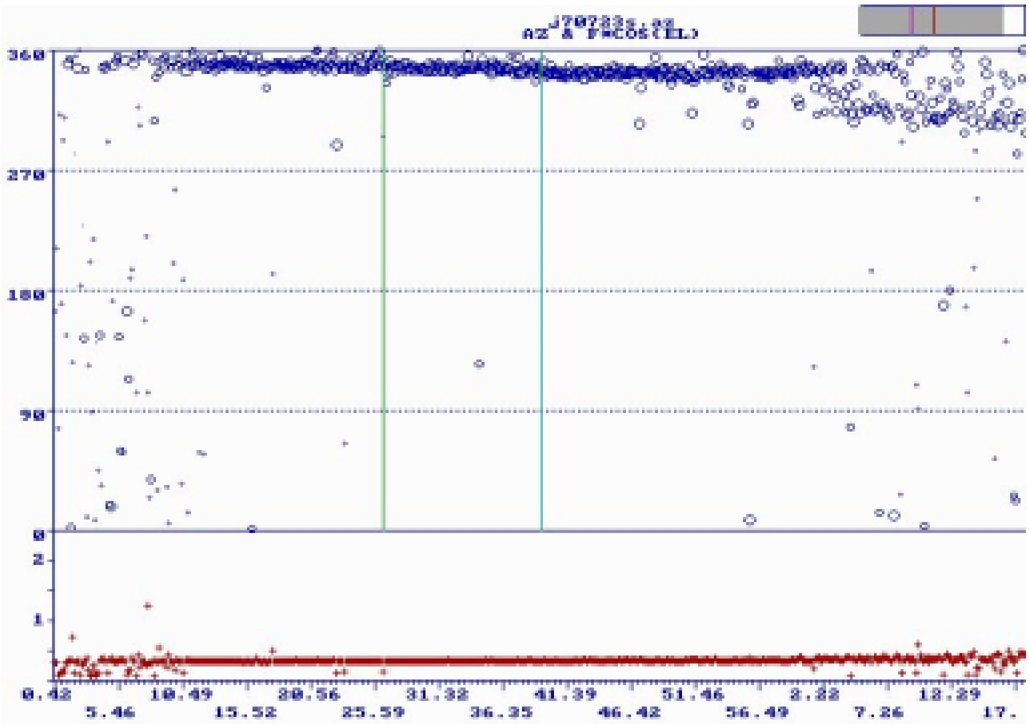

Figure 11. Recording of angle-of-arrival of infrasound (upper graph) in the frequency range 0.5 - 3 Hz arriving from directions of 340 - 360° corresponding to the central part of the thunderstorm region seen in the right hand image of Fig. 10. The lower graph shows a variable proportional to the phase velocity of the signal.

## B. Boundary Layer Connections with the Presence of a Convective Thunderstorm near Jämtön on July 23, 1997.

Making the precise connection between the thermistor data and local thunderstorms is much more difficult. Nevertheless, as stated earlier there are two types of oscillations in temperature that have been observed by our instruments. One is connected with the propagation of infrasonic pressure waves from the Concorde (Liszka, 1974, Liszka and Waldemark, 1995) in winter acting as a trigger of the temperature oscillations and another is connected directly with summertime thunderstorms. In this paper we have tried to relate our observations to the latter type of source regions. We have argued that it is the presence of shear layers aloft forming in association with divergent and convergent outflow winds from thunderstorms that are responsible for the triggering of the observed surface layer temperature oscillations. This argument is based upon our successful modeling of the observed oscillations using the one-dimensional computer code, BLMARC. On the other hand, if these signals are forced gravity waves, they can also be radiated by shear layers aloft directly as has been repeatedly demonstrated both observationally (Greene and Hooke, 1979)and theoretically (McIntosh and ReVelle, 1984).

## VI. Acknowledgments

We would like to acknowledge support from the IRF (Swedish Institute of Space Physics) and from the DOE Office of Non-proliferation and International Security Affairs (NN-20). This work benefited greatly from two scientific visits by the first author (D.O.R) to Umeå, Sweden (in May and early June and again in late November and December, 1998). The technical support staff at Umeå was extremely helpful during this period and made the normal, quite tedious process of producing a manuscript, instead a very enjoyable one. Satellite images courtesy of the Dundee Satellite Receiving Station, Dundee University, Scotland.

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