Calculation of Atmospheric Neutrino Flux with NRLMSISE-00

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Abstract: We calculate the atmospheric neutrino flux using NRLMSISE-00 [1] as the atmosphere model in ATMNC (ATmospheric Moon and Neutrino calculation Code) instead of the US-standard76 [2], which was generally used in the study of cosmic rays in the atmosphere for a long time. While the density profile of US-standard76 is given as a function of the height only, that of NRLMSISE-00 is expressed as the function of position on the earth and the time in a year. When we extend the calculation of atmospheric neutrino flux to the tropical region and to the polar region, the NRLMSISE-00 would be very useful. Also we can study the time variation of the atmospheric neutrino with it.

Keywords: Atmospheric neutrino, SouthPole, NRLMSISE-00

1 Introduction

We have calculated atmospheric neutrino spectra for Kamioka, Sudbery, etc with ATMNC (ATmospheric Moon and Neutrino calculation Code) [3]. In this calculation, we used the primary flux model based on AMS [5] and BESS [6, 7] data, and the hadronic interaction model DPMJET-III [8] above 32 GeV and JAM used PHITS (Particle and Heavy-Ion Transport code System) [9] below 32 GeV. For the atmosphere model, we used the US-standard76, and IGRF2010 model [10] as the geomagnetic field. We note, the atmospheric neutrino is calculated in a 3-dimensional scheme below 32 GeV, and in a 1-dimensional scheme above that. The flux calculated in both scheme agree each other at 32 GeV [3].

In Ref [4], we extended our calculation to a tropical experimental site (INO) [11], and to the South pole [12]. In this extension, we have installed new atmosphere model NRLMSISE-00 instead of US-standard76, since US-standard76 model gives the density profile as the function of altitude only. For these new sites, the position dependence and the time variation in year, which are not considered in US-standard76, are important.

The NRLMSISE-00 express the air density as the function of position on the Earth and the time in the year. With NRLMSISE-00, we may calculate the atmospheric neutrino flux for the new sites more accurately than with US-standard76. We also expect we can study the time variation of atmospheric neutrino flux in a year, and azimuth angle dependence of it at high energies, which is not expected with the US-standard 76. In this paper, we present the calculation of atmospheric neutrino flux with NRLMSISE-00, at Kamioka, INO and South Pole sites, then compare with that calculated with US-standard76, and study of variations of atmospheric neutrino flux at higher energies.

2 NRLMSISE-00 and US-standard76

In Fig. 1 we show the ratio of profile density between NRLMSISE-00 and US-standard76 as the function of altitude for Kamioka, INO, and South pole sites, up to 35 km above sea level. Since most of the cosmic ray interaction takes place below 35km above sea level, we limit the comparison up to this height. In our calculation scheme, however, we assume the atmosphere extends to the height of 100 km with US-standard76 and to 200km in NRLMSISE-00.

The primary cosmic rays interact with the air nuclei mainly in the altitude range from 10 km to 20 km. In these heights, the difference of US-standard and the NRLMSISE-00 is expressed by the difference of the scale height with the difference of absolute density around 10 'The scale height of NRLMSISE-00 varies within $\pm$ 5 % difference from that of US-standard76 in a year at these heights. According to the study of the relation between atmospheric neutrino flux and the atmosphere density profile [13], the atmospheric neutrino flux calculated with NRLMSISE-00 would not be largely different from that with US-standard76. Note, the difference of absolute density causes difference of the interaction height of 0.5 – 1 km, but the air density is the same if the same scale height is the same. When the density profile is averaged over one year, the difference is much smaller.

3 Atmospheric neutrino flux with NRLMSISE-00

In Fig. 2, we show the calculated atmospheric neutrino flux with NRLMSISE-00 averaging over all directions and summing all kind of neutrinos for Kamioka, INO-site, and South Pole in one year average. The results with US-standard76 is also plotted in the figure, but both calcula-

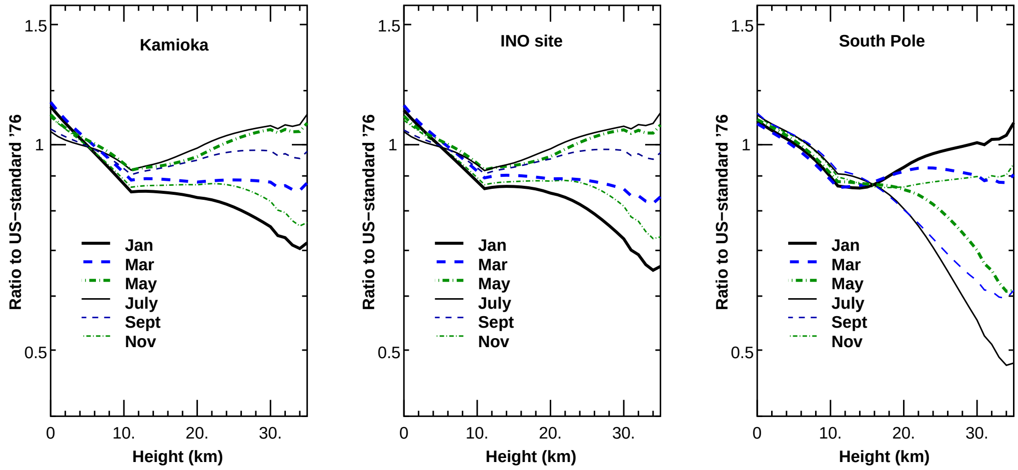

Figure 1: The ratio of air density in NRLMSISE-00 model to that of US-standard 76, and the variation for every 2 month.

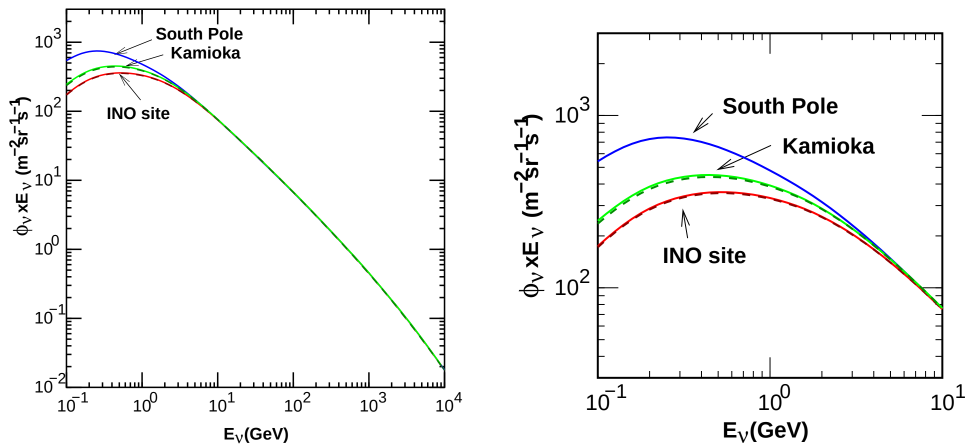

Figure 2: Atmospheric neutrino flux averaged over all directions and summed all kind neutrino, as the function of neutrino energy for Kamioka, INO-site, and South Pole. Left panel is for the all the energy range of the calculation, and right panel is the zoom up of lower energies. The fluxes calculated with US-standard76 are also plotted in dashed line for the Kamioka and the INO sites.

tions agrees each other within the thickness of the line in the figure. This agreement supports the calculation with US-standard76, and the study in Ref [13]. The results below 100 GeV are virtually identical to the former calculations [3].

On the other hand, the variation of atmospheric density profile could cause a larger variation of atmospheric neutrino flux at higher energies, since a little change of air density at the first interaction point of cosmic ray is critical for the flux of atmospheric neutrino at higher energies. However, we do not find a appreciable difference between the atmospheric neutrino fluxes calculated with NRLMSISE-00 and US-standard76 in Fig. 2. This is considered because we averaged the fluxes over one year.

We plot the atmospheric muon neutrino flux for each month averaging over azimuth angles in Fig. 3, and electron flux in Fig. 4. We find around 20 % variation of atmospheric muon neutrino flux calculated for south pole both for vertical downward going and horizontal directions. The vertical upward going neutrino flux also shows a variation, but in the opposite sense to that of downward going neutrino. This is considered due to the fact that the upward going neutrino is produced in the North Polar region. The variations of atmospheric muon neutrino at Kamioka and INO site are invisible in the figures at this energy yet. The variation of atmosphere may be too small to give the difference of atmospheric neutrino flux at 10 TeV. The atmospheric electron neutrino flux shows a rapid variations in the figures. However, the statistical error are large at this energy. We need more statistics to conclude the time variation of atmospheric electron neutrino flux.

With US-standard76, and in a 1-dimensional calculation scheme, the production process of atmospheric neutrino take place in exactly the same way both for upward and downward going neutrino if the arrival zenith angle is the same. Therefore, the calculated atmospheric flux for the same arrival zenith angle is the same for all azimuth angles, in 1-dimensional calculation scheme, or at higher energies.

With NRLMSISE-00, however, the position dependence of the atmosphere profile causes differences in the neutrino flux at different azimuth angles with the same arrival zenith angle for the upward going atmospheric neutrino flux, even in the 1-dimensional calculation scheme, then in actual neutrino flux at higher energies.

In the Figs.5,6,7, we show the variation of atmospheric neutrino flux in the zenith angle band from $\cos\theta_z = -0.8$ to $\cos\theta_z = -0.6$ at 10 TeV. The production position of these neutrino consists a band on the surface of the Earth,

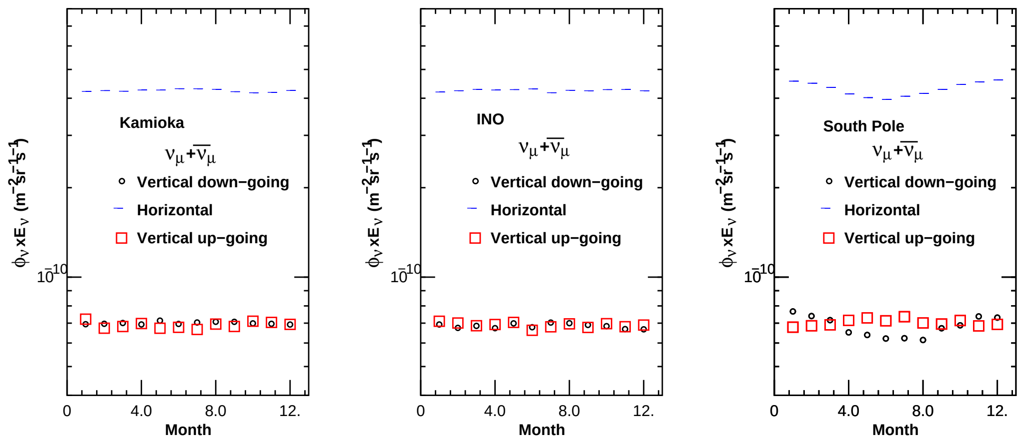

Figure 3: Variation of azimuth averaged atmospheric muon neutrino flux in a year at 10 TeV. The left panel is for Kamioka, the center panel for INO, and the right panel for South Pole. Small circle stands for electron neutrinos with arrival zenith angle θ_z in $1 > \cos\theta_z > 0.9$, horizontal bar in $0.1 > \cos\theta_z > 0$, and square in θ_z in $-0.9 > \cos\theta_z > -1$.

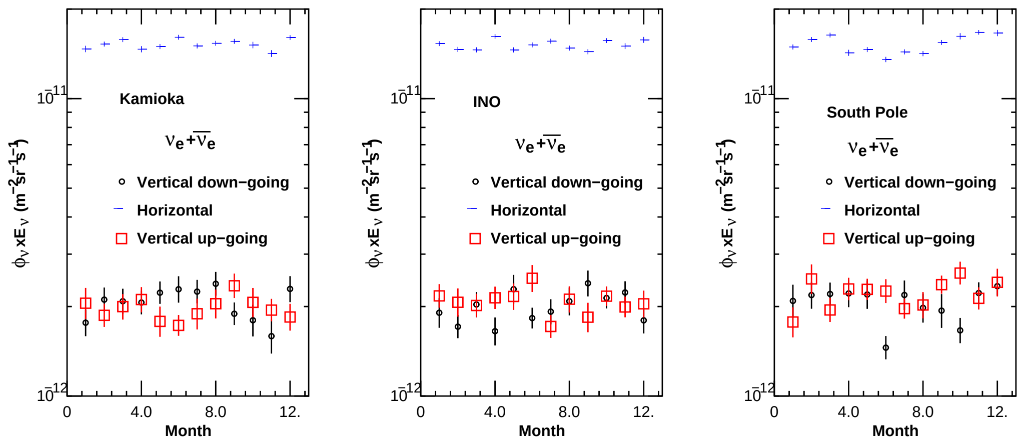

Figure 4: Variation of azimuth averaged atmospheric electron neutrino flux in a year at 10 TeV. The left panel is for Kamioka, the center panel for INO, and the right panel for South Pole. Small circle stands for electron neutrinos with arrival zenith angle θ_z in $1 > \cos\theta_z > 0.9$, horizontal bar in $0.1 > \cos\theta_z > 0$, and square in θ_z in $-0.9 > \cos\theta_z > -1$.

and the great circle perpendicular to the zenith directions runs nearly the center of this band (at $\theta_z = 135^o$) on the surface of the Earth.

In the one year average, the variation is smaller at all the sites. But, in the half year average (from April to September and from October to March), we see some variations in all the sites, especially at INO site. Note, the great circle on the surface of Earth runs North Polar region and South Polar region for INO site. At INO site, the amplitude of the variation reaches around 10 %.

The atmospheric electron neutrino flux also shows a rapid variation in the azimuth angles, but the statistical error are large. We need more statistics for electron neutrinos.

4 Conclusions

We have calculated the atmospheric neutrino flux with NRLMSISE-00 atmosphere model, and compared with that calculated with US-standard76 atmosphere model. We find that the difference is generally small at lower energies, ($\leq$ 100 GeV), and at higher energies when the fluxes are averaged over one year. However, there are seasonal and azimuthal variations of atmospheric neutrino fluxes at higher energies ($\geq$ 1TeV).

As the statistical error is crucial, we need to accumulate a larger statistics to describe the variations accurately.

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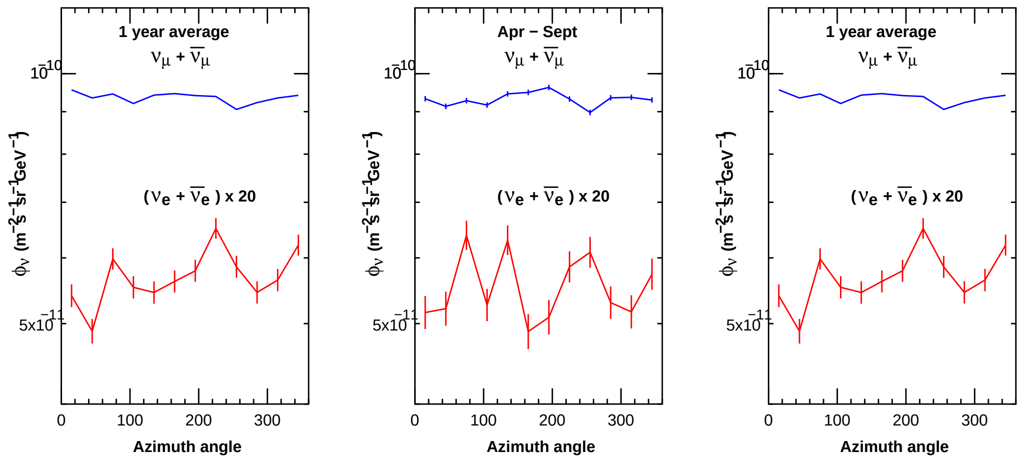

Figure 5: Azimuth variation of atmospheric neutrino flux at Kamioka in the zenith angle band from $\cos\theta_z = -0.8$ to $\cos\theta_z = -0.6$ at 10 TeV. Left panel show the average in a year, center show that from April to September, and right show that from October to March.

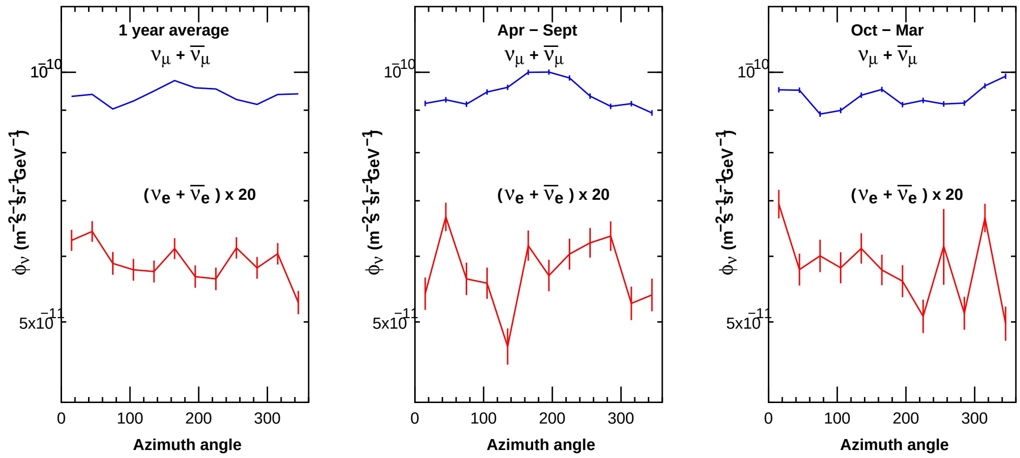

Figure 6: Azimuth variation of atmospheric neutrino flux at INO in the zenith angle band from $\cos\theta_z = -0.8$ to $\cos\theta_z = -0.6$ at 10 TeV. Left panel show the average in a year, center show that from April to September, and right show that from October to March.

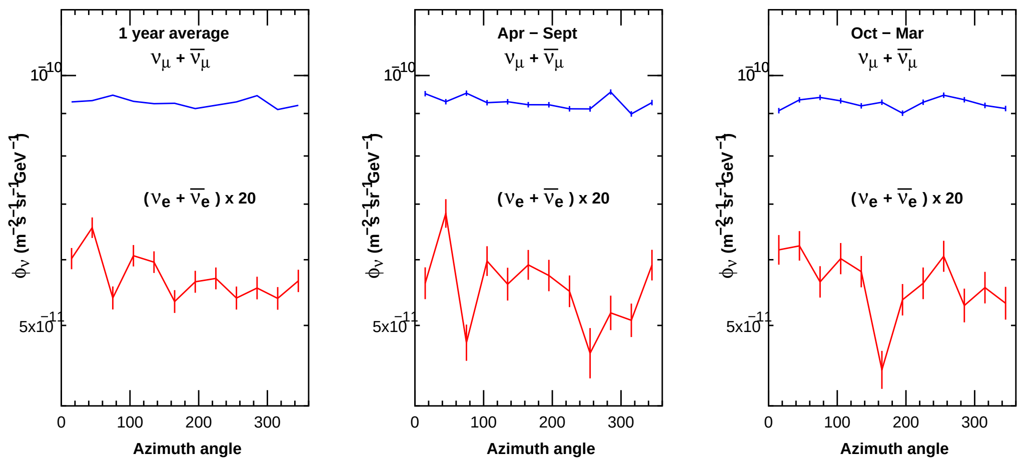

Figure 7: Azimuth variation of atmospheric neutrino flux at South Pole in the zenith angle band from $\cos\theta_z = -0.8$ to $\cos\theta_z = -0.6$ at 10 TeV. Left panel show the average in a year, center show that from April to September, and right show that from October to March.