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SAGE II-UMKEHR CASE STUDY OF OZONE DIFFERENCES AND AEROSOL EFFECTS FROM OCTOBER 1984 TO APRIL 1989

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Abstract

A comparison of 1262 cases of coincident ozone profiles derived from 666 Umkehrs at 17 different stations and 901 SAGE II profiles within 1000 km and 12 hours between October 1984 and April 1989 indicates the following layer percentage differences with 2-sigma error bars: layer three (14.6 +/- 3.3)%, layer four (17.6 +/- 1.1)%, layer five (-1.3 +/- 0.5)%, layer six (-5.7 +/- 0.7)%, layer seven (-1.0 +/- 0.7)%, layer eight (4.2 +/- 0.7)%, and layer nine (6.8 +/- 1.2)%. Comparing SAGE II-Umkehr differences to SAGE I version 5.5-Umkehr differences shows SAGE II higher than or equal to SAGE I relative to Umkehr in all layers except layer three. Adjustment for this bias would produce trends derived from SAGE II-SAGE I differences and Umkehr observations in the 1980s more nearly equal to each other in layers six, seven, and eight. A possible explanation of these differences is a systematic shift in the reference altitude between SAGE I and SAGE II, but there is no independent evidence of this.

While the shape of the vertical profile of differences at 17 individual Umkehr stations (mostly in mid-latitudes) is generally consistent at all stations except at Poker Flat, Seoul, and Lauder, significant variation does exists among the stations. The profile of mean differences is similar to previously observed differences between Umkehr and both SAGE II and SBUV and also to an eigenvector analysis, but with site-dependent amplitude discrepancies.

Because of the close correspondence of stratospheric aerosol optical depth at the SAGE II-measured 0.525 micron wavelength and the extrapolated 0.32 Umkehr wavelength determined in this study, we use the 0.525 micron data to determine the aerosol effect on Umkehr profiles. The aerosol errors to the Umkehr ozone amounts in percent ozone amount per 0.01 stratospheric aerosol optical depth range from +2% in layer six to -3% in layer nine. These results agree with previous theoretical and empirical studies within their respective error bounds in layers nine, eight, and five. The result in layer six differs significantly from previous works. In view of the fact that SAGE II and Umkehr produce different ozone retrievals in layers eight and nine and because the intra-layer correlation of SAGE II ozone and aerosol in layers eight and nine is non-zero, one must exercise some caution in attributing the entire SAGE II-Umkehr difference in the upper layers to an aerosol effect.

Introduction

Stratospheric Aerosol and Gas Experiment (SAGE) I and II and Umkehr measurements provide time series for ozone-trend evaluation [WMO, 1988; Reinsel et al.; 1989; DeLuisi et al., 1989]. Because stratospheric photochemical models predict the altitude of greatest percentage ozone decrease near 40 km, a good deal of effort has focused on determining the actual ozone trend in this region. While the WMO Trends Report [1988] presented a number of comparisons of various ozone-profile measurement systems and some comparisons of both SAGE and Umkehr measurements, a case study of SAGE II/Umkehr ozone profile comparisons has been unavailable.

The decreasing trend in upper-stratospheric ozone determined from Umkehr measurements is three to five times as large as the trend inferred from SAGE II-SAGE I differences. While the SAGE and Umkehr trend estimates do overlap if each is taken to its two-sigma limit toward concurrence, the likelihood of this simultaneous occurrence is low.

Because the expected change in stratospheric ozone in the upper Umkehr layers 7, 8, and 9 is especially sensitive to anthropogenic influences [WMO, 1988; WMO, 1989], accurate assessment of the ozone trend in this region (35 to 45 km) is particularly important. The ground-based Dobson network operating in the Umkehr mode provides the longest record of stratospheric ozone; however, it suffers from sensitivity to stratospheric aerosols [DeLuisi, 1979; Dave, 1979; DeLuisi et al., 1989].

Case-study Parameters

The results of this research derive from using SAGE II and World Ozone Data Center Umkehr (WODC) data in a case study of coincident ozone profile measurements between October 1984 and April 1989. While a similar comparison using SAGE I version 5.5 data [Newchurch et al., 1987] and the preliminary results of the SAGE II study in Newchurch and Cunnold [1990] both allowed coincidences within 4000 km and 30 hours, the results reported here use only cases within 1000 km and 12 hours. These SAGE I results appear in some of the figures for comparison purposes; however, the version of SAGE I used for the 1987 analysis preceded the slightly-modified version 6.0 used in the Ozone Trends Analysis Report. Furthermore, the SAGE I study used a weighted average of ozone profiles in the vicinity of an Umkehr observation. A comparison of version 6.0 to version 5.5 ozone amounts for the cases considered by Newchurch et al.[1987] indicates that the newer version contains approximately 10% more ozone in layer nine, 2% more ozone in layer eight, 2% less in layers seven and six, 1% less in layer five, 5% more in layer four, and roughly 10% more in layer three. Therefore, in layers six, seven, and eight, where the trends report (WMO, 1988) addresses Umkehr-derived trends, the SAGE version 5.5 displayed here is within 2% of the archived version 6.0.

This study treats each SAGE II profile within 1000 km and 12 hours of an Umkehr observation as a distinct case, often producing more than one case using the same Umkehr profile. After restricting the population to Umkehr stations with at least 9 SAGE II coincidences and eliminating a few cases with unreasonable values for one of the parameters, 1262 cases using 666 Umkehr profiles and 901 SAGE II profiles remained. The population included 17 Umkehr stations representing both hemispheres.

SAGE II percentage ozone differences by station

The layer-ozone differences between SAGE II and Umkehr at 17 individual Umkehr stations appear in Figures 1-4. Note the change of scale in Figure 4. The solid lines represent SAGE II-Umkehr ozone differences while the dashed lines, taken from Newchurch et al., [1987] represent SAGE I-Umkehr differences. All error bars indicate 95% confidence levels.

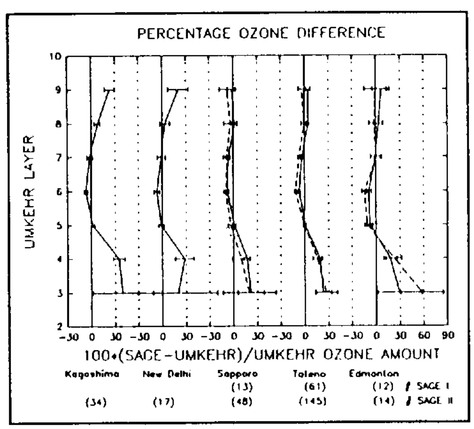

Figure 1. Percentage ozone difference between SAGE II and Umkehr (solid line) and between SAGE I and Umkehr (dashed line) at Kagoshima, New Delhi, Sapporo, Tateno, and Edmonton. First row numbers =number of SAGE I cases; second row = SAGE II cases.

The shape of the vertical profile of differences is generally consistent at all stations except at Poker Flat, Seoul, and Lauder where it is the mirror-image shape. Additionally, the excursions from zero are larger at those three stations compared to the other stations. Because the satellite measurement is not subject to average variation between measurement locations, differences between SAGE II and the

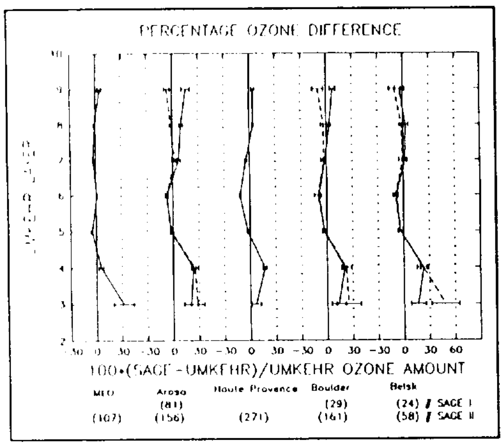

Figure 2. Same as figure one for MLO, Arosa, Haute Provence, Boulder, and Belsk.

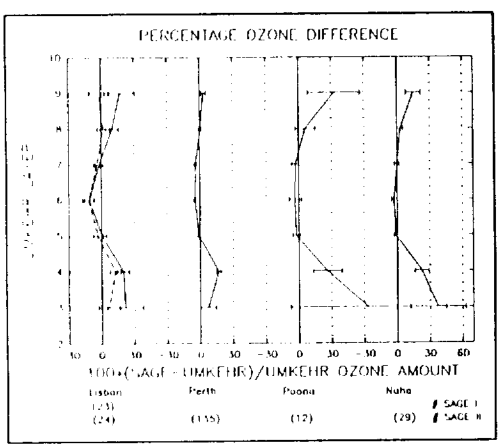

Figure 3. Same as figure one for Lisbon, Perth, Poona, and Naha.

Umkehr measurements must be attributed to differences in the Umkehr profiles. While a number of the difference profiles are quite similar, indicating a discrepancy that applies equally to all stations, a few stations mentioned above deviate considerably from the group and their profiles indicate a discrepancy that applies to an individual station. These individual-station discrepancies may be due to instrument calibration or to the a priori profiles used to initialize the Umkehr inversion algorithm.

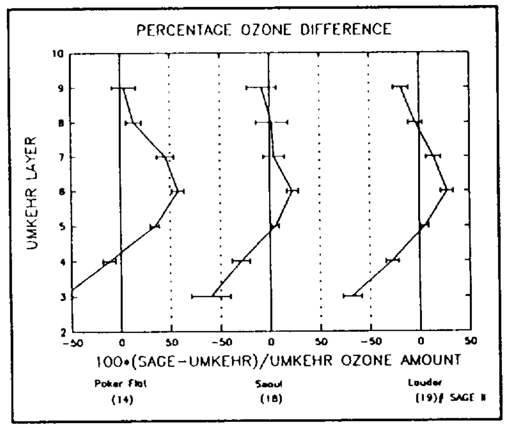

Figure 4. Same as figure one for Poker Flat, Seoul, and Lauder. Note the change of abscissa scale.

__Average Layer-ozone Differences__

Figure 5 portrays the average percentage ozone differences of all 1262 SAGE II cases for layers three through nine by the solid line.

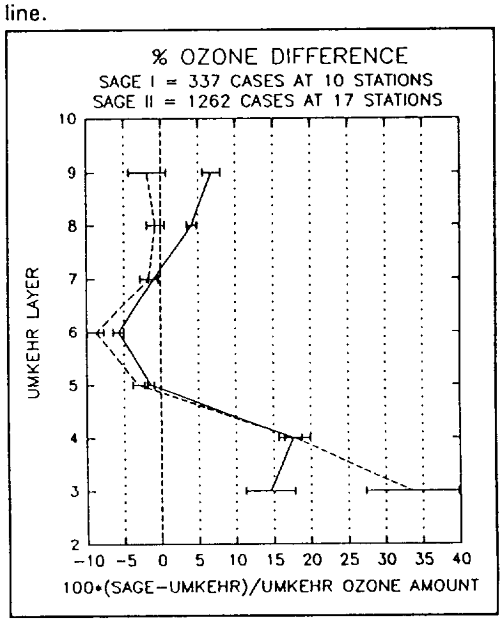

Figure 5. Percentage ozone difference between SAGE II and Umkehr (solid line) from this work and between SAGE I and Umkehr (dashed line) from Newchurch et al., [1987]. Error bars are 95% confidence intervals.

The dashed line indicates the SAGE I version 5.5-Umkehr average percentage ozone difference of 337 cases at 10 Umkehr stations taken from Newchurch et al. [1987]. In layer nine, Umkehr is 7% lower than SAGE II, on average, while Umkehr is 2% higher than SAGE I. The SAGE I-Umkehr and SAGE II-Umkehr differences are significantly different from each other at the 95% confidence level. The 5% disparity between the SAGE I-Umkehr and SAGE II-Umkehr in layer eight is consistent with the disparity between SAGE II-I trends and Umkehr trends reported in WMO [1988]. However, the disparity is less than 2% in layers four, five, six, and seven indicating that the disparity is a function of altitude and significant only in the upper two layers.

A small systematic error in reference altitude for SAGE I or SAGE II observations would change ozone concentrations in proportion to the gradient of the ozone profile. This potential error would produce the largest percentage ozone changes in layers eight and nine with changes of opposite sign below the ozone peak concentration (i.e., layer three). A 0.25 km reference altitude change would change ozone by approximately 5% in layers eight and nine. The procedures for obtaining reference altitude are different for SAGE I and SAGE II with somewhat more confidence in the SAGE II values. An explanation for at least part of the SAGE/Umkehr differences observed between the two satellites could be a reference altitude change of 0.25 km. For Arosa and Boulder comparisons, in particular, the layer-three differences are negative but of comparable magnitude to the layer-eight differences. Unfortunately, the site-to-site variability precludes our making any definitive conclusions based on this study. Independent confirmation of such an altitude shift will be sought in future investigations.

The SAGE I-Umkehr percentage ozone differences at seven individual stations taken from Newchurch et al. [1987] are shown together with the SAGE II-Umkehr differences in Figures 1-4. Three of the ten SAGE I stations used in the average contained fewer than six cases and were omitted from the individual station comparisons. At all seven stations in layer nine, the SAGE II mean is higher than the SAGE I mean relative to Umkehr; however, they are significantly different from each other at the 95% confidence level only at Arosa and Boulder. The same relationship occurs in layer eight, with two-sigma differences at Arosa and Tateno.

<u>Stratospheric Aerosol Optical Depth</u>

The stratospheric aerosol optical depth at wavelengths of 1.02, 0.525, 0.453, and 0.385 microns results from integrating the aerosol extinction values from 2 km above the reported tropopause to the top of the SAGE II profile. Because the sample of cases with acceptable 0.525-micron stratospheric aerosol optical depth values is significantly higher than the sample of cases with shorter wavelength optical depths, and because the correspondence between the 0.525 and 0.320 values is so close, we chose to use the 0.525-micron aerosol optical depth as the best estimate of the aerosol effect in the following stepwise regression analysis. The 0.525 micron aerosol optical depth ranged form 0.003 to 0.04 with a mean of 0.01 +/- 0.01 (2 SEM).

<u>Aerosol Effect</u>

Figure 6 displays the percentage ozone difference between SAGE II and Umkehr profiles as a function of stratospheric aerosol optical depth at 0.525 microns [-100*(SAGEII-Umkehr)/Umkehr per 0.01 stratospheric aerosol optical depth] averaged over all 17 stations. The abscissa is plotted as the negative of the SAGE II - Umkehr difference to be directly comparable to estimates of this aerosol effect found in the literature one of which is also plotted on Figure 6. Figures 7-10 describe the ozone percentage differences as a function of stratospheric aerosol optical depth at each of 17 individual stations. All error bars represent 95% confidence intervals.

Also shown in Figure 6 are circles, offset somewhat downward for clarity, representing the average aerosol effects and 2-sigma confidence intervals derived from using only the data at stations with more than 47 cases. The results of using those eight stations (Arosa, Belsk, Boulder, Haute Provence, MLO, Perth, Sapporo, and Tateno) are not significantly different from the 17-station results, although the means are somewhat closer to the

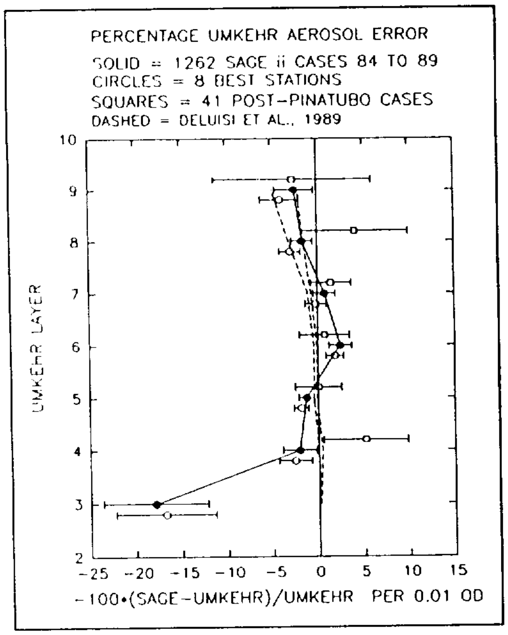

Figure 6. Percentage Umkehr aerosol error and 95% conficence intervals (solid line) averaged over 1262 cases at 17 stations from this work and 95% confidence intervals of aerosol error from DeLuisi et al., 1989 table 1 (dashed line). Means and 95% confidence intervals using the eight stations with more than 47 cases from this work appear as circles displaced somewhat downward for clarity. The squares represent 41 (+ /-28 hrs and 4000 km) post-Pinatubo cases.

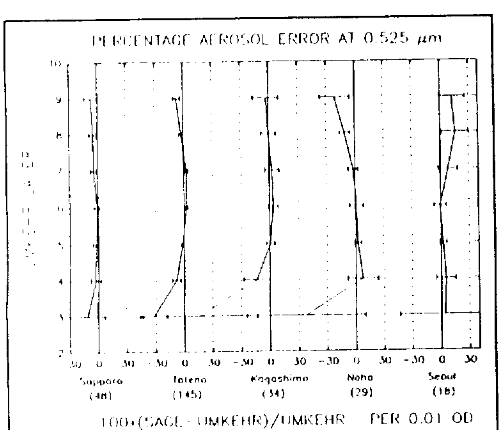

Figure 7. Results of a layer-by-layer regression (number of cases below station name) of 0.525 micron total stratospheric aerosol optical depth on SAGE II-Umkehr ozone differences as percentage ozone difference per 0.01 aerosol optical depth.

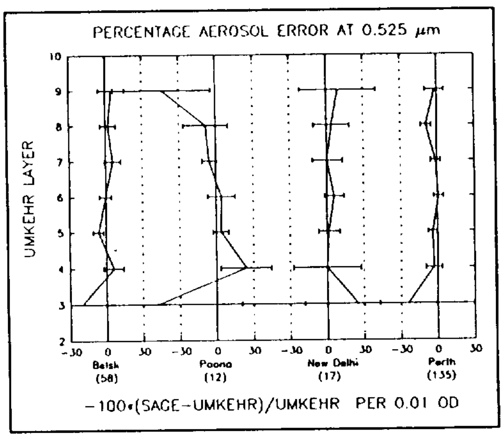

Figure 8. Same as figure seven for Belsk, Poona, New Delhi, and Perth.

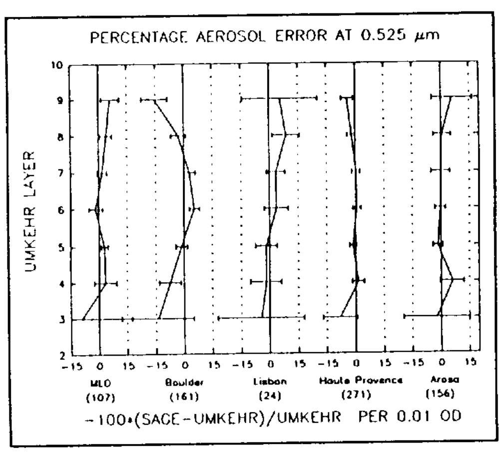

Figure 9. Same as figure seven, but for MLO, Boulder, Lisbon, Haute Provence, and Arosa. Note change of scale on absissa.

DeLuisi et al. [1989] results in the upper layers. The squares in Figure 6 result from 41 cases between July and October 1991 after the Mt. Pinatubo eruption. The stratospheric aerosol optical depth ranged from 0.008 to 0.08 with a mean of 0.04 +/- 0.004 (2 SEM). The time and space coincidence criteria for these 41 post-Pinatubo cases were relaxed to 28 hours and 4000 km because of the small amount of available data.

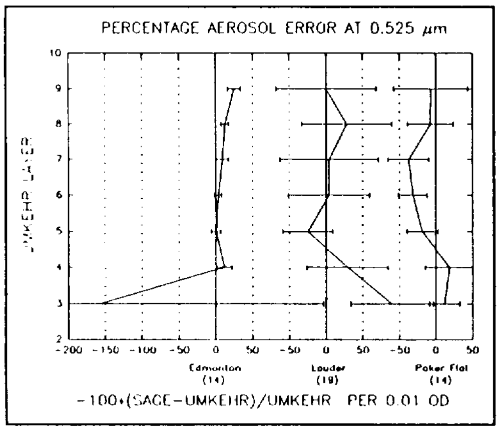

Figure 10. Same as figure seven except for Edmonton, Lauder, and Poker Flat. Note change of scale on abscissa.

The work of Reinsel et al. [1989] discusses two aerosol corrections to Umkehr data. Table five of that work lists the empirically-derived aerosol corrections and Figure 6 summarizes the theoretically-derived corrections. Both of these error estimates are similar to the results of DeLuisi et al. [1989] table one from which the aerosol errors applicable to December 1985 are extracted for use in Figure 6 of this study. The results from both the DeLuisi et al. [1989] work and this study agree within their respective error bounds in layers nine, eight, and five. Their two sigma error limits nearly overlap in layers seven, and four. The results in layers six and three differ significantly.

Figures 7-10 contain the percentage aerosol effect per 0.01 total stratospheric aerosol optical depth at each of the 17 individual Umkehr stations. Among the individual stations in layer nine, the upper layer predicted to be most susceptible to aerosol errors [DeLuisi, et al., 1989], the effect is almost equally divided between negative and positive results on the order of +/- 10 to 20% except at Poona where it is -44%.

Because the intra-layer SAGE II ozone/aerosol correlation is 0.3 in layers eight and nine, not all of the SAGE II-Umkehr ozone difference is attributable to an aerosol effect. Additionally, as discussed in Newchurch and Cunnold [1992], SAGE II and Umkehr produce different ozone retrievals in layers eight and nine. These relationships suggest the need for further study to fully resolve this question.

Conclusions

A case study of 1262 comparisons between SAGE II and Umkehr ozone using 666 Umkehr profiles and 901 SAGE II profiles within 1000 km and 12 hours representing 17 Umkehr stations reveals that the average layer-ozone differences are 15% in layer three, 18% in layer four and less than 7% in layers five, six, seven, eight, and nine. The differences are significantly different from zero at the two-sigma level in all layers except four and seven. At most stations, Umkehr is less than SAGE II in the upper and lower layers and is higher than SAGE II in the middle layers. The vertical profile of mean differences is similar in shape to previously observed Umkehr differences [DeLuisi et al., 1985, 1989] and to the shape of eigenvector three reported by Mateer [1965]. At three stations -- Poker Flat, Seoul, and Lauder -- the differences occur in a direction opposite to the average.

The larger negative ozone trend over the period 1979 to 1986 indicated by Umkehr measurements in layer eight is reflected in the result that the average SAGE II-Umkehr layer-ozone difference is 5% greater than the average SAGE I-Umkehr layer-ozone difference. This result is consistent with the disparity between SAGE II-I trends and Umkehr trends in layer eight reported in WMO [1988]. The difference between SAGE II-Umkehr and SAGE I-Umkehr is even larger, 9%, in layer nine. In layers four, five, six, and seven the average layer-ozone differences between SAGE II-Umkehr and SAGE I-Umkehr are less than 3%; however, they are significantly different from each other at the two-sigma level in layers five and six. Layer three is the only layer in which SAGE II-Umkehr average ozone difference is less than SAGE I-Umkehr layer ozone and the 19% difference is the largest of all the layers. Because layer three is difficult for the Umkehr technique to measure, the layer-three differences between SAGE II-Umkehr and SAGE I-Umkehr are not as relevant as the differences in layer eight where both systems should be operating near their optimum efficiency. At least part of the explanation of these differences might be a systematic shift in reference height of approximately 0.25 km between SAGE I and SAGE II; however, because of the site-to-site differences in the Umkehr comparisons and a lack of independent information available in this study, independent confirmation of such a difference is needed.

Using SAGE II stratospheric aerosol measurements to determine the aerosol error in Umkehr profiles indicate errors of approximately -2 to -3% in layers nine, eight, five, and four; 0% in layer seven; +2% in layer 6; and -18% in layer 3. While the layer-three result is suspect because of widely scattered data and site-to-site differences, the results in other layers reflect higher confidence. Using only those eight stations with more than 47 coincidences (Arosa, Belsk, Boulder, Haute Provence, MLO, Perth, Sapporo, and Tateno) results in mean aerosol effects that are closer to the results of other researchers, but are not significantly different from the 17-station results. A possible reason for the positive aerosol effect in layer six is that the differences between SAGE and Umkehr ozone possess a characteristic shape (like eigenvector three [Newchurch and Cunnold, 1992; Mateer, 1965]). Therefore, a true negative effect in layers eight and nine will quite likely produce a small positive effect in layer six. Because of the non-zero intra-layer SAGE II ozone/aerosol correlation in layers eight and nine and, also, because of the differences in SAGE II and Umkehr ozone retrievals, further study is needed to fully resolve the aerosol effect in the upper layers.

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