PROCEEDINGS OF SCIENCE

The WRF model contribution to the Cloud Top Height retrieval in EUSO-Balloon experiment

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EUSO-Balloon is a first prototype of the spaced-based JEM-EUSO telescope. Built on a stratospheric balloon, the telescope flew for eight hours, the night of August 25, 2014, above Canada. Interactions of light with clouds might impact the signal received by JEM-EUSO and EUSO-Balloon from cosmic-ray events. Reliable informations on cloud properties, such as the Cloud Top Height (CTH), are thus crucial to properly reconstruct air showers. For that purpose, atmospheric vertical profiles are needed to convert the Cloud Top Temperature (CTT), measured by the InfraRed (IR) camera onboard the telescope, to the CTH. When real profiles from radiosoundings are not available, real-time vertical profiles simulated by Numerical Weather Prediction (NWP) models can be used. In this preliminary work, the mesoscale Weather Research and Forecasting (WRF) model is applied to the EUSO-Balloon scene to check its reliability in evaluating atmospheric vertical profiles. We first test WRF simulated profiles by comparing with real radiosounding observations. Then, we consider EUSO-balloon scene observations from the very accurate satellite sensor MODIS.

The 34th International Cosmic Ray Conference,
30 July- 6 August, 2015
The Hague, The Netherlands

*Speaker.

PoS(ICRC2015)642

1. Introduction

EUSO-Balloon is a precursor mission for JEM-EUSO [1], the ISS space-based observatory devoted to detection of Extreme Energy Cosmic Rays (EECRs) by observing the fluorescent light produced by the Extensive Air Shower (EAS) during its propagation in the Earth's atmosphere.
The EUSO-Balloon experiment has been conceived to test the technologies and methods that will be exploited in the space mission [2]. To fulfill this aim a prototype of JEM-EUSO telescope was installed on a stratospheric balloon that flew for eight hours in the night of 25 August 2014 above Canada under conditions that could be standard for JEM-EUSO. Launched from the Timmins Stratospheric Balloon Base - CYTZ (Ontario, Canada), reached an altitude of about 40 km covering in the flight a ground path of about 200 km (WE direction) for 30 km (NS direction). The entire operation was ensured and monitored by the balloon division of the French Space Agency CNES.

It is known that cosmic ray detection is strictly dependent on the atmospheric conditions [3]: the presence of clouds may influence the EAS signal received by the telescope leading to a possible misinterpretation of the observed data. Particularly depending on their Cloud Top Height (CTH) and Cloud Optical Depth, clouds may impact on the detected signal in different ways [4]. Estimating with good accuracy the atmospheric conditions in the telescope Field of View (FoV) during the experiment is therefore fundamental. A first guess about the cloudiness present during the flight can be obtained from GOES-13 [5], a geostationary satellite that provides images of the EUSO-Balloon area about every 15 minutes covering the entire duration of the flight. From its radiance images it can be noticed that the weather was characterized by the presence of scattered and broken clouds.

For a deeper study, the EUSO-Balloon has been equipped with an IR-camera that monitored the troposphere observed by the balloon for the entire flight. From the measured radiance, the Brightness Temperature (BT) can be retrieved through the employment of the inverted Planck's Law, while, to evaluate the CTT from the BT, a correction of the non-blackbody effect of the atmosphere is needed. To do this many methodologies have been recently improved. Wang [6] purposes a weighting function for the BT-11μm band calculated using LIDAR-measured and simulated vertical profiles of optical depth, temperature and humidity. Other algorithms based on specific approximations of the radiative transfer equation in a cloudy atmosphere use the infrared split-window wavelengths (BT-12μm and BT-11μm bands) to correct the atmospheric effects [7] [8] [9].

The height of the cloud can be then estimated from the CTT using the atmospheric relation between the temperature and the height, therefore an atmospheric vertical temperature profile is required. Usually profiles from Standard Atmosphere models or from radiosoundings are used for that purpose. However, it is necessary to bear in mind that the first ones provide an oversimplified model of the troposphere as they assume the temperature varying linearly with the height. Even if distinct standard profiles are available for specific geographical regions (midlatitudes, tropics, etc.) and seasons, they are modeled through avarage conditions that do not allow to consider the day-by-day temperature-height variability. Therefore, frequent phenomenas such as the thermal inversions, that typically occur in the winter midlatitude nights when the air close to the surface cools down faster than the adjacent upper layers, are in principle not taken into account. On the other hand, profiles provided by real observations are rare, as atmospheric soundings are available only few times a day (1, 2, or 4) and usually carried out in land populated areas. Considering that for the most of the time the JEM-EUSO telescope will observe the atmosphere above oceans, it is clear that soundings can be used in a limited way. For these reasons more appropriate profiles have to be considered. Atmospheric vertical temperature profiles can be simulated by Numerical Weather Prediction (NWP) models, here used in post-event analysis. Such profiles are always available, and using mesoscale NWP models, high spatial resolutions can be achieved (up to tens of meters), providing for the whole area detected by the IR-camera a large number of simulated profiles.

This work aims to test the reliability of the mesoscale Weather Research and Forecasting (WRF) model [10] in simulating atmospheric vertical temperature profiles in the frame of the EUSO-Balloon experiment. WRF is a mesoscale, non-hydrostatic, Eulerian and full compressible model with regional and global applications that supports multiple-nesting facilities. Microphysics, long and short wave radiation, surface layer physics, planetary boundary layer physics and cloud physics are the main parametrized features.
In this study two tests have been carried on. In the first one WRF profiles are compared to real radiosoundings close to the EUSO-Balloon flight path recorded in the course of the experiment. In the second test WRF temperature profiles are applied to the CTT directly provided by the very accurate spectroradiometer MODIS, here used as a reference sensor, and the retrieved heights are then compared to the MODIS CTH. The same concept of using WRF model is used in [11] where a different analysis is carried out and the results are compared with the very accurate CALIOP Lidar.

2. Data

2.1 Radiosoundings data

Three real radiosounding stations close to the EUSO-Balloon flight have been considered: Moosonee (YMO), Green Bay (GRB) and Gaylord (APX). The soundings have been recorded the 25 August 2014 at 00UTC. A fourth real vertical temperature profile, recorded in the first 40 minutes of flight by a thermometer installed on the balloon, until the reachment of about 17 km of altitude (the launch of the balloon occured at 00:54 UTC), has been used in addition.

2.2 WRF simulation data

The WRF model version 3.6 has been used in this study. A simulation of the entire balloon flight time has been done. In order to get the best resolution for the area involved in the balloon flight, the simulation has been set with a finer-resolution model inside the wider coarses domain containing all the considered sounding locations (Figure 1). Both domains are centered in 42N latitude and 82W longitude. The spatial resolutions are set to 3 km (nest) and 9 km (courser domain), 40 vertical levels and a time of running of 4.5 days (from 21 August 2014, 00UTC). The model initialization is done using the ECMWF global model output data released with a resolution of 0.125x0.125 degrees. The microphysics parametrization has been set to the Morrison-Double-Moment scheme, usually recommended for cloud-resolving simulations. The Planetary Boundary Layer has been parametrized with the YSU scheme, Short-Wave radiation with the Dudhia scheme, Long-Wave radiation with the RRTM scheme while no cumulus parametrization has been used.

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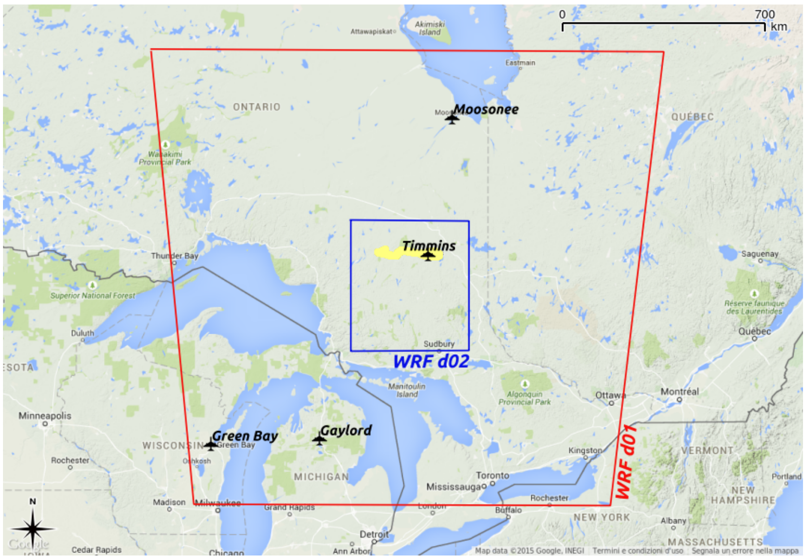

Figure 1: Domain of the WRF simulation used. The WRF courser domain (in blue - WRF d01), the finest-resoluted model domain (in red - WRF d02), the EUSO-balloon flight path (in yellow) and the considered radiosounsing stations are shown.

2.3 MODIS data

The MODIS (MODerate Resolution Imaging Spectroradiometer, on board the Terra satellite) [12] data considered in this work are the ones observed in the scan occured above canadian lands the 25 August 2014 at 02:59 UTC, that means that the sensor passed approximatively at 02:55 UTC above Timmins area. In this work the MODIS Cloud Top Pressure and the MODIS Cloud Top Temperature products are taken into account. The errors estimated for the MODIS Cloud Properties are related to the CO2 slicing technique used in the retrieval. The heights appear to be consistent with radiosonde profiles within 40 hPa RMS (Root Mean Square), lidar scans within 80 hPa RMS and other measurements within 50 hPa [13].

3. Results

3.1 Comparison between WRF simulated temperature profiles and radiosoundings

As mentioned in the introduction, the first part of the presented study is dedicated to the comparison between the atmosperic vertical temperature profiles provided by the radiosoundings recorded close to (and in) the EUSO-Balloon path flight during the experiment and the WRF model profiles simulated at the same time and in the same locations (Figure 2). From Figure 2 a very good agreement between the real curves and the WRF simulated ones can be noticed, expecially for the tropospheric region above the first 3 km of altitude. Also the thermal inversions close to the surface are properly recognized, although some discrepancies between the curves are present in the lowest layers.
To quantitatively evaluate the temperature deviations between real and simulated profiles, the RMSE (Root Mean Square Error) values for each comparison are reported in Table 1. All the errors are computed within 1°C of temperature deviation, result that clearly confirms that the profiles simulated by WRF model are in very good correspondence with real observed data.

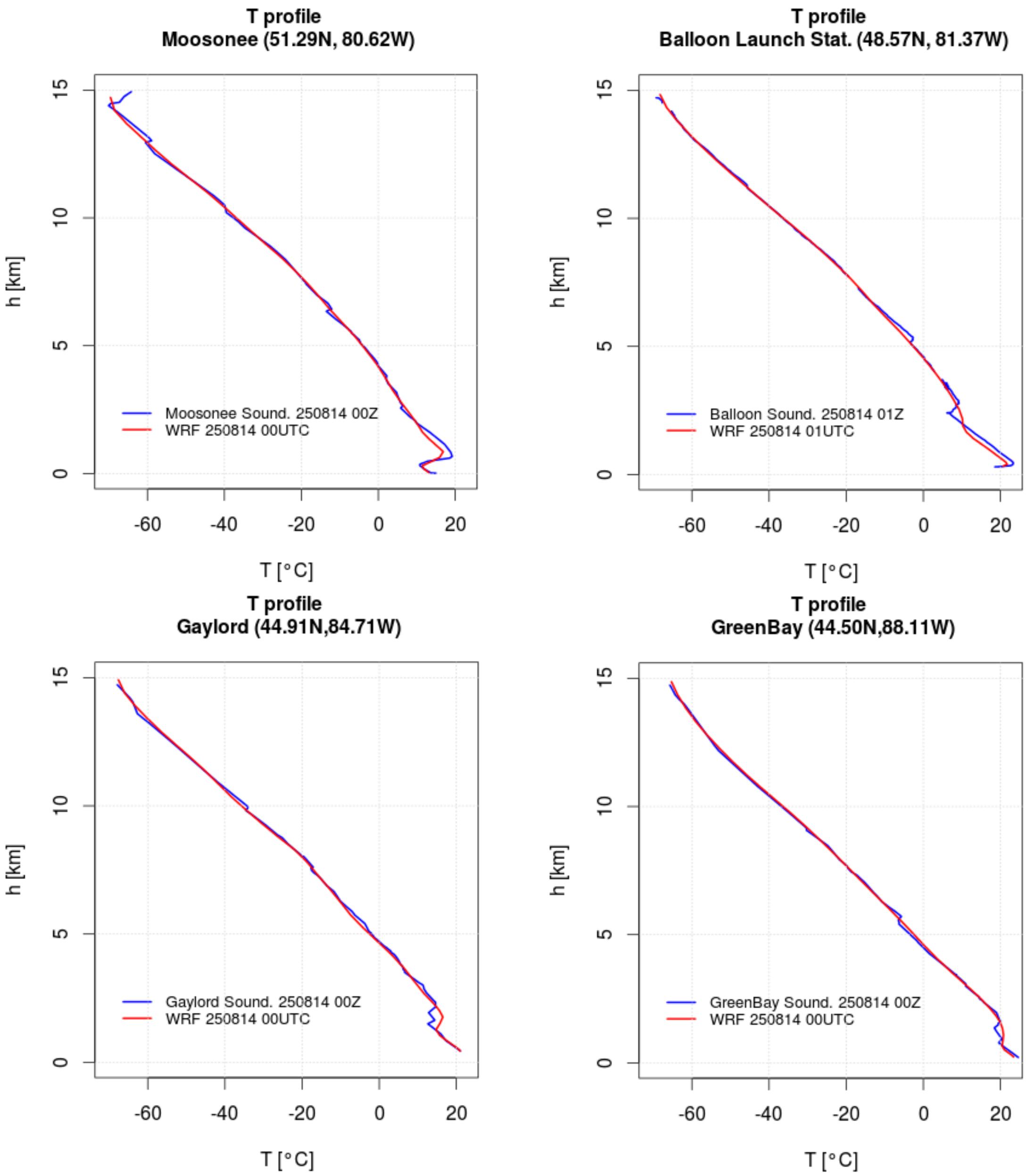

Figure 2: Atmospheric vertical temperature profiles provided by real radiosounding observations (blue lines) compared with WRF model ones (red lines) simulated at the same time and at the same locations for each considered sounding.

	Balloon Lauch Stat.	**Moosonee**	**Gaylord**	**Green Bay**
RMSE [$^\circ C$]	0.87	0.93	0.81	0.60

Table 1: RMSE values for the differences in temperature between the real radiosounding profiles and the WRF simulated ones at the same time and in the same location.

3.2 Analysis of the impact on CTH retrieval using WRF simulated temperature profiles

The convertion of the cloud temperature in height depends very strictly on the temperature profile used, thus the application of one profile rather than another can lead to very different CTHs. This section aims to demonstrate how much the choice of a specific temperature-height relation can influence the performance in CTH retrieval, but above all intends to evaluate the improvements in CTH estimation by using WRF simulated profiles. To fulfill this objective, firstly, the MODIS

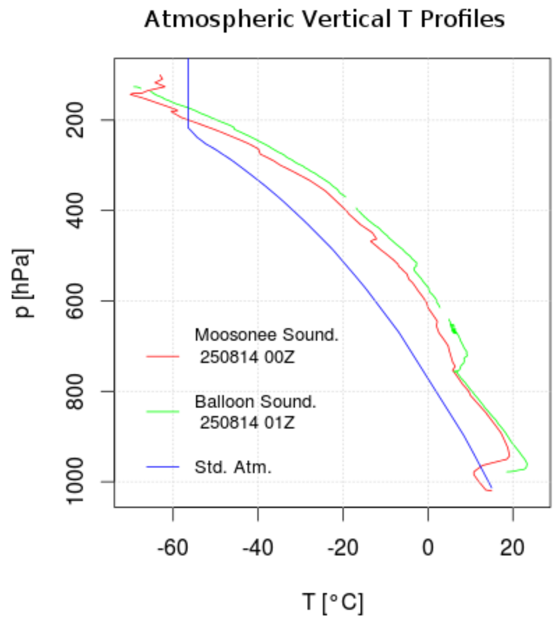

Figure 3: The three atmospheric vertical temperature profiles used in the test to retrieve the CTP from the MODIS CTT data. Differently from the WRF profiles applied pixel-by-pixel, all these profiles have been applied to the entire temperature matrix.

CTP product (that essentially expresses a height in pressure terms) (from 02:59 UTC MODIS scan) has been compared to the CTP retrieved from MODIS CTT data having applied the WRF profiles derived from the model simulation described in Section 2.2. The potential of using an NWP model is that for each surface grid-point a specific atmospheric vertical temperature profile can be retrieved. Moreover, using a mesoscale model as WRF, high resoluted grid boxes can be set and finest profiles are achievable. To each single element of the CTT matrix its closest WRF simulated vertical profile can be applied and the CTP of the entire image is thus evaluated. Secondly, the performance in CTH retrieval of other three temperature profiles has been investigated: the profiles, reported in Figure 3, are taken from the Moosonee and EUSO-Balloon soundings and from a Standard Atmosphere model developed for midlatitudes. Differently from the WRF profiles techique just described, in this procedure the same real or standard profile has been applied to the whole CTT matrix.
Figure 4 shows the histograms of the difference between the MODIS CTP and the CTPs retrieved using the profiles aforementioned. From the InterQuartil Range (IQR) value and the median, it is clear that the best performance in pressure (height) retrieval is achieved using the WRF simulated profiles applied element-by-element to the CTT matrix. A further confirmation of this preliminary

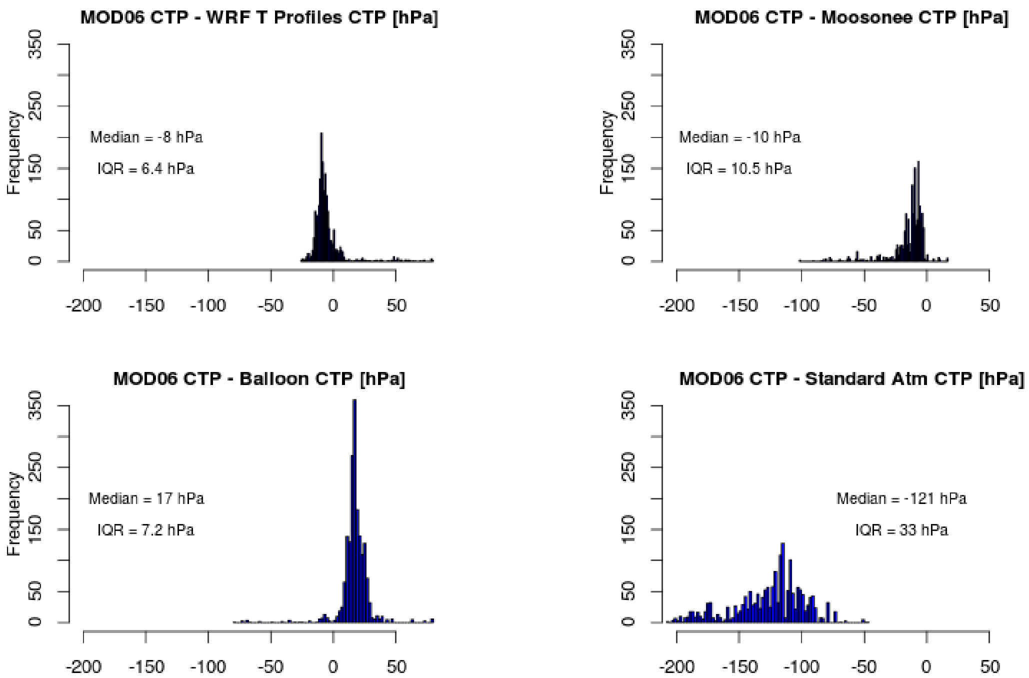

Figure 4: Histograms of the discrepancies from MODIS CTP and the CTPs retrieved using the test profiles.

deduction can be obtained from Figure 5 where the boxplot of the differences is reported. Beyond the worst performance achieved by using a standard atmospheric profile, it is clear how the usage of the WRF simulated ones can improve the CTP (CTH) retrieval.

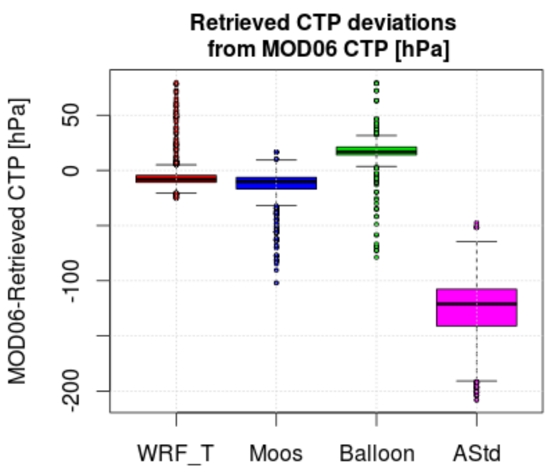

Figure 5: Boxplot of the discrepancies from MODIS CTP and the CTPs retrieved applying different profiles to the MODIS CTT image.

4. Conclusions

In order to understand the atmospheric conditions present during the EUSO-Balloon flight, the IR-camera observations have to be converted in height, thus an atmospheric vertical temperature

profile is required. As mentioned in the introduction, depending on the profile used, very disparate CTHs can be obtained, strongly influencing the final CTH retrieval. Standard Atmospheric profiles do not consider the daily temperature-height variability and many other factors that influence the real temperature level by level in the atmosphere. On the other hand, real radiosounding observations are scarce and provided only few times a day. For these reasons, more suitable instruments for the temperature-height conversion are necessary.
The aim of this work is to check the reliability of WRF model simulated temperature profiles in retrieving the CTH from CTT data in the frame of the EUSO-Balloon experiment. The investigations performed in this study first show that the vertical temperature profiles derived from the WRF simulation of the EUSO-Balloon scene are in very good agreement with real observed data. It has also been demostrated that applying to each element of the CTT matrix its closest WRF simulated profile, the CTH retrieval improves, leading to consider the WRF profiles as reliable instruments and reasonable substitutes of standard/real observed profiles in CTH estimation. These results are confirmed by an independent analysis conducted in the collaboration [11] which supports the conclusions here presented.

References

[1] T. A. Ebisuzaki et al., *The JEM-EUSO mission*, Adv. Space Res., **53**, 10 (2014).

[2] P. von Ballmoos et al., *A balloon-borne prototype for demonstrating the concept of JEM-EUSO*, Adv. Space Res., **53**, 10 (2014).

[3] J.H. Adams Jr et al., *An evaluation of the exposure in nadir observation of the JEM-EUSO mission*, Astropart. Phys., **44** (2013).

[4] G. Saez-Cano et al., *Observation of extensive air showers in cloudy conditions by the JEM-EUSO Space Mission*, Adv. Space Res., **53**, 10 (2014).

[5] GOES website, *http://www.goes.noaa.gov/*.

[6] C. Wang et al., *A Physically Based Algorithm for Non-Blackbody Correction of Cloud-Top Temperature and Application to Convection Study*, J. Appl. Meteor. and Clim., **53**, 7 (2014).

[7] A. Hamada and N. Noriyuki, *Development of a cloud-top height estimation method by geostationary satellite split-window measurements trained with CloudSat data.* J. of Appl. Meteor. and Climat. **49**, 9 (2010).

[8] C. K. Carbajal Henken et al. *FAME-C: cloud property retrieval using synergistic AATSR and MERIS observations.* Atmos. Measur. Techn., **7**, 11 (2014).

[9] S. Briz et al., *Remote sensing of water clouds temperature with an infrared camera on board the ISS in the frame of JEM-EUSO mission.* , J. Appl. Remote Sensing, **8** (2014).

[10] W. C. Skamarock et al., *A Description of the Advanced Research WRF Version 3*, NCAR technical note (2008).

[11] A. Merino et al., *Coud Top Height estimation from WRF model: application to the InfraRed camera onboard EUSO-Balloon*, Proceedings of the 34th ICRC (2015).

[12] MODIS website, *http://modis.gsfc.nasa.gov/*.

[13] W. P. Menzel et al., *Cloud Top Properties and Cloud Phase algorithm theoretical basis document*, MODIS technical note (last version 2015)