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Cloud Coverage and its Implications for Cosmic Ray Observation from Space

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Abstract: JEM-EUSO is an International mission planning to observe Extreme High Energy Particles from Space. Flying on the ISS, during its operation, JEM-EUSO will experience all possible weather conditions inside its field of view. In order to estimate the effective aperture of the detector, one key point is the evaluation of the role of clouds, in particular their frequency as a function of altitude and optical depth for the different geographical areas of the planet. The probability of occurrence of a defined atmospheric condition has been assessed in this study by means of different meteorological databases: TOVS, ISCCP and CACOLO data. Because of the specific peculiarities of each dataset, the comparison of the different results is used to assess the systematic uncertainty on the derived conclusions.

Keywords: JEM-EUSO, meteorological databases, cloud information.

1 Introduction

JEM-EUSO [1, 2] is a new type of observatory under development with the aim of detecting Extreme Energy Cosmic Rays (EECR) from the International Space Station (ISS), by using the whole Earth as a detector. JEM-EUSO telescope will orbit around the Earth every ∼90 minutes at the altitude of 350-400 km to capture the moving track of the Ultra Violet (UV) photons produced during the development of Extensive Air Showers (EAS) in the atmosphere. The telescope has a super-wide (±30°) Field-of-View with optics composed by Fresnel lenses [3]. The telescope records the track of an EAS with a time resolution of 2.5μs and a spatial resolution of about 0.5 km (corresponding to 0.07°) in nadir mode by using a highly pixelized focal surface (3×10^5 pixels) [4]. These time-segmented images allow determining energy and direction of the primary particles [5].

During its operation JEM-EUSO will experience all possible weather conditions. The amount of both fluorescence and Cherenkov signals reaching JEM-EUSO depends on the extinction and scatteringt of UV light in atmosphere. Correct reconstruction of EECR energy and of the type of the primary cosmic ray particle requires, therefore, information about absorption and scattering properties of the atmosphere. For this reasons the JEM-EUSO observatory will include an Atmospheric Monitoring System (AM) [6] which will consist of an infrared camera [7], and a LIDAR device. Moreover, it will benefit from the real time global atmospheric models like those generated by the Global Modeling and Assimilation Office (GMAO) [8], the European Center for Medium range Weather Forecasts (ECMWF) [9] and other similar services.

The cloud coverage in the FoV of JEM-EUSO will be continuously monitored by the infrared camera, which will also measure the altitude of the top of optically thick clouds. LIDAR will determine the detailed scattering and extinction properties of the atmosphere at the location of each triggered EAS event. Real-time models of the atmosphere are used to deduce the parameters relevant for the modeling of the transmission and extinction properties of the air, neeeded for the analysis of the LIDAR data, for the calibration of the infrared camera, and for the modeling of development of EAS in the atmosphere.

The peculiarity of the observation from space is the possibility of observing CR also in some cloudy conditions, which is tipically not the case for ground-based telescopes. In a simplified way, we can assume that if the maximum of the shower is above the cloud layer the reconstruction of the shower parameters will be possible. It is clear that the same top cloud layer will affect in a different way showers of various inclination or originating from the different type of primary particles (i.e. neutrino will develop much deeper in the atmosphere compared to EECR). Thin clouds ($\tau < 1$, typical of cirrus) will affect the energy estimation but the measurement of the arrival direction will still be possible with acceptable uncertainty. Thick clouds ($\tau > 1$) will compromise, or prevent, the measurement only if located at high altitudes. As an example, 60° zenith-angle inclined showers will have the shower maximum at 6-7 km altitude, much higher than the typical range of stratus [10]. As the location of the clouds will affect either the duty cycle or the effective aperture of the instrument, and, consequently, the exposure, a detailed analysis of the probability of occurrence of the differect atmospheric conditions has been evaluated by means of different meteorological databases. The main reason is that each database has its own peculiarity, therefore, their comparison will allow to study the variability of the results and assess an uncertainty on the cloud distribution.

2 The meteorological databases

TOVS, ISCCP and CACOLO meteorological databases have been used in the following analysis. The NASA project TOVS (TIROS Operational Vertical Sounder) [11] on board NOAA's TIROS series of polar orbiting satellites consists of three instruments: a high-resolution infrared radiation sounder modification 2 (HIRS/2), a stratospheric sounding unit (SSU) and a microwave ounding unit (MSU). The three instruments have been designed to determine the radiance needed to calculate temperature and humidity profiles of the atmosphere from the surface to the stratosphere. These data have a good spectral distribution and provide optical depth and altitude of clouds. They are distributed irregularly and to obtain a complete data-set, the application of the transport radiative model has been necessary. In this study, data from January 1988 to December 1994 have been used, divided between land and ocean data.

The International Satellite Cloud Climatology Project (ISCCP) [12] was established in 1982 as part of the World Climate Research Program (WCRP) to collect and analyze satellite radiance measurements to infer the global distribution of clouds, their properties, and their diurnal, seasonal and interannual variations. Data collection is still on. The resulting data-sets and analysis products are being used to improve the understanding and the modeling of the role of clouds in climate, the primary focus being the elucidation of the effects of clouds on the radiation balance. These data can be also used to support a number of other cloud studies, including the understanding of the hydrological cycle. The data are collected from the suite of weather satellites operated by several nations and processed by groups in government agencies, laboratories, and universities. ISCCP has developed cloud detection schemes using visible and infrared window radiance (infrared during nighttime and daytime, while visible during daytime). The data from July 1983 to June 2008 have been used in this analysis. The data have the following characteristics: a) possibility to obtain monthly, seasonal and annual means; b) the cloud types are defined by the VIS/IR (visible/infrared) top pressure and optical depth and they are divided in 3 levels (low clouds with a top pressure greater than 680 mb, about 3.2 Km, high clouds with a top pressure minor than 440 mb, about 6.5 Km, and middle clouds with a pressure between the other types); c) no division between ocean data and land data; d) frequency of occurrence of cloudy conditions in individual satellite image pixels, each of which covers an area of about 4 to 49 square kilometers; e) data are given on a 2.5 degree square latitude-longitude grid, so we obtained a map divided in 10368 boxes (144 X 72 - longitude X latitude). As the data of this dataset can be extracted also on a monthly basis, they allow to reconstruct the interannual variability of cloud coverage for low, middle and high clouds.

The CACOLO (Climatc Atlas of Clouds Over Land and Ocean data) database [13] presents maps introduced in the atlases of cloud climatological data obtained from visual observations from Earth. The cloud averages presented on these maps have been extracted from a digital archive of gridded land and ocean cloud climatological data. Maps are given for total cloud cover, clear-sky frequency, and the average of nine cloud types within the low, middle, and high levels of the troposphere. The amount of cloud is defined as the fraction of the sky-hemisphere covered by the cloud. Maps of precipitation frequency are also included. Monthly, seasonal, and annual averages are given for both daytime and night-time. Land and ocean data have been analyzed separately, and are mapped separately for most quantities. Two grid sizes are used to display the cloud averages. Most data are given at 5-degree latitude-longitude resolution. A 10-degree grid is used to map some ocean data. The land data are based on analysis of 185 million visual cloud observations made at 5388 weather stations on continents and islands over a 26-year period (1971-1996). The ocean maps are based on analysis of 50 million cloud observations made from ships over a 44-year period (1954-1997).

In this sense CACOLO is a truly complementary database compared to the other two as the information is coming from ground observations instead from space.

3 Data analysis

A first study has been conducted in order to evaluate the differences between night-time and daytime, oceans and lands, using the TOVS data-set. Data have been used only in the range of latitudes 50N-50S since this is the range of latitudes spanned by the ISS. Clouds have been classified into 16 categories, according to their top altitude (h) (h <3 km, 3< h <7 km, 7< h <10 km, $h > 10$ km) and optical depth (OD) ($OD < 0.1$, $0.1 < OD < 1$, $1 < OD < 2$, $OD > 2$). Table 1 reports the results of the occurence of each cloud tipology for oceans during daytime. This configuration has been chosen as data taken during daytime are in general more reliable and the same applies to the ocean data compared to the land ones. The comparison between day and night has been performed then on lands as higher variations are expected on land surface compared to oceans. Slight differences among the tables exist, however, the general trend seems to be indepen-

Table 4: Distribution of the cloud properties (%) for 5 different geographical areas using ISCCP data. Data refer to daytime.

Sky condition	Geographical area									
	ocean					land				
	51.6-35N	35-15N	15N-15S	15-35S	35-51.6S	51.6-35N	35-15N	15N-15S	15-35S	35-51.6S
high clouds	23.5	18.9	27.8	17.2	20.1	26.1	19.4	33.5	24.2	28.1
middle clouds	24.2	12.4	12.1	13.6	24.2	22.0	12.4	14.8	11.8	18.9
low clouds	35.7	28.7	21.0	33.1	38.9	18.4	18.6	15.2	16.0	22.8
clear sky	16.6	40.0	39.1	36.1	16.8	33.5	49.6	36.5	48.0	30.2

Table 1: Relative occurrence (%) of clouds between 50°N and 50°S latitudes on TOVS database in the matrix of cloud-top altitude vs optical depth. Daytime and ocean data are used for the better accuracy of the measurement.

Optical Depth	Cloud-top altitude			
	<3km	3-7km	7-10km	>10km
>2	17.2	5.2	6.4	6.1
1-2	5.9	2.9	3.5	3.1
0.1-1	6.4	2.4	3.7	6.8
<0.1	29.2	<0.1	<0.1	1.2

dent from the geographical and temporal conditions. Table 2 shows the highest deviations from tab. 1 obtained in all possible combinations spanned with TOVS data (oceans, land, day, night). The results of tab. 1 can be classified in the following way. OD< 0.1 corresponds to clear sky and it accounts for $\sim$30%. Clouds below 3 km height do not hamper the measurements as the shower maximum will develop at higher altitudes, regardless of their OD and they account for another $\sim$30%, which gives a total of $\sim$60% of the time when the measurement is clearly possible. Thick (OD$>$1) and high (h$>$7km) will prevent the possibility of measurement, and they account for $\sim$19%. The remaining $\sim$21% will limit the measurement to very inclined showers (zenith angle $>$60°, which by the way correspond to the best category of data in terms of light intensity, angular accuracy and energy resolution - see [5]), or to the study of the arrival direction analysis, as the energy estimation will be worsened by the shower attenuation in atmosphere.

Table 2: Highest deviations from tab. 1 obtained in all possible combinations spanned with TOVS data (oceans, land, day, night)

Optical Depth	Cloud-top altitude			
	<3km	3-7km	7-10km	>10km
>2	-5.1	+1.6	-0.6	+2.7
1-2	-2.9	-0.2	+0.4	+0.3
0.1-1	-2.0	-0.8	-0.4	+0.3
<0.1	+7.6	+0.1	<0.1	+1.4

The study performed with TOVS data is important to have a first estimation of the uncertainty of the cloud distribution and its effects on shower-reconstruction capabilities, however, possible systematic effects of the technique employed in the TOVS measurement can not be inferred. For this reason, the same type of study has been applied to ISCCP and CACOLO data and results have been compared. As previously explained, the ISCCP and CACOLO data divide the clouds only in low, middle and high type, without distinguish according to their OD. In order to compare these data with the TOVS ones, the latter data were grouped only on the basis of their top altitude: clear sky, low clouds (h$<$3 km), middle clouds (3-7km), high clouds (h$>$7km). Tab. 3 shows the comparison between the 3 data sets in the case of lands and oceans during day-time. Results look quite different at a first glance. However, if clear sky and low clouds are averaged together, they give almost similar results, with a minimum of 57.1% for CACOLO to a maximum of 60.7% in case of ISCCP. As a consequence also the sum of middle and high clouds gives similar results. More in detail, TOVS data seem to overestimate high clouds meanwhile CACOLO data tend to overestimate the low ones. This overestimation might be due to the fact that CACOLO data are taken by ship and weather stations in the visual band only (so they tend to underestimate high clouds, especially in presence of low and middle clouds), while TOVS data are taken by satellites (for a similar reason, the low and middle clouds tend to be underestimated, because 'masked' as high clouds). ISCCP data are a sort of average of the other two data sets, since they are taken from satellite in the visual and infrared bands and this fact facilitates to distinguish the various levels. In this sense, as the TOVS data provide the highest value for high clouds, the results presented before can be considered as a conservative estimation of the fraction of events that could be measured by JEM-EUSO.

Table 3: Comparison among TOVS, ISCCP and CACOLO databases for the relative cloud occurence (%) in the different meteorological situations. Data refer to day-time, with a weighted average between oceans and lands.

Sky condition	Database		
	TOVS	ISCCP	CACOLO
high clouds	32.7	23.3	17.9
middle clouds	8.4	16.0	25.0
low clouds	28.4	26.0	40.4
clear sky	30.5	34.7	16.7

Finally, ISCCP data have been used to check the dependence of the above mentioned results according to their geographical area. Data have been divided into 5 latitude layers, separating among equatorial area, tropics and middle latitudes. Results are provided in tab. 4. In general the combination of low clouds and clear sky is slight higher onto oceans, which by the way account for the higher fraction of time. High clouds are particularly frequent in the equatorial region. This is normal, as it is correlated also with the big storms occurring in that area.

4 Conclusions

Flying on the ISS, during its operation, JEM-EUSO will experience all possible weather conditions inside its field of view. In order to estimate the effective aperture of the detector, one key point is the evaluation of the role of clouds, in particular their frequency as a function of altitude and optical depth for the different geographical areas of the planet.

The probability of occurrence of a defined atmospheric condition has been assessed in this study by means of different meteorological databases: TOVS, ISCCP and CACOLO data. The peculiarity of the observation of cosmic rays from space is the fact that the presence of low clouds ($h < 3$ km) is de facto equivalent to clear-sky conditions as the shower maximum will be located at altitudes higher than the cloud top altitude. The results of the present analysis, which is based on visible and infrared data, indicate that showers will develop in the atmosphere in clear-sky conditions for at least $\sim$60% of the time. The results are marginally dependent on the database adopted in the analysis ($\sim$5%). A precise evaluation of the effective fraction of time in which shower observation will be possible as a function of the arrival direction of the primary cosmic rays and how this will impact on the exposure of the experiment is reported in [10].

In the future we plan to extend the analysis by using other databases such as MERIS and CALIPSO. Furthermore, CALIPSO data will be used to assess the effects of the ISS orbital displacement on the inferred cloud structure along the effectively probed line of sight.

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