

In Situ Measurement of Waves and Turbulence in the T-REX Campaign

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The Air Force Research Laboratory participated in the NSF Terrain Rotor Experiment (T-REX) from 20 March through 6 April 2006, which included 3 intensive observation periods (IOPs) of the 15 IOPs of the two month T-REX campaign. AFRL focused on the higher altitude turbulence associated with mountain waves. The AFRL flew thermosondes to measure optical turbulence up to 30km. They include a radiosonde to measure meteorological data. Standard radiosondes were also launched to sense atmospheric data including atmospheric wave signatures. These instruments were launched from the windward side of the Sierra Nevada Mountains in order to try to examine the atmosphere at high altitudes. Fifteen thermosondes launches and 10 radiosonde launches were successful. Many of the launches showed evidence of mountain waves, some accompanied by high levels of optical turbulence

Nomenclature

a_d	=	constant in structure constant formula (K/Pa)
C_n^2	=	Index of refraction structure constant ($m^{-2/3}$)
C_T^2	=	Temperature structure constant ($K^2 m^{-2/3}$)
P	=	Pressure (Pa)
T	=	Temperature (K)
λ	=	Wavelength of propagated electromagnetic radiation

I. Introduction

The Air Force Research Laboratory was a participant in the T-REX Campaign^{1,2} from 20 March 2006 through 6 April 2006. T-REX itself was a two month campaign with a primary objective to explore the structure and evolution of atmospheric rotors and other lower altitude phenomena associated with flow over a mountain and into a valley. The secondary objective was to study higher altitude phenomena associated with flow over the mountainous region. Many organizations participated in the campaign which included comprehensive ground-based and airborne, in situ and remote sensing measurements during strongly perturbed conditions favoring rotor formation and comprehensive observations of complex-terrain boundary layer structure and evolution from undisturbed to strongly perturbed conditions.³ The major sponsor of the campaign was the NSF. Some participants were the Desert Research Institute, the Naval Research Laboratory, the National Center for Atmospheric Research, the University of Utah, Arizona State University, the British Met Office, the University of Wyoming, the Army Research Laboratory, and the Air Force Research Laboratory. Three aircraft participated in the campaign, The University of Wyoming King Air 200T, The UK Natural Environmental Research Council BAe146, and the NSF/NCAR Hiaper, a Gulfstream V.

The objective of the AF participation was to study higher altitude mountain waves and associated turbulence to improve our understanding of high altitude waves and turbulence associated with flow over mountains. We will also use the data to compare to predictions from various models of atmospheric waves and turbulence. Optical turbulence was measured using the balloon-borne thermosonde instrument, which includes a radiosonde. Those

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radiosondes and other radiosondes that were launched without a thermosonde were used to study atmospheric properties including signatures for gravity or buoyancy waves. In order to sample the atmosphere well above the Sierra Ridge and the Owens Valley, the instruments were launched from the windward side of the Sierra Nevada Mountains near Three Rivers California. The purpose of this paper is to present the details of the experiment, and to present some of the data obtained from the experiment.

The AFRL thermosonde⁴ estimates the optical turbulence profile by measuring a 1m horizontal temperature structure function as it ascends through the atmosphere, suspended 110m below a large weather balloon. The temperature difference is sensed by two 3.45 μ m diameter tungsten wires which are legs of a Wheatstone bridge detecting temperature differences as small as 0.001K. Onboard circuitry computes a 4 to 8 second running root-mean-square of the difference, which is transmitted to the ground station as spare channel data along with the met data from the attached RS-80GE radiosonde. The temperature structure function is converted to the temperature structure constant assuming that the turbulence follows Kolmogorov⁵ behavior and using Obukhov⁶ and Yaglom's⁷ deduction for passive scalars. The radiosonde data is then used to convert the temperature structure constant to the structure constant for the index of refraction, C_n^2 . For radiation near the visible spectrum, and when the moisture contribution can be ignored (everywhere except in immediate proximity to a body of water) it is customary to use the formula⁸:

$$C_n^2 = \left(a_d(\lambda) \frac{P}{T^2} \right)^2 C_T^2$$

where $a_d(\lambda) = 79 \times 10^{-8}$ K/Pa for visible and near-infrared wavelengths.

Eighteen thermosondes were launched with their radiosondes, 15 of which had good C_n^2 data, and 22 additional radiosondes were launched, often in poor weather conditions; only 10 had usable data. Radiosonde data from all launches is being used to detect mountain wave parameters to include variance in ascent rate, horizontal wind velocity, and potential temperature. Where possible, the optical turbulence strength will be tested for correlation with the wave parameters. In addition, there will be comparisons to various numerical model forecasts and possibly to other measurements in the T-REX Campaign.

II. The Campaign

The Three Rivers location was chosen to attempt to have the balloons sampling the waves and turbulence at reasonably high altitude over the Sierra Nevada Mountains. The Three Rivers site would be upwind of the mountain during the west-southwest flows that could generate mountain waves, and for those winds, the balloons should cross the Owens Valley near the T-REX instrument sites for maximum support of the other research teams. Three Rivers is located by the star in the lower left hand corner of the map in Figure 1. The actual balloon launch site was the Ash Mountain Helibase near the Ash Mountain Entrance to the Sequoia National Park, an 8 mile drive from Three Rivers. The launch area is shown in Figure 2, looking toward the north. The coordinates of the launch site are: Lat. 36.48720N, Long. 118.84048W, Alt. 503m.

Air Force participation was limited to about three weeks. We selected the period from late March through early April to achieve maximum overlap with the aircraft measurements, since the BAE146 from the UK Natural Environmental Research Council was joining the NSF/NCAR HIAPER Gulfstream V and the University of Wyoming King Air 200T during that period.

The radiosondes were Vaisala⁹ RS-80-15GE. When the radiosonde was part of the thermosonde payload, an ozone interface card was added (OIF11). Two Vaisala DigiCORA[®] ground stations were used: the MW15 and the MW21. The latter exhibited occasional noisy signals, and finally failed near the end of the campaign. The ground station output included listing of time (s), pressure (hPa), temperature(deg C), and relative humidity (%) every ~1.4s for the MW15, and about every 2s for the MW21. For thermosondes, the temperature structure function information is received as "counts" in additional columns to these files. The GPS wind data comes down every 2s for the MW15 and every 0.5s for the MW21 in a file that shows the time (min + s), altitude (km), temperature (deg C), humidity (%), wind speed (m/s) and wind direction (deg).

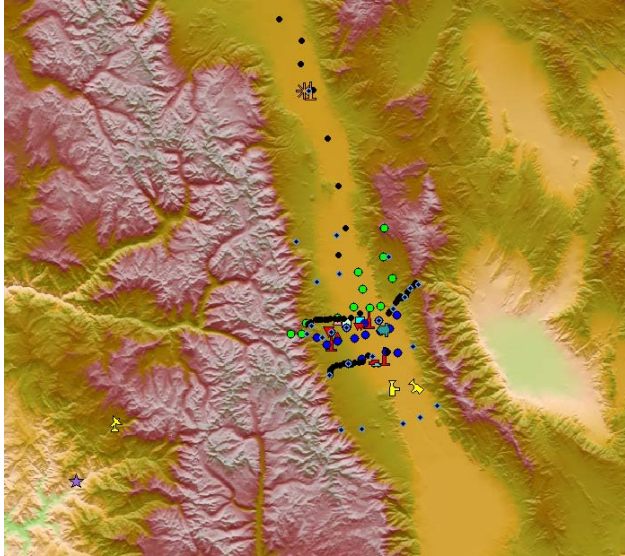


Figure 1. Color Relief map of the central portion of Owens Valley California from the T-REX web site. The Sierra Nevada Mountains are the darkest purple ridge funning down from the northwest corner. The balloons were launched from near Three Rivers California, located at the purple star in the lower left of the map. The other symbols are locations of other instruments in the T-REX Campaign.



Figure 2. Radiosonde ready for launch near helium tanks on the northern edge of the Ash Mountain Helibase.

III. Flights

The campaign period was marked by an abundance of bad weather on the upslope side that interfered with data collection. Rainfall reached record and near-record levels. The fine wire temperature sensors of the thermosonde are susceptible to breakage in heavy rain and ice, which reduced the number of thermosonde flights. Many

Table 1. T-REX flights. T/S if for thermosonde flights, R/S for radiosonde flights, green denotes good data for most of a 30km flight, yellow denotes at least part of the flight is good, red indicates not enough usable data to analyze.

Launch Date Time (UTC)	Flight ID	Radiosonde or thermosonde	Ground Station	Result
3/21/06 2:15	T-REX001	R/S	MW-21	Red
3/21/06 2:20	T-REX002	R/S	MW-15	Red
3/22/06 2:13	T-REX003	R/S	MW-21	Red
3/22/06 2:07	T-REX004	T/S	MW-15	Green
3/23/06 2:18	T-REX005	T/S	MW-21	Green
3/23/06 2:19	T-REX006	T/S	MW-15	Green
3/25/06 5:50	T-REX007	T/S	MW-15	Green
3/25/06 5:59	T-REX008	R/S	MW-21	Green
3/25/06 7:53	T-REX009	T/S	MW-15	Green
3/25/06 8:00	T-REX010	R/S	MW-21	Green
3/25/06 9:47	T-REX011	T/S	MW-15	Green
3/25/06 9:57	T-REX012	T/S	MW-21	Green
3/26/06 1:33	T-REX013	R/S	MW-15	Red
3/26/06 3:06	T-REX014	R/S	MW-15,21	Red
3/28/06 2:11	T-REX015	T/S	MW-15	Red
3/28/06 2:17	T-REX016	R/S	MW-21	Red
3/28/06 3:47	T-REX017	T/S	MW-15	Green
3/28/06 3:53	T-REX018	R/S	MW-21	Yellow
3/31/06 0:48	T-REX019	T/S	MW-15	Green
3/31/06 0:54	T-REX020	R/S	MW-21	Red
3/31/06 2:52	T-REX021	T/S	MW-15	Green
3/31/06 2:58	T-REX022	R/S	MW-21	Green
3/31/06 4:35	T-REX023	T/S	MW-15	Green
3/31/06 4:49	T-REX024	T/S	MW-21	Yellow
4/1/06 7:50	T-REX025	R/S	MW-15	Green
4/1/06 10:04	T-REX026	R/S	MW-15	Green
4/1/06 11:50	T-REX027	R/S	MW-15,21	Green
4/1/06 13:41	T-REX028	R/S	MW-15	Green
4/3/06 0:02	T-REX029	T/S	MW-15	Green
4/3/06 0:11	T-REX030	R/S	MW-21	Yellow
4/3/06 1:51	T-REX031	T/S	MW-15	Green
4/3/06 1:57	T-REX032	R/S	MW-21	Yellow
4/3/06 3:44	T-REX033	R/S	MW-15	Green
4/3/06 5:42	T-REX034	R/S	MW-15	Green
4/4/06 17:41	T-REX035	R/S	MW-15	Red
4/4/06 18:40	T-REX036	R/S	MW-15	Red
4/4/06 20:52	T-REX037	R/S	MW-15	Red
4/5/06 23:44	T-REX038	R/S	MW-15	Green
4/6/06 1:40	T-REX039	T/S	MW-15	Green
4/6/06 3:27	T-REX040	T/S	MW-15	Green
4/6/06 5:14	T-REX041	T/S	MW-15	Green

radiosonde-only flights suffered early terminations due to broken balloons. In addition, attempts to launch two balloons at the same time were thwarted by a ground station that did not work properly at the start of the campaign, and completely failed later in the campaign. There were also instances of loss of signal from mountain obstruction of signal. That being said, the campaign was certainly a success in that there were many successful thermosonde flights, some showing very high levels of turbulence. In addition, there were several flights showing evidence of strong gravity waves. The flight data acquisition results are summarized in Table 1.

IV. Data Reduction

The “raw” ground station files are often corrupted by noise, dropouts, and obviously incorrect information. Various in-house utility programs are used to process the files, including removing obviously incorrect data. In some cases, gaps in a particular variable might be filled by interpolating between the nearest reliable data points. The processing program recomputes the altitude by using the more accurate, variable gravitational acceleration and the hypsometric equations. Time is then used to assign the proper altitude for the wind data. The temperature structure function is determined using calibration data and conversion equations.

The processing program computes the vertical ascent rate using the time rate of change of pressure and the hydrostatic equations. It has been well documented that any excursions in ascent rate above 0.5m/s difference from a constant or slowly varying rate can be attributed to vertical wind velocity¹⁰. This is after obvious instrument errors are corrected. If the variation is oscillatory, the variations can be attributed to the presence of gravity waves. Since many T-REX experimenters are interested in the inferred vertical velocity of the air, the ascent data were further analyzed using signal processing techniques. The objective was to determine the mean ascent rate and variations about the mean. For the stratosphere, mean quantities were determined using a low pass filter with a pass band of 1/(5km) and a stop band at 1/(2km) spatial frequency. In order to get the fluctuating components within the spatial frequencies of the apparent gravity waves, the data were high passed with a stop band and pass band of 1/(5km) and 1/(3.2km) respectively. Next, the resulting signal was low pass filtered with a pass band and stop band of 1/(400m) and 1/(348m) respectively. The filtering was accomplished using non-causal, zero-phase digital filters¹¹.

V. Thermosonde Results

The major results of a thermosonde flight can be summarized in a composite plot like that shown in Figure 3. The y coordinate for all plots is altitude (km) from mean sea level to 30km.

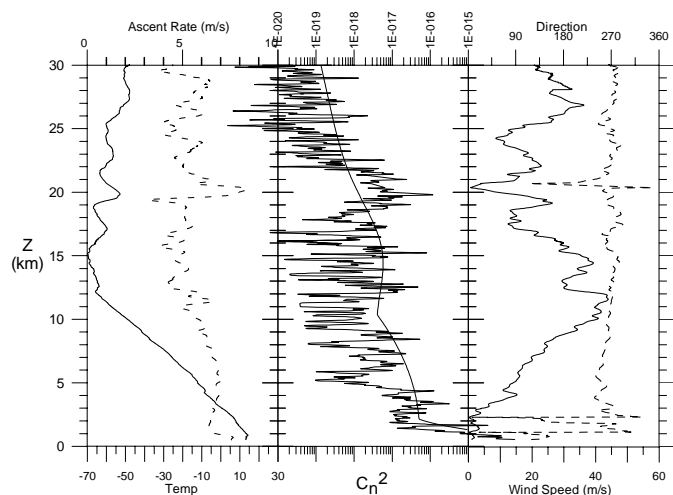


Figure 3. Output of some of the data from Flight t-rex007, launched at UTC 05:50 03/25/06. The left panel shows temperature (deg C) and vertical ascent rate. The structure constant for index of refraction (C_n^2) and the smoother reference atmospheric average (CLEAR1) are shown in the central panel. The wind speed and direction are shown in the right hand panel.

In the center is the structure constant for index of refraction, C_n^2 , using a \log_{10} scale. The C_n^2 data from the thermosonde is quite oscillatory, varying over orders of magnitudes as the instrument goes in and out of turbulent layers. The smoother line in the center plot is CLEAR1, a reference atmospheric average, which is close to the mean experienced in several locations around the Earth over the year. In the right hand panel are shown the wind speed (m/s) (solid) and direction (deg) (dashed).

This sounding from 05:50 on 25 March 2006 (UTC) is unusual in that it shows some of the highest stratospheric temperature variations that we have observed to date, shown in the left hand panel of the chart from 15 to 23km. The oscillatory variation of ascent rate, temperature, and wind speed are indicative of the presence of gravity waves¹². The C_n^2 is quite high in the altitude region from 19 to 22km. The horizontal wind speed essentially stops slightly above 20km where the vertical ascent

rate is at a local maximum, which is a possible indicator of a gravity wave reaching critical amplitude. The wave could have broken into turbulence at this altitude, and there is a lot of turbulence around this altitude. Oscillations in

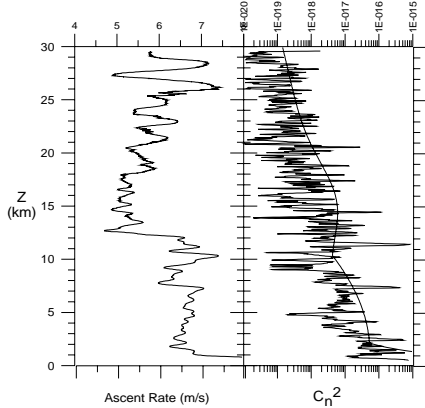


Figure 4a. Ascent rate and C_n^2 for thermosonde launched 3/22/06 2:07 UTC

ascent velocity are reduced above 20km.

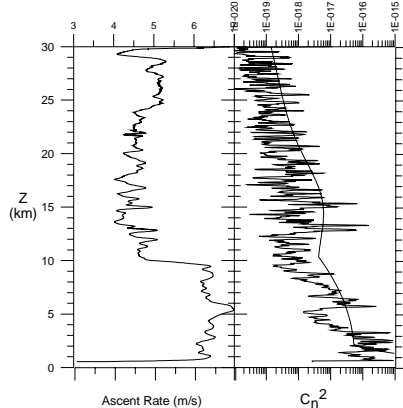


Figure 4b. Ascent rate and C_n^2 for thermosonde launched 3/23/06 2:18 UTC

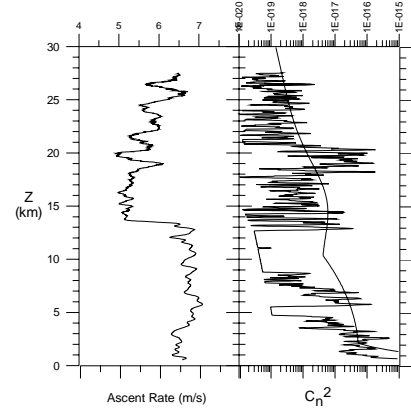


Figure 4c. Ascent rate and C_n^2 for thermosonde launched 3/22/06 2:19 UTC

Three thermosonde ascents are shown in Figures 4a, b, and c. The first shows an interesting decrease in vertical ascent at around 12km, which corresponds to the location when the balloon trajectory crossed over the Sierra Ridge and began to pass over the Owens Valley, which could indicate a sudden downdraft in the flow. This happened on this day, but was not always present. The balloon begins showing good evidence of a wave building in the top third of the flight. A day later, the thermosondes shown in b and c were launched. They were launched at about the same time, but at different ascent rates. The Balloon in Figure 4c lost signal at around 28km. Both show the reduction in ascent velocity as they begin over flying the Owens Valley, although the second balloon crosses at a higher altitude.

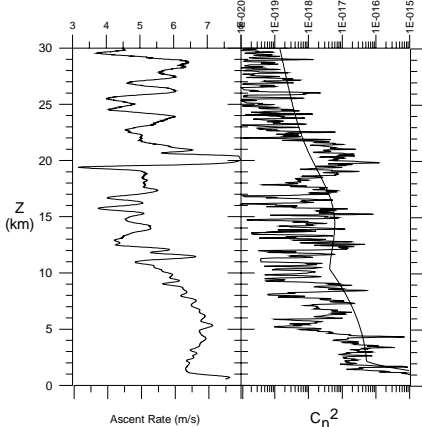


Figure 5a. Ascent rate and C_n^2 for thermosonde launched 3/25/06 5:50 UTC

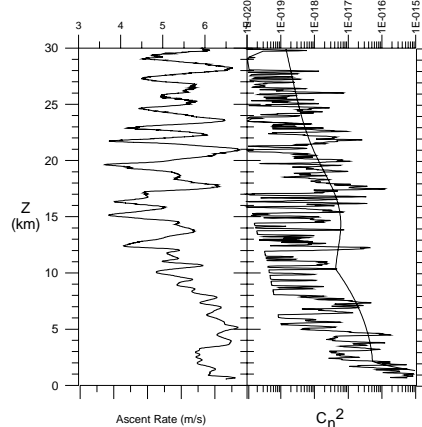


Figure 5b. Ascent rate and C_n^2 for thermosonde launched 3/25/06 7:53 UTC

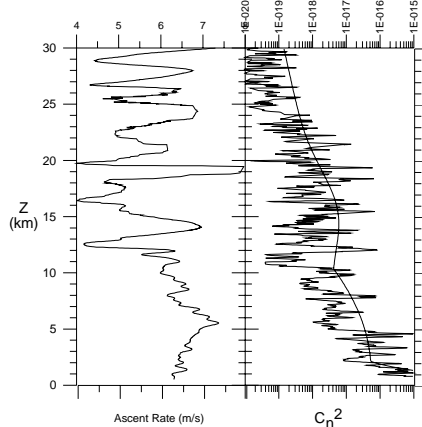


Figure 5c. Ascent rate and C_n^2 for thermosonde launched 3/25/06 9:57 UTC

This balloon shows more oscillation above 18km, and it enters a large patch of turbulence between 18 and 21km. The three thermosondes launches shown in Figure 5a, b, and occurred on the night of 25 March. The first is the same flight as shown in Figure 3 and discussed above. Figure 5b, two hours later shows even more wave-like oscillations in ascent rate, but the turbulence has settled down a bit. In the Figure 5c, two hours later, the oscillations are not as regular, but are still strong. The turbulence seems to be reduced in magnitude from the earlier flights.

Three launches from 31 March are shown in Figure 6a, b, and c. All times are showing a fair amount of wave-like oscillations in the ascent rate; although they are quite different from each other. Turbulence levels appear lower then for some of the earlier flights.

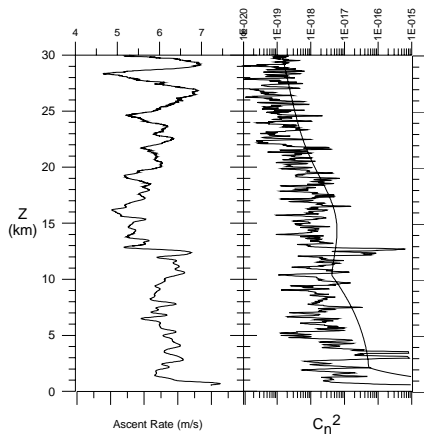


Figure 6a. Ascent rate and C_n^2 for thermosonde launched 3/31/06 0:48 UTC

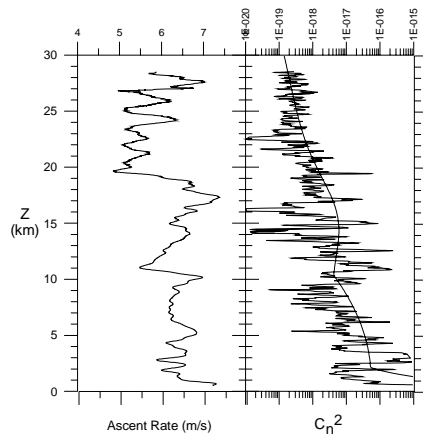


Figure 6b. Ascent rate and C_n^2 for thermosonde launched 3/25/06 2:52 UTC

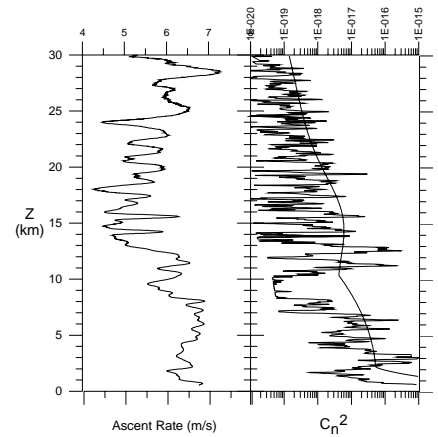


Figure 6c. Ascent rate and C_n^2 for thermosonde launched 3/25/06 4:35 UTC

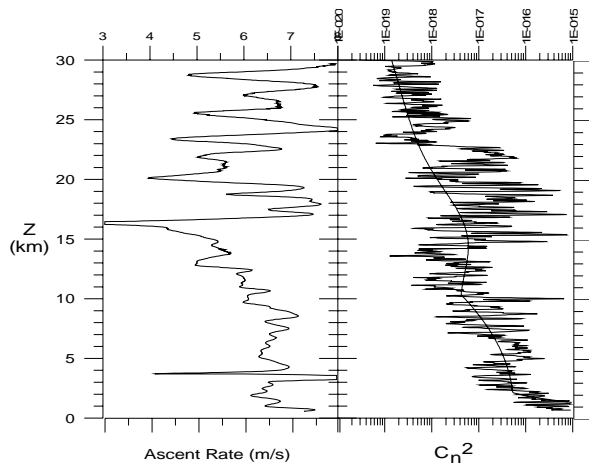


Figure 7a. Ascent rate and C_n^2 for thermosonde launched 4/03/06 0:02 UTC

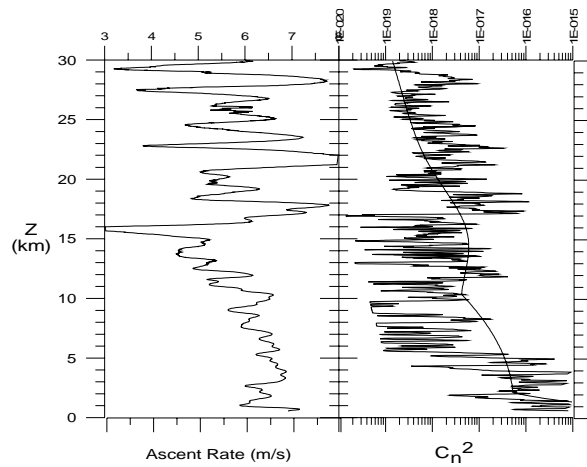


Figure 7b. Ascent rate and C_n^2 for thermosonde launched 4/03/06 1:51 UTC

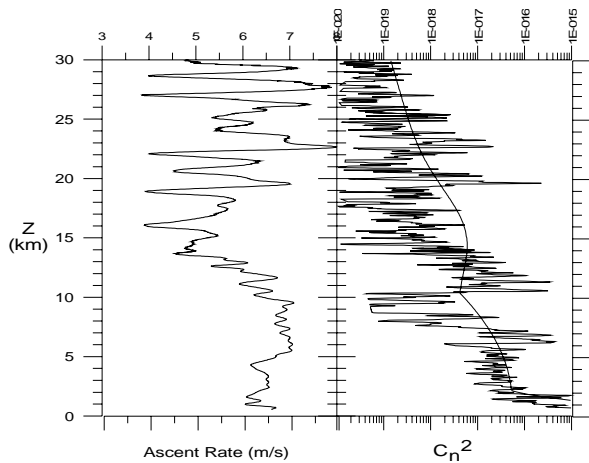


Figure 8a. Ascent rate and C_n^2 for thermosonde launched 4/06/06 3:27 UTC

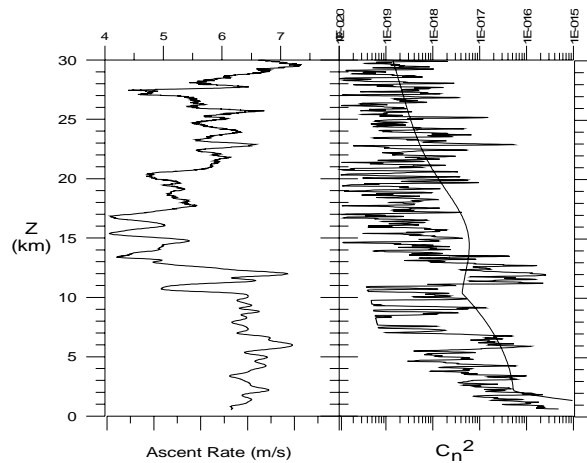


Figure 8b. Ascent rate and C_n^2 for thermosonde launched 4/03/06 5:14 UTC

Two launches on 3 April, shown in Figure 7a and 7b, indicated strong wave activity and strong optical turbulence. The strong wave activity starts around 16km, which is about where the C_n^2 gets higher than the CLEAR1 profile. Two launches on the last day, 6 April, shown in 8a and 8b, again show wave activity and turbulence, although quite different in profile.

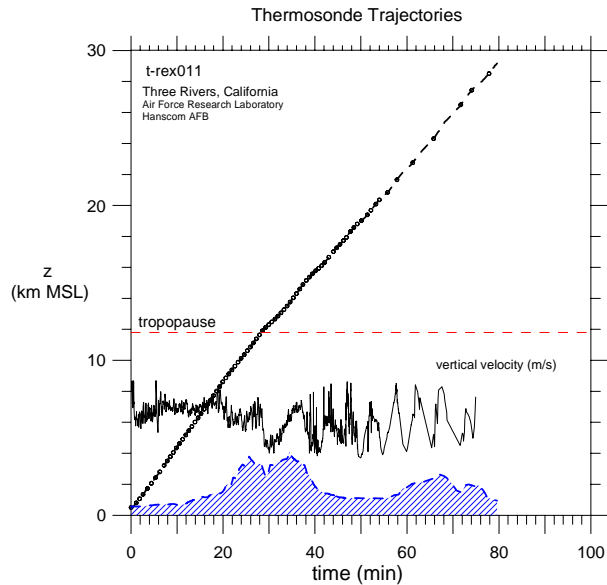


Figure 9. Balloon ascent rate, balloon altitude, and terrain altitude versus time for a thermosonde flight launched on 25 March at 9:47 UTC.

One fact should be kept in mind as these results are studied. The balloon has a horizontal velocity essentially equal to the wind velocity, so it is traveling many kilometers in the downwind direction as it rises through the atmosphere. As shown in Figure 9, the balloon traverses the Sierra Ridge, then the Owens Valley, and finally the Inyo mountains as it exhibits the different wave motion for each segment. It obviously cannot be assumed that this wave signature can be interpreted as a vertical profile over a single location on the ground.

In an analysis of the thermosonde flights, the trajectories for many of the flights seemed to follow one of three branches shown in Figure 10. The first group headed nearly due east across the region, the second group headed in a more northerly trajectory, the final group headed in a more southerly direction. When comparing the turbulence of the three trajectory branches, the thermosondes on the more northerly trajectory exhibited the higher integrated turbulence than the central and southerly branches.

VI. Conclusion

Participation in the T-REX campaign was a success in that it provided an abundance of atmospheric data for conditions of strong mountain waves and turbulence. The data will be used to compare to models of mountain waves and turbulence, both for a better understanding of the basic phenomena, and for forecasts.

Acknowledgments

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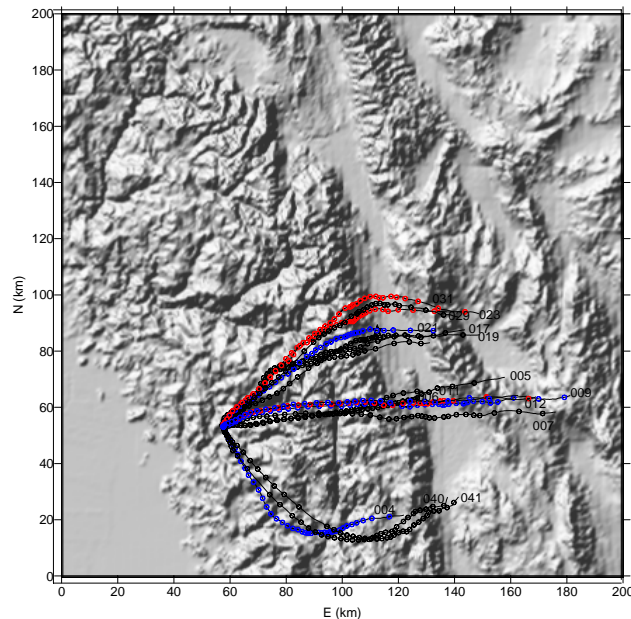


Figure 10. Trajectories of the T-REX thermosonde flights. The first group headed nearly eastward over the Sierra Nevadas and the Owens Vally. The second group headed in a more northerly direction, the third more southerly.

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