# ATMOSPHERIC STABILITY & TURBULENCE FROM TEMPERATURE PROFILES OVER SICILY DURING SUMMER 2002 & 2003 HASI BALLOON CAMPAIGNS

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## 1. ABSTRACT

Experimental results and interpretation of the temperature measurements data retrieved during the balloon campaigns (in 2002 and in 2003) for testing HASI (Huygens Atmospheric Structure Instrument), launched from the Italian Space Agency Base in Trapani (Sicily), are presented.
Both ascending and descending phases are analysed; data reveal interesting features near the tropopause (present in the region between 11km-14km), where temperature cooling can be related to layers with strong winds (2002 flight); in the troposphere a multi-stratified structure of the temperature field is observed and discussed (particularly in the 2003 flight)
Finally, stability and turbulence of the atmosphere are analysed; the buoyancy $N^2$ parameters for both the flights show lowers value respect to standard tropospheric values corresponding to a lower stability of the atmosphere; still there is a higher stability above the tropopause. The energy spectrum of temperature data is consistent with the Kolmogorov theory: the characteristic $k^{-5/3}$ behaviour is reproduced.

## 2. Introduction

Up to now, no temperature profiles of the summer atmosphere from 30km altitude down to ground above Sicily have been published.
The aim of this study is to analyse the features observed during two balloon flights: the observed physical phenomena require some interpretation. Furthermore, the analysis of the temperature data will help the understanding of the temperature profiles that will be measured during the 2005 Titan mission; a training with a real set of data will help the investigation on the features that will be measured in 2005.
Scope of this work is to present the evolution of temperature profiles over Sicily during the campaigns that where conducted in the years 2002 & 2003; during the summer, two balloon tests where performed with a mock-up of the Huygens probe. On board the mock-up, HASI's temperature sensors where mounted and temperature profiles where measured both during ascent and descent phases.
In Section 3 the complete experimental set-up is described: a general presentation of the balloon flight train is followed by a description of the Huygens mock-up; the paper will focus on the instruments used for the temperature measurements.
A general description of the balloon flight is presented in Section 4 showing the balloon ground tracks and the balloon ascent and descent velocities. Horizontal displacement from launch site is measured via a GPS (Global Positioning System); horizontal velocities of the probe are assumed to be the same of the horizontal winds.
Detailed analysis of the temperature measurements is presented in Section 5; the investigation will focus on the descent phase since it's the most significant for comparison with the future real Titan profile, and is, probably, less affected by the flight train disturbances.
Finally, discussion on atmospheric stability and turbulence is carried on in Section 0.

## 3. Experimental set-up

The balloon flight consists in raising a specially engineered probe, a 1:1 scale mock-up of the HUYGENS probe (see), to an altitude higher than 30km with a stratospheric helium balloon and then releasing it in a parachute driven descent and collecting several scientific data measurements during the parachute drop (for a more detailed description see Fulchignoni et al., 2004; Bettanini et al., 2004).

### 3.1. HASI TEM & MTEM Temperature Instrument

HASI TEM sensor is a dual element platinum resistance thermometer [Ruffino et al. 1996] mounted on a fixed stem (STUB) and located outside the mock-ups' boundary layer (see), in a region where the local flow velocity is high, in order to avoid thermal contamination and promote very fast response. Resolution is less than 0.07 K and absolute accuracy less than 2 K. HASI has two redundant TEM units (TEM1 and TEM2) , each one composed by 2 sensing elements (Fine and Coarse); each sensor is sampled at a frequency of 0.2 Hz; but the measurements are in sequence giving a frequency of 0.8 Hz [Fulchignoni et al., 2002]
MTEM sensor is a platinum resistance thermometer, evolution of the one mounted on the HASI experiment, designed for descent measurements in Mars' atmosphere [Angrilli et al., 1999]. In its new configuration (see Figure 1), the sensing elements (Pt wires) are suspended on a very thin non-metallic fibres truss, in order to thermally de-couple it from the supporting structure. The expected overall accuracy in the measurement is less than 0.1 K in the range 200-

Figure 1. left: HASI TEM close up (circles - PT100s used as housekeeping sensors); right: MTEM temperature sensors.

300 and resolution is 0.05K. The sensors are sampled at a frequency of 8 Hz.
In Figure 2 the spatial resolution as function of altitude level for the HASI TEM sensor for both ascent and descent phases is reported; after the separation phase the spatial vertical resolution is increasing because the vertical velocity of the probe is decreasing, reaching values of around 25m below height 7000m. This resolution enables us to highlight features of several tens of meters and to emphasise their evolution.

## 4. Balloon flight experiments

The flights were performed during two sunny days, with almost no clouds or strong winds during the launch phase; these favourable meteorological conditions ensure a local flight: maximum distance of the landing point from the launch pad was approximately 50km.
Both flight reached an altitude higher than 30km; 2003 flight reached an altitude level of 33km, requested for testing of a special operational mode of the Huygens RADAR bread-board altimeter

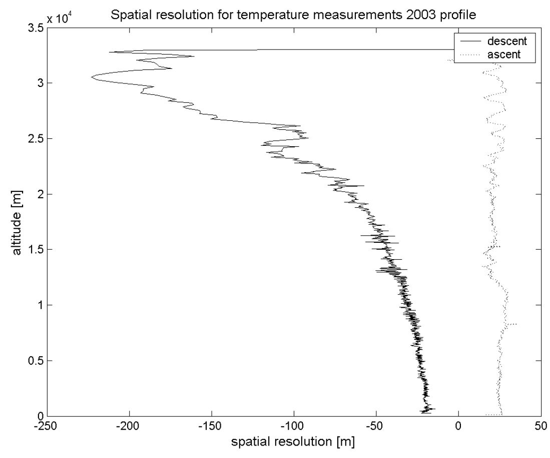


Figure 2. Spatial resolution for HASI TEM sensors for flight 2003

Ascent velocity can be considered constant with a value close to 5 m/s while descent velocity, after the transient separation phase, was measured in between 5 and 10 m/s and impact velocity was around 5-6 m/s.
The desired time at float altitude was the minimum possible compatibly with technical operations and constrains for secure landing on ground. In Figure 3 are shown the ground tracks of the balloon flight over Sicily as derived from the GPS data. For the 2002 flight it must be considered that a 2 hour floating phase at 30km was ensured for a secure prediction ground landing. During the descent phase the probe mock-up is spinning thanks to a set of vans fixed at the bottom shell of the probe so as will do Huygens probe in Titan's atmosphere.

### 4.1. Balloon 2002 & 2003 wind profiles

We assume that the wind, driving the probe-parachute-balloon system has only an horizontal component; so that the vertical velocity (ascending & descending) is the velocity of the probe-parachute-balloon system during ascent and descent.
Descent vertical profile for the 2002 and 2003 flights is similar, with velocities between 40 m/s and 4 m/s, for both the flights; descent velocity values above 30km altitude are relative to the transient phase after probe separation from the balloon.
As it can be seen (Figure 4 and Figure 5) the two profiles have the same trend; differences in the profiles can be observed at altitude of 25km, 14km (features present in 2003 profile but not in 2002 profile) and 3km where, locally, vertical descent velocities increase (feature present in 2002 flight).
In the 2002 profile the interesting feature occurs at around 3km: three variations in the horizontal wind velocities have been detected; in case A the velocity varies of 10m/s in 500m; this strong change is related to a layer of winds in NS direction. In B the variation is not very significant (2m/s in 180m ) but there will be a good correlation with temperature data. In C the variations is smaller (6m/s in 200m) but GPS wind velocity data are incomplete due to loss of the telemetry link with the probe due to topographic configuration.

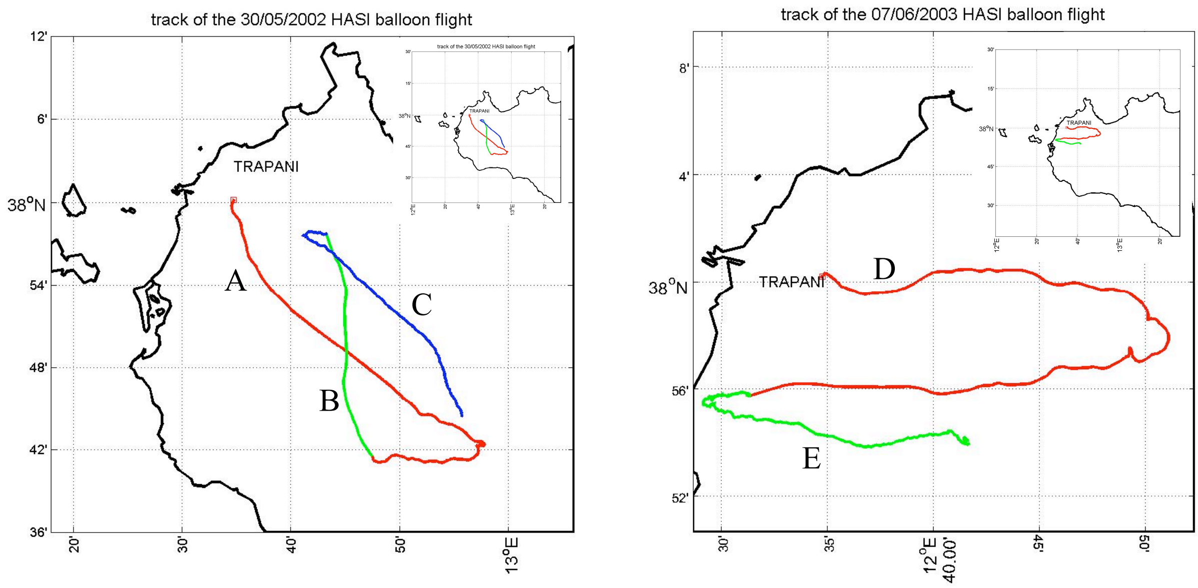


Figure 3 left: Balloon 2002 track over west Sicily; A is the ascending phase; B is the floating phase at 30km necessary for secure landing and C is the descent phase; right: Balloon 2003 track over west Sicily; D is the ascending phase and E is the descending phase

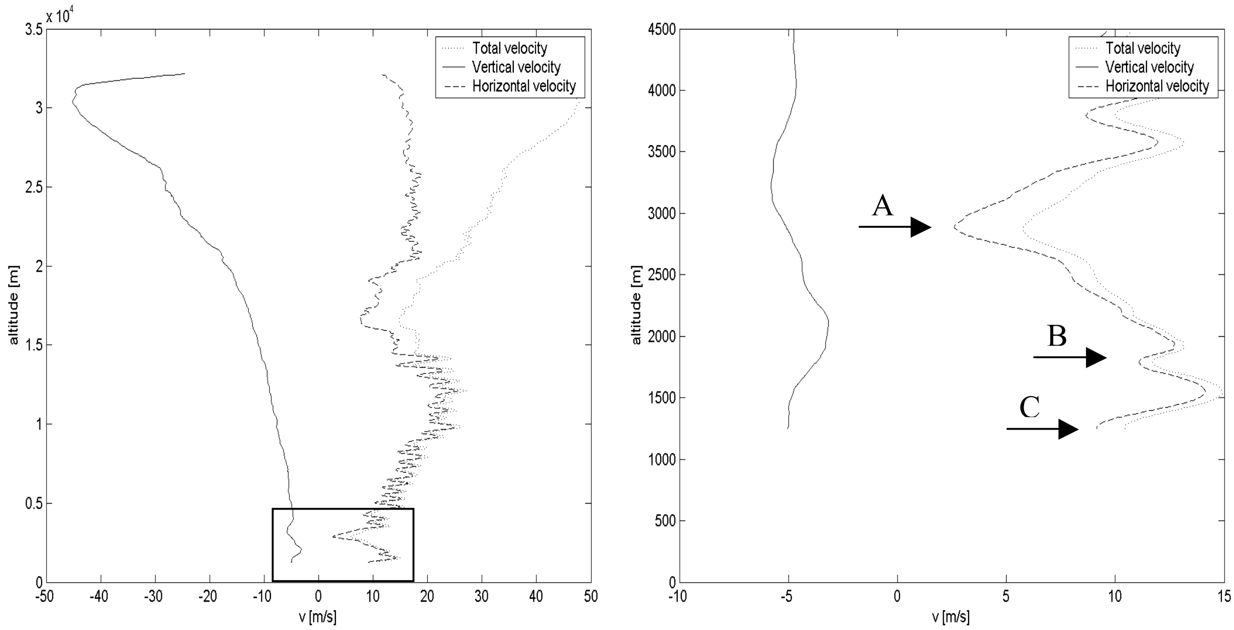


Figure 4. Wind profiles during the 2002 balloon experiment. Left: vertical velocity (line), horizontal velocity (dash) and total velocity (points)- obtained combining vertical and horizontal components-; right: close-up view of box showing features (A, B, C) at 3km altitude.

In the 2003 profile (Figure 5) at 25km the vertical velocity variation is between 2-5 m/s related to 2-3 km thick lower density layer in the atmosphere where the probe-parachute system is accelerating while the feature at 14km (see box) is due to a wind gust that accelerates the mock-up; the latter shows an oscillating velocity for 1km and an amplitude of the oscillations of around 0.2 m/s.

Different between the two horizontal wind profiles are the stronger winds that are present in 2002 near the tropopause; a Δv of more than 10m/s where the 2002 winds have values around 25 m/s reflects in a lower temperature measured by the temperature sensors.

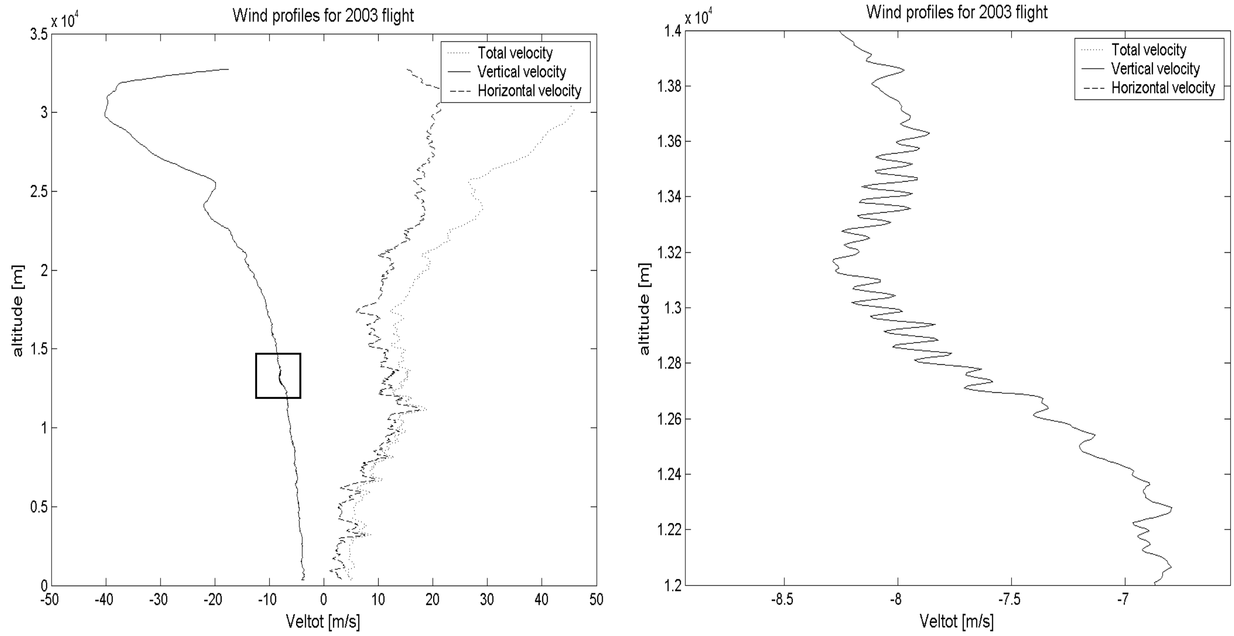


Figure 5. Wind profiles during the 2003 balloon experiment: vertical velocity (line), horizontal velocity (dash) and total velocity (points) obtained by combining vertical and horizontal components. In the close-up box the evolution of the descending velocity due to a wind gust

## 5. Measurements of the temperature vertical profile

During the flight campaign the temperature instruments measured data both during ascent and descent phases.
For the 2002 year campaign data recorded by HASI Tem and MTEM will be analysed; for year 2003 only data from HASI Tem will be used.
Analysis of the difference of the measured temperature respect to the static temperature shows that, since vertical velocity is less than 20-25m/s, the Mach number is less than 0.06 and the relative error is less than 4 $10^{-3}$; following this considerations no dynamic correction (refer to Fulchignoni et al. 1999, Gaborit et al. 2004) has been applied on temperature data.

### 5.1. 2002 balloon flight experiment: results

Focusing on the descent profiles, both the data sets present the same features; temperature at 32km are around 268K and drop down to 208K at 12.5km near the tropopause and then grow up again to 278K at 1km where the data link was lost.
In the stratosphere the temperature gradient is around 7.4 K/km for all the sensors except F1 which has a value of 7.8 K/km; the latter seems to be too high for a standard summer atmosphere above Sicily and must be disregarded (inconsistencies have been discovered in the calibration of the sensor).
Another important feature that must be analysed is the very low temperature at the inversion; in fact it can be seen that between 14km and 11.5km the temperature is not constant but decreases from 214K down to 208K (see Figure 6 and Figure 7). This behaviour is easily correlated to the horizontal wind velocities variations measured by the GPS: winds higher than 20m/s are measured at same altitudes (see Figure 4).
The variation observed in temperature profile could be mainly due to two reasons: the mock-up passes through a layer of colder air or through a layer where stronger winds are present. From the previous observation on the wind profiles and from theoretical considerations on thermal exchange, an increase of velocity of the horizontal flow of about 5m/s (from 17m/s to 22m/s) leads to a variation, in a forced convective regime with same pressure and flow velocity values, of about 5÷10K in temperature. The conclusion is that a layer of about 3km thickness with stronger winds than the neighbours has been crossed.
At lower altitudes, below 3km, some other variations in the temperature profile are measured, respectively of 2K and 1.5K; these two variations are perfectly in accordance with feature A and B present in the wind profile (see Figure 6 & Figure 7; in MTEM profile also another feature can be observed: $\Delta T$ 1.5K correlated to variation C in wind profile, see Fig.4).
Also in this case, we argue that the mock-up is crossing layers of 200-500m thickness of stronger winds respect to upper and lower layers.

### 5.2. 2003 balloon flight experiment: results

In Figure 8 the HASI TEM profiles for both ascent and descent phases are presented; ascent profile is artificially shifted by 10K for graphical representation; time delay between the two profiles is decreasing at higher altitudes starting from more or less 2 hours on ground level data. The overall structure of the atmosphere is similar; inversion occurs at same altitude (see Figure 6 and Figure 7 for a similar stratification, at

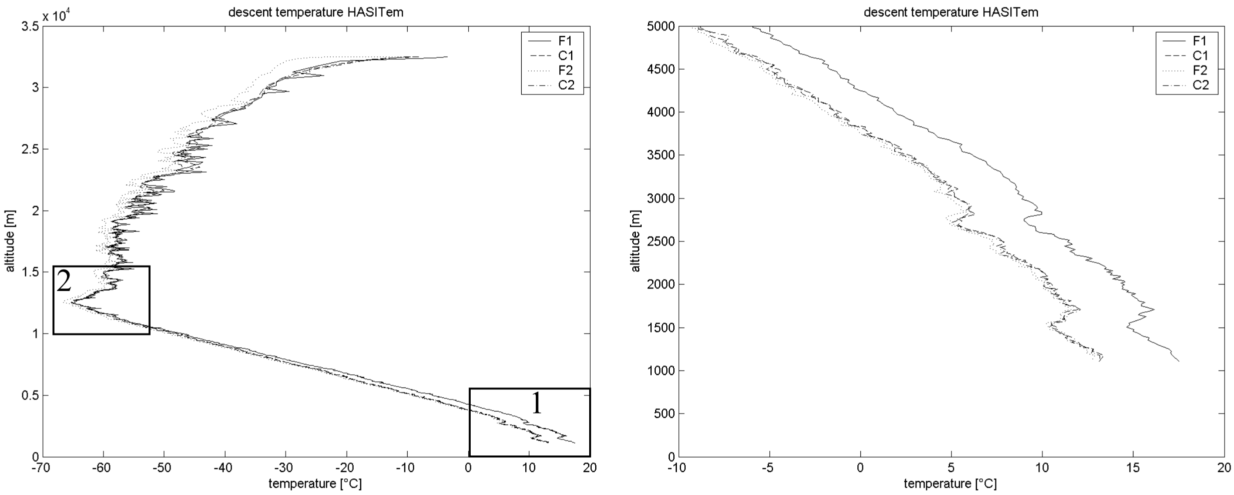


Figure 6. Balloon 2002 temperature profiles for HASI TEM; in box 2 the decrease in temperature due to increase in horizontal winds of 5m/s and on the right a close up view for box 1 showing the features below 5000m.

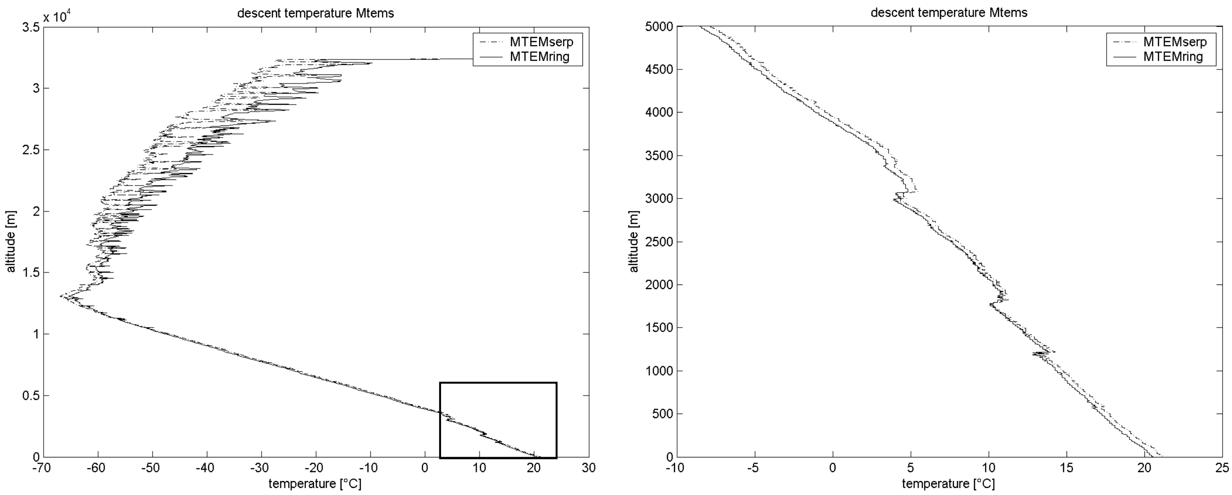


Figure 7. Balloon 2002 temperature profiles for MTEM; right: temperature variations measured when crossing layers with stronger winds.

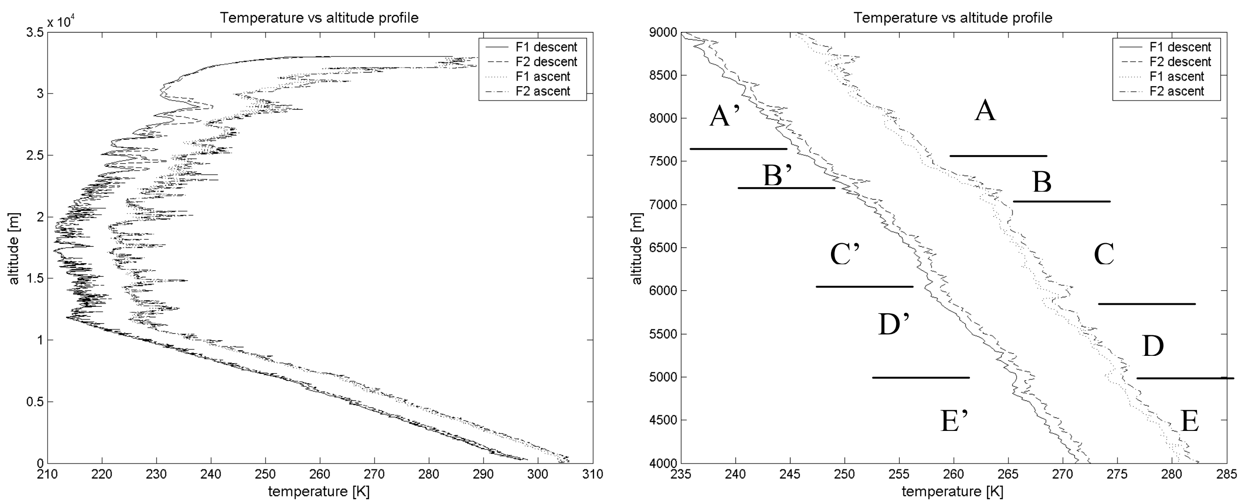


Figure 8. left: descent profile for HASI Tem; centre: temperature gradient evolution between 4000-9000m

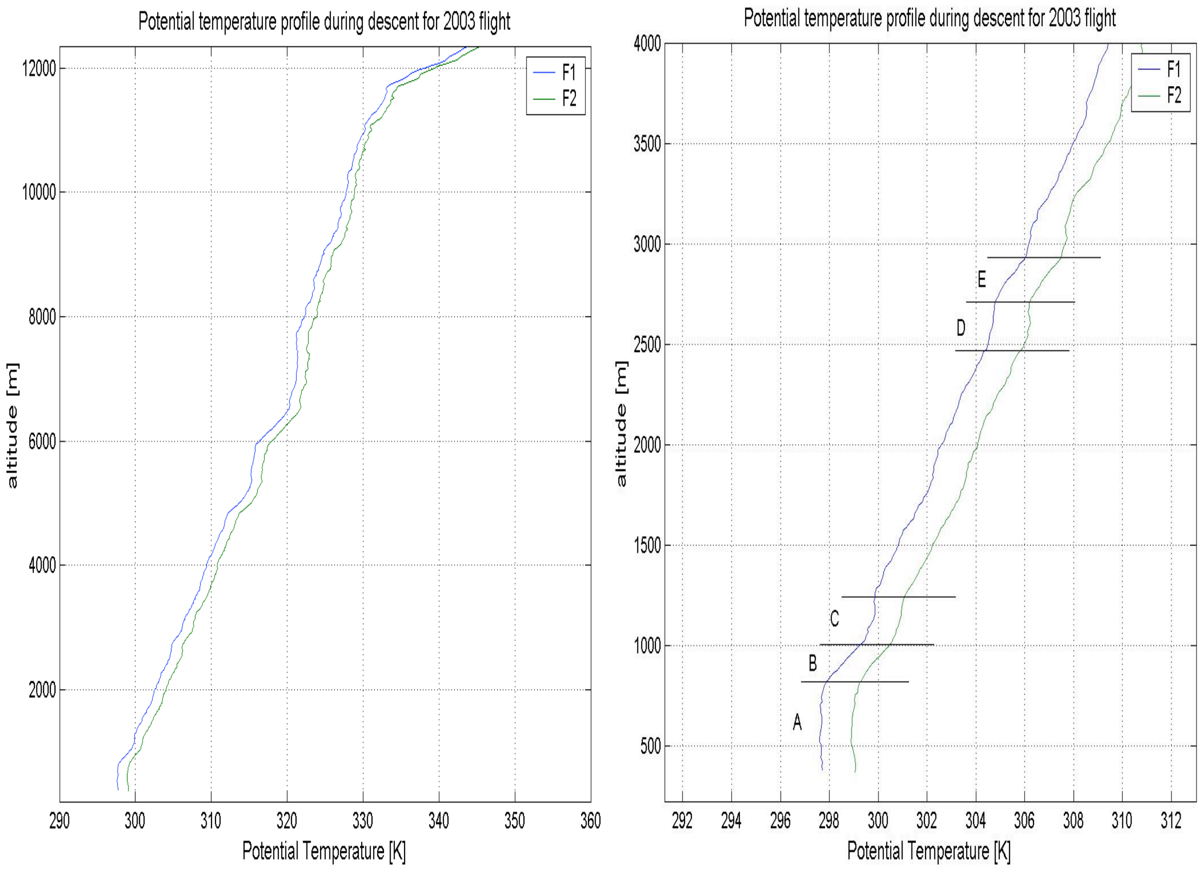


Figure 9. Balloon 2003 descent potential temperature profile between 1000m and 12000m (left) and below 4000m (right); several different regions of stability are shown (in particular B and E).

lower altitudes, measured in the 2002 flight). Above the tropopause, while the general evolution of temperature profile is uniform, the structures that are present show several changes. Some features can be recognised in both the profiles, at same altitudes while others have moved or present higher values. This is an evidence of an evolution of the temperature profile that outlines how the atmospheric structure, even in short-time windows, has a dynamic behaviour (see Figure 8; layers with prime are in descent phase). Several layers can be identified in the lower troposphere; the layers (thickness: B=400m; C=1100m; D=800m and E=5000m) are separated by a ΔT of 2K in 50m (for C/D) and 1K in 70m (for D/E); the overall structure is maintained and visible in both ascending and descending phases showing a well fixed stratification in the temperature field. In A' the gradient is –8.3K/km, in B ~ -17K/km and in C', D' and E' it's around –6.0K/km. It can be observed that during the descent phase the two layers B' and C' are not so well distinguishable but show a mixing (confirmed by the potential temperature plot showing a constant potential temperature layer between 7000-8000m; see Figure 9). Thickness of layer D' is higher than layer D confirming the evolution of the atmosphere. An overall temperature gradient of 7.1 K/km is measured in the troposphere. Other features can be observed in the upper troposphere: several sets of spikes of 3÷5K peaks in 50÷80m are present from 7000m to 11000m; these peaks are present both in ascent and in descent phases, they are not due to fluido-dynamic effects since the configurations of the probe in the two phases are completely different and the incoming flow is different. A possible correlation between these peaks and the attitude of the probe (rotation and inclination) shows no direct correlation. Observed features must be related to the structure and configuration of the measured temperature field.

### 5.3. Potential temperature

The potential temperature is usually defined as the temperature a water parcel has when it is brought adiabatically to an atmospheric pressure of 1000 millibars.

The formula used for calculating the Potential Temperature (θ) is:

$$\theta = T\left(\frac{P_0}{P}\right)^{\frac{\gamma-1}{\gamma}} \qquad (1)$$

where T is the measured temperature, P is the measured Pressure, $P_0$ is the Pressure at 1000millibars level and γ is the heat capacity ratio of the gas.

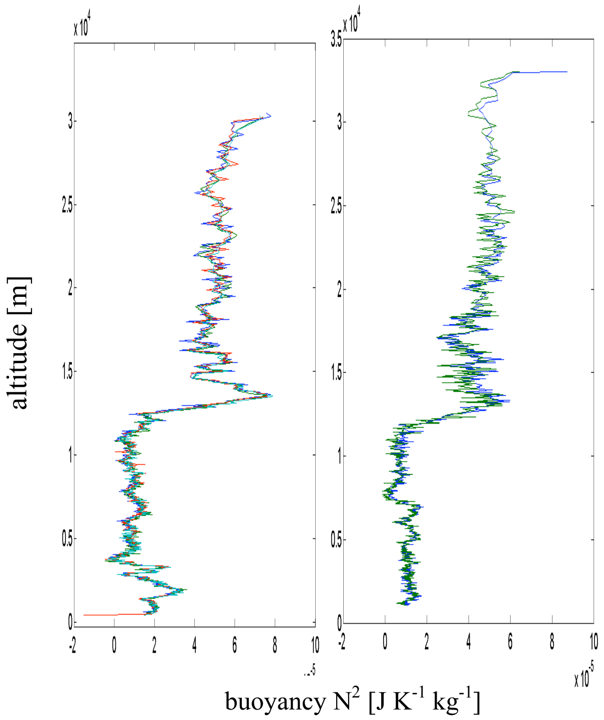


Figure 10. $N^2$ profiles deduced from balloon measurements from: (left) HASI TEM 2002 – mean of 40 data; (right) HASI TEM 2003– mean of 40 data

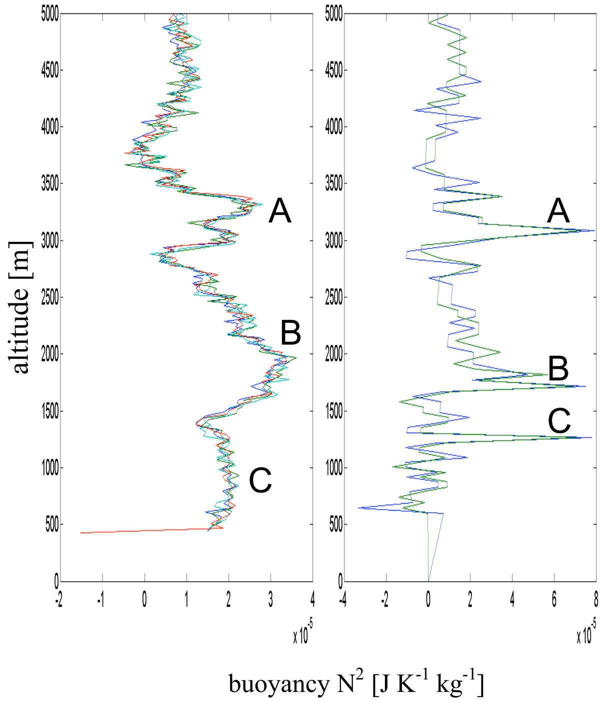


Figure 11. Close up of the N2 profiles deduced from balloon measurements below 5000m: (left) HASI TEM2002 – mean of 40 data; (right) MTEM 2002 – mean of 100 data.

Vertical stability of a dry atmosphere can be characterized by a constant variation of θ with height (9.8K/km).

The region up to 3000m shows several layers where the potential temperature is constant (see in Figure 9-right the layers A, C and D) revealing convective layers; layer A is the first layer near surface where the interactions between surface and atmosphere take place (Ekman layer); the other two layers of mixing air (C and D) can be observed at higher altitude (1100 and 2100 respectively); what is the interesting thing is that between A and C there is a layer of stable air and again above layer D; two other regions (see Figure 9 left), between 5500m-5900m and 6500m-7700m, reveal unstable regions showing the presence of two adiabatic regions where the potential temperature remains constant: this is evidence that convective mixing is taking place. Two layers, that show a more stable atmosphere are visible just below these mixing layers; these are relative thick layers (400m and 1200m respectively) that are not restricted to be in the vicinity of the tropopause revealing presence of mixing regions where density is high and where horizontal winds are mainly constant (see Figure 10).

Above 11900m the potential temperature profile reveals a stable atmosphere: above the inversion layer the stratosphere shows, as expected, a more stable behaviour.

## 6. Discussion

### 6.1. Atmospheric stability (buoyancy)

Stability of the atmosphere depends on the value of the square of the buoyancy frequency $N$; $N^2$ is defined as:

$$N^2 = \frac{g}{T}\left(\frac{\partial T}{\partial z} + \frac{g}{C_p}\right) \quad (2)$$

where $g$ is the gravitational acceleration, $T$ is the atmospheric temperature (in Kelvin), $C_p$ (=1004 J $K^{-1}$ $kg^{-1}$) is the specific heat at a constant pressure and $z$ is the altitude (in meters).

When $N^2$ is negative, i.e if the atmospheric lapse rate $\Gamma = \partial T/\partial z$ is bigger than the adiabatic lapse rate $g/C_p$, the atmosphere is unstable.

If this is the case an atmospheric air parcel will escape continuously from it's equilibrium position.

An unstable atmosphere can have an amplifying effect on small perturbations.

Stability of the atmosphere is strongly dependent on the temperature profile. Instabilities are generally present in those regions where the lapse rate Γ is high and the $N^2$ is low.

In Figure 10 the squared Brunt-Väisälä frequency profile N2 is shown both for the 2002 and the 2003 campaigns. It can be observed that between 12 and 14 km the stability of the atmosphere is increasing, indicating

Considering that typical stratospheric value for N2 is 4 10-5 (J K-1 kg-1), stability of the region crossed is higher in the stratosphere.

In the 2003 profile it can be observed that two layers of higher stability than the neighbour regions between 5000m and 8000m are crossed: here the potential temperature trend shows a higher stability.

Similar values of $N^2$ are measured in the two campaigns suggesting that no climate change has affected the Sicilian region. The $N^2$ profile differs a lot below the 4000m region between the 2 years: 2002 data are much more variable revealing a much more complex stratification in the lower troposphere.

It can be observed that the increased $N^2$ values for the features A, B and C can show a perfect correspondence to variations, at same altitudes, in the wind and temperature profiles; layers of mixing air contribute to the increase of stability of the atmosphere itself. Feature A is a 1000m layer where a corresponding drop in the wind velocity is measured and a much more stable layer is crossed and the $N^2$ values decrease again in less than 500m; the same happens with feature B. these profiles suggest the presence of alternate layers of stable and unstable air; in fact in the wind profiles it can be observed that there are weaker horizontal winds layers.

Same altitudes for the increased stability layers are found by the MTEM sensors for features A and B while feature C is measured at a slightly higher altitude.

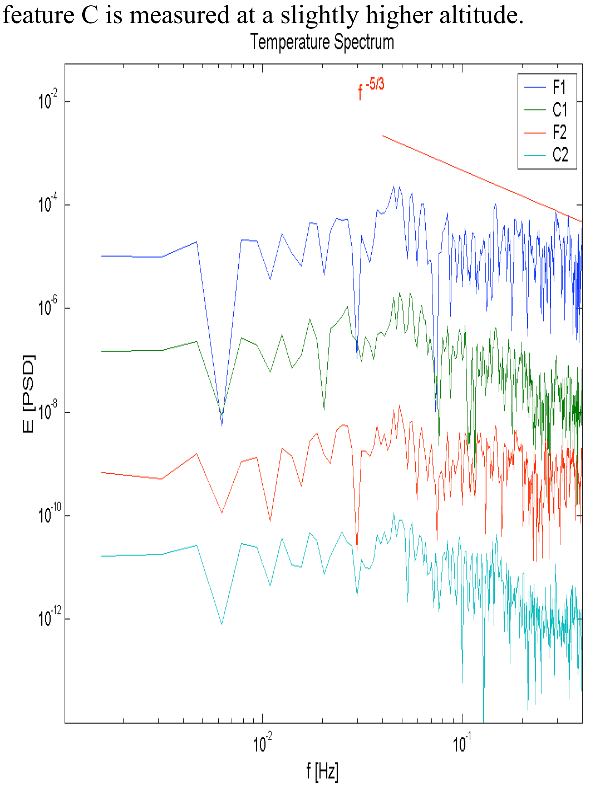


Figure 12. Temperature spectra of 2002 flight: HASI TEM (left).

### 6.2. Atmospheric turbulence (Kolmogorov)

Kolmogorov [1941] showed how for a 3D homogeneous and isotropic turbulence, with a downscale energy flux – positive from large to small scales, the spectrum of energy distribution follows the $k^{-5/3}$ power law and similarly Obukhov [1949] predicted a $k^{-5/3}$ spectrum for temperature fluctuations. For an analysis of global atmospheric fluxes this assumption is not realistic, horizontal dimensions are much larger than the vertical dimension, but if horizontal scales are of order of magnitude of few kilometres the Kolmogorov theory is not far from nature. With this assumption the plots (Fig. 12 and 13) show how the $k^{-5/3}$ law is followed in both the years: HASI TEM follows exactly the $k^{-5/3}$ power law; the housekeeping temperature sensor heads (PT100, see Fig. 1) show the same perfect agreement with theory.

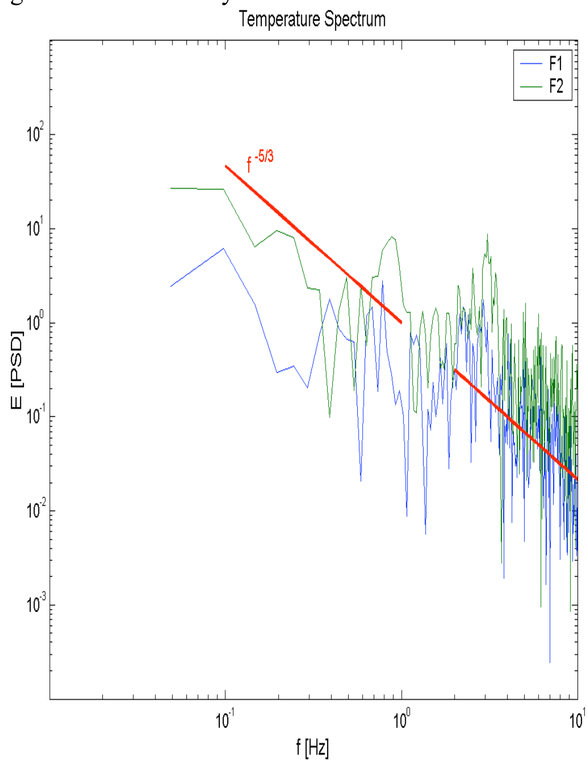


Figure 13. Temperature spectra of 2003 flight: HASI TEM (left).

## 7. Concluding remarks

Balloon flight experiments allowed to check performance of HASI TEM with real data sets in dynamical conditions similar to those they will experience in Titan's atmosphere. Several features and structure are observed and described.

Thermo-structure of troposphere and lower stratosphere reveal that local variations on the temperature measurements can be due to variations in the wind, both in value and in direction.

Tropopause is found to be at the same altitudes than the standard atmosphere, for the 2002 flight temperature is lower at the inversion point due to higher horizontal winds.

Analysis of both ascending and descending profiles show how several features have changed both in altitude and in intensity due to solar heating of the atmosphere.

Stability of the atmosphere is analysed and several layers of stable air are followed by unstable layers, especially in the troposphere. Atmosphere seems to be

more unstable respect to standard atmosphere but still the increase in stability is found for altitudes higher than the tropopause.
Finally stability and turbulence of the atmosphere are investigated analysing the buoyancy frequency profile and the temperature spectra.
The conducted analysis has helped the understanding of the features observed in the temperature profile and will help the interpretation of the temperature measurements retrieved in the 2005 Titan mission.

**8. Acknowledgements**
This work has been funded by the Italian Space Agency "ASI".

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