5.8 QUANTIFYING PRECIPITATION REDUCTION DUE TO AIR POLLUTION DOWNWIND OF MAJOR URBAN AREAS

Amir Givati and Daniel Rosenfeld
The Hebrew University of Jerusalem, Jerusalem, Israel

1. INTRODUCTION

Previous studies had showed qualitatively that urban and industrial air pollution suppresses the cloud drop coalescence and so reduces the precipitation from the Polluted clouds (Rosenfeld, 2000). Here we present the first study that attempts to quantify these effects based on time series of rain gauge data during the last century, on comparison with air pollution emissions records and on an independent precipitation predictor based on upper air data from radiosonde.

2. BACKGROUND

The most vulnerable areas for the suppression effects are hills downwind of coastal cities, which receive most of their precipitation from micro physically maritime convective clouds forming in air that flows from sea inland. The urban polluted air ascends over the topographic barrier and gets incorporated in the clouds that are generated over the hills. The urban aerosols have already been shown to serve as small CCN that suppress the precipitation by forming large concentrations of small cloud droplets. This in turn suppresses the coalescence and the warm rain processes, as well as the ice precipitation (Rosenfeld, 2000). This effect is mostly pronounced in short living and shallow clouds, but also deep convective clouds can be affected (Rosenfeld and Woodley, 2003, Khain et al., 2001).

Clouds that form in winter storms across orographic barriers can be short living and not very deep, rendering them sensitive to these precipitation suppression effects of upwind urban air pollution sources. Therefore, we expect that the orographic enhancement of rainfall downwind of a major city would decrease with the growth of the city and its air pollution. We further expect that the orographic enhancement factor side wind in a rural area would not change with the years. Measuring the relative trends between the urban and pristine orographic rainfall should provide an estimate of the magnitude of the impact of the growth of the city on the rainfall. We selected as study areas California and Israel. In both places most of the rainfall occurs with flow from the sea inland, over major coastal cities and inland over hills.

The analysis was done according to the following principles: We selected pairs of mountain / coast rain stations, with large orographic enhancement factor and high correlations of the rainfall between the two stations. The high correlation is required for using the coastal station to predict the “natural” rainfall in the hilly station. The large orographic factor indicates that much of the rainfall is generated by the orographic uplift of the air that flows through the upwind coastal station. The high correlation is also essential for assuring that the mountain station that was selected is indeed downwind to the costal station.

The data points were the annual rainfall in a station. For each pair of stations the trend of the yearly average ratio between the mountains and the coast was tested. This was done for both urban and rural pairs of rain stations. The nearby rural side wind coast-hill ratios were used as control areas for the precipitation trend analysis of the urban pairs.

3. THE STUDY AREA AND DATA COLLECTION

The urban areas in California, especially in Los Angeles County, experienced rapid and huge human and industrial development in the 20th century witch caused a significant air pollution problem. Similar process, but in smaller scale, accrued in the last 50 years also in Tel Aviv metropolitan area. According to the above physical principles the study was held in San Diego, Los Angeles and San Francisco metropolitan coastal areas and the mountain ranges that are Located downwind of them, and in Tel Aviv metropolitan and Judea and Samaria hills.

Corresponding author address:
Amir Givati, Earth Sciences, Hebrew Univ. of Jerusalem, Jerusalem, Israel , 91904
Email : givati@vms.huji.ac.il

3.1. *Time series of mountains /coast*

Fifteen pairs of rain gauge stations where selected from mountains and coastal metropolitan areas in California. Several pairs had time series of over 100 years, and the rest contains yearly rain data since 1945. In order to avoid bias caused by relying on one station, groups of stations that represent each geographical area (coast and mountains) were assembled, and the average ratio between them was calculated. The grouping was done on stations that were operative the whole period. The stations in each region (hill or coast) where highly correlated between themselves, and with the group in the other geographical region.

In order to test the trends between coast and mountain stations, there was a need to learn about the tendency in the transition zones between the coast and the mountains, which is the foothills area. Those areas are downwind from the coast and the pollution sources, but yet do not enjoy the orographic enhancement. Pairs of stations from those regions where selected both in California and Israel.

Groups of 7 mountain and 16 coastal stations where chosen from unpolluted, “clean” areas, from the counties of Ventura, Monterey and Santa Barbara in order to be used as control area to the pollutes metropolitan areas.

In Israel the ratio of hill to coast stations from polluted area was tested since 1945 in two areas. A group of 7 hill stations from the Samaria hills and 8 stations from the Tel Aviv coast area, and 8 hill stations from the Judea hills and 6 stations from the internal coast area.

Group of 3 mountain station from the Hebron mountains and 3 coast stations from the south coast area where chosen in order to be used as control area.

3.2. *Emissions data*

The major products of urban and industrial air pollution are SO_2 and NO_2 emissions. In addition to the fact that they produce aerosols in the atmosphere, those gases are also play a role in the formation of ozone and particulate matters (EPA , 2002).

Daily emissions inventories of SO_2 and NO_2 where collected from 3 monitoring stations that have been operating in Los Angeles county since 1963. The trends of the emissions values where compared to the trends of the mountain / coast rainfall ratio.

3.3. *The radiosonde model*

Changes in the orographic factor along decades can occur not only as a response to human activity but also due to natural process such as changes in the atmospheric circulation. In order to separate and identify these two potential causes to the changes in the orographic enhancement factor, a model that predicts the natural rain in the mountain was needed. It is commonly known that moist flow ascending a mountain barrier will enhance precipitation along the windward slop of the barrier. The amount of precipitation that falls is related to the magnitude of the upslope flow impinging upon windward mountain slopes. Pervious observational studies have shown a dependence of orographic precipitation on the upslope component of the flow (Collier 1975; Bell 1978; Sinclair 1994). Alpert and Shafir (1989,1991) have shown that orographic component of the rain in Israel can be explained by a model that takes into account the slope of the terrain, the component of the wind in the direction of the slope, and the relative humidity of the air near the surface.

Pandey et al.(1999) estimated precipitation in the Sirra Nevada, California, as a function of moisture transport from the south-westly winds toward the mountains, while Neiman et al. (2002) provided statistical links between hourly meseared rainfall rates in California coastal mountains to hourly averaged upslope component of the wind flow.

We applied the radiosonde model of Rosenfeld and Farbstein (1992) to predict the daily rain amounts in mountains. A multiple regression was calculated in which the daily rain in the coast and the wind component at 850 mb (speed and direction) across the mountains, multiplied by the 850 mb absolute humidity were the predictors, and the daily rainfall in the mountains on days with rain at the coast was the depended variable :

$$\mathbf{RMM = RCM\ (WS*W)}$$

Where:

RMM is the predicted precipitations In the mountains from the model

RCM is the gauged precipitations In the coast

WS is the wind speed component toward the mountain azimuth

W is the absolute humidity

4. RESULTS

4.1. ***Trends in orographic factor***

The results from California shows significant decrease, up to 25% , in the ratio between the mountain and coastal stations along the years. All the mountain/coast pairs in San Diego, Los Angeles and San Francisco metropolitan areas had the same trends – decrease in the ratio along the years, with the sharpest decrease between the 1940's to the 1970's.

From the 120 years record since 1880 it can be seen that while in San Diego and San Francisco areas there were hardly changes in the ratio until the beginning of the century (around 1910), in Los Angeles areas the ratio already decreased in those years (fig. 1). This fit with the fact that the smog appeared in Los Angeles already in 1903.(South coast air quality management district, 1997).

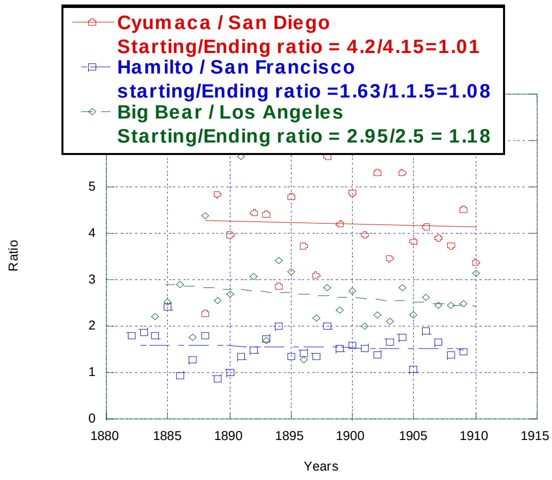


Fig.1 : Ratio between mountain and coast stations in California between 1880-1910.

4.1.1 San Diego area

Fig. 2 shows the decrease in the ratio between the mountain station of Cuyamaca, witch is the highest and rainy point in the mountain range that located west from San Diego, to the coast station in San Diego. A decrease by a factor of 1.33 was noted, significant at the 0.0003 level, where 0.05 is considered already statistically significant.

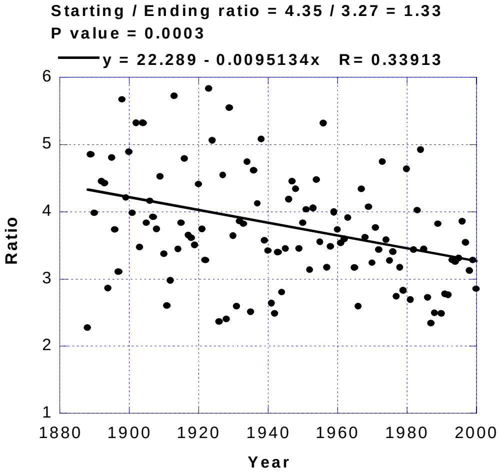


Fig.2: Ratio of the annual rainfall in Cuyamaca (32.980N, 116.580W, El 4650', Yearly average 940 mm) over San Diego (32.730N, 117.180W, El 13', Yearly average 257 mm). The correlation between the two stations is 0.81

4.1.2 Los Angeles area

Figure 3 and 4 shows the decrease in the orographic factor between group of 8 pairs of mountain and coast stations in Los Angeles county, and group of 8 station in the Judea against mountains against group of 6 stations in the upwind internal coast.

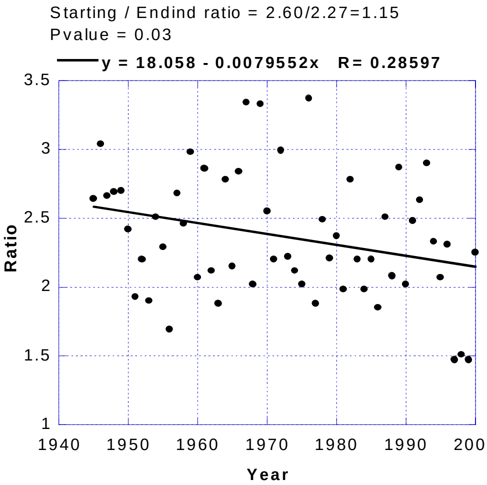
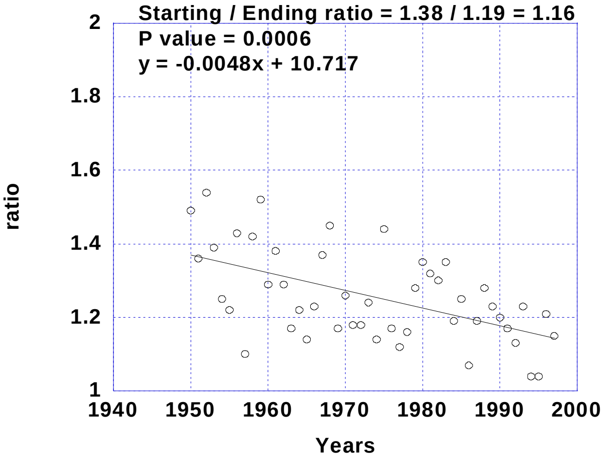


Fig. 3: Ratio of the annual rainfall between averages of 8 mountains (Lake Arrowhead, Crystal, Big Bear L. Dam, Sierra PH, Big Pines, Sawmill Mtn, Fairmont Res and Opids) and 8 coast stations (Los Angeles CC, ontebello, Downey, Whittier, Long Beach AP, Los Angeles AP and Newport Beach Harbor).

Yearly average for the mountain stations is 771 mm and 345 mm for the coast stations. Correlation Between the mountains, coast stations is 0.91.



4.1.3. Judea hills and the central coast

Fig. 4: Ratio of the annual rainfall between averages of 8 mountains (Kieryat Anavim, Maale Hachamisha, Shoresh, Zova, Biet Meir, Bido, Bitonia and Ramalla) and 6 coast stations (Nacshon, Hulda, Zora, Yesodot, Mishmar David and Tel Shahar). Yearly average for the mountain stations is 648 mm and 521 mm for the coast stations. Correlation Between the mountains, coast stations is 0.96.

4.1.4 The transition zones

The ratio between the coast stations of Los Angeles and Santa Monica and the foothill station of San Bernandino shows that no change occurred in the ratio between them. The same results where found between the coast station of Ashdod to foothills stations in of Judea and Samaria mountains in Israel.

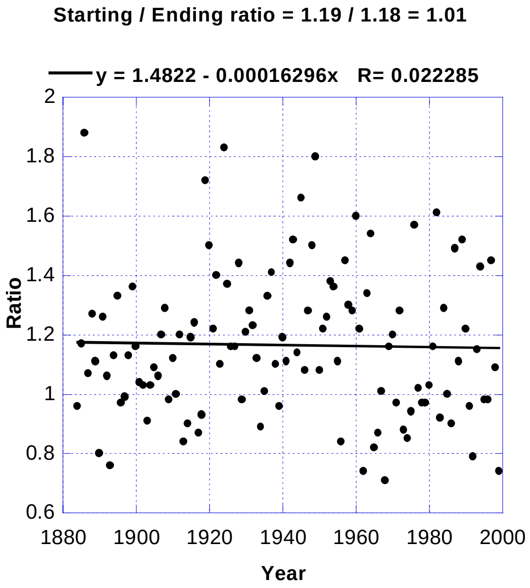


Fig. 5: Ratio of the annual rainfall between San Bernandino station (1050f, 431mm) to coast stations in Los Angeles (417f, 381mm) and Santa Monica (64f, 373 mm). Correlation Between San Bernandino and the coast stations is 0.87.

4.1.5 The ratio in Unpolluted areas

In contrast with the tendency in the polluted areas, no trend was found in the “clean”, side wind areas in California and in Israel which are used as control areas. The ratio between the group of mountain stations to the coast stations remains stable along the years.

Figures 5 and 6 show that the mountain / coast ratio in the unpolluted areas in Monterey, Ventura and Santa Barbara counties in California and in the Hebron Mountains, Israel, stayed stable along the years.

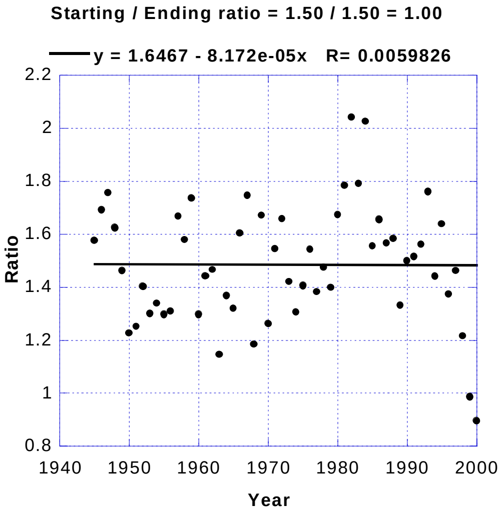


Fig.6: The ratio between 7 mountain stations (Fillmore Sespe, Pine Mtn Inn, Graham , Orcutt Ranch, Priest Valley, San Marcos and So Porta) and 16 coast stations (Santa Ynez , Lompoc , Los Alamos, Moorepark, San Ardo, Casitas Dam, Ventura, Buellton, Montecito, Kingston Res, Santa Paula, Santa Rosa Valley, Forest Lake, Limoneria, Monterey and Filmore) in Monterey ,Ventura and Santa Barbara counties. Yearly average for the mountain stations is 628 mm and 402 mm for the coast stations. Correlation Between the mountains, coast stations is 0.96. The orographic factor remain 1.6 since 1945 until today.

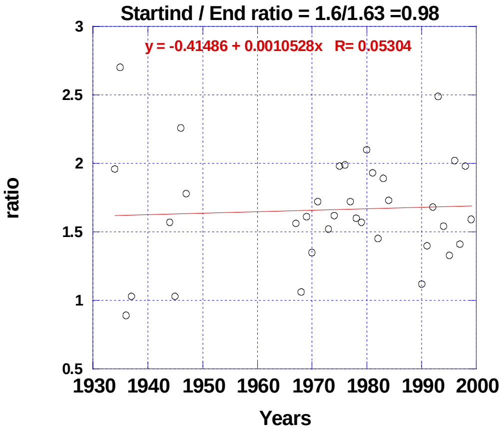


Fig. 7: The ratio in unpolluted areas in Israel. ratio between the mountain station of Hebron to the internal coast station of Ruhama and Dorot.

4.2. *Emission trends and the orographic factor*

4.2.1 Emission values

The yearly average emissions values of SO_2 and NO_2 in Los Angeles County increased since the 1950's and peaked at the beginning of the 1970's. Since Those years there was a turning point in the trend and a sharp decrease in the values accord due to the "clean air laws" that where legislated in the state of California.

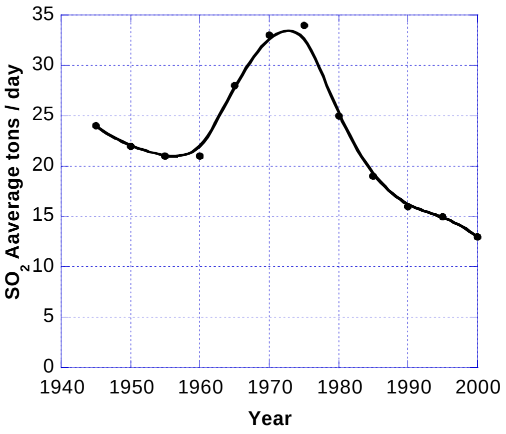


Fig. 8: Calculated and estimated SO_2 emissions inventories in Los Angeles county.
Source: California Air Resource Board

4.2.2 Comparison between trends of emission and rainfall

Measured emissions inventories from monitoring stations are available in California since 1963, when monitoring stations started to operate. Figure 9 shows the emission trends for SO_2 and NO_2 since 1963 in Los Angeles county, together with groups of mountain / coast ratio from the county, at the same years. It can be seen that in this period the emissions decreased sharply, but the ratio decreasing that was presented before (fig. 3) stopped and even tend to increase slightly. The correlation between the emission value to the ratio was found to be negative of
– 0.30.

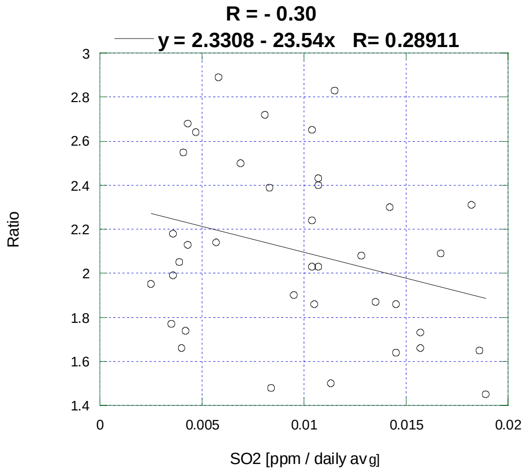


Fig.9: Negative correlation between SO_2 emission values and the mountain coast ratio between 1963 – 2000.

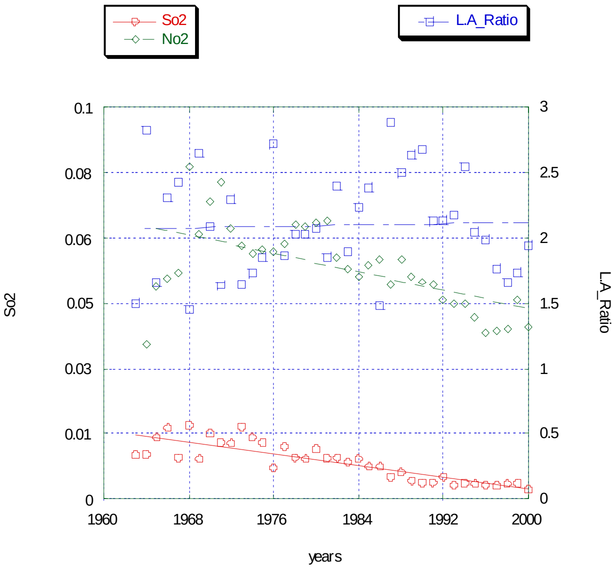


Fig. 10 : Decrease in SO_2 and NO_2 emission values and recovery of the mountain / coast station ratio.

It can be viewed in fig. 10 that the last 4 points that represents the ratio for the years 1996-2000 decrease again, despite the fact that the emission values did not increase. Possible explanation for the decreasing can be related to the fact that in the last few years PM 2.5 aerosols increased in the Los Angeles (ARB,2002), but direct measurement are available only since 1999 since the PM 2.5 network was established in California.

4.3 ***The radiosonde model***

Table 1 describes the model results. It shows the correlation between the predicted yearly daily average rain in the mountains (that where calculated by the model) and the yearly daily average precipitations gauged at mountains.

Fig.11 shows the ratio between the predicted rain and the measured rain in San Diego (Cuymaca) and Los Angeles areas (Lake Arrowhead). For both areas a decrease was inscribed in the ratio between the measured daily rain and the predicted daily rain. The predicted values represents the natural rain for the mountains so a decrease in the ratio means that something else, witch is not related to natural conditions caused the reduction in the ratio the rain in the mountains (The wind component across the mountains multiplied by the absolute humidity didn't change along the years).

The model includes just rainy days with full radiosonde record. There are missing days that where not included.

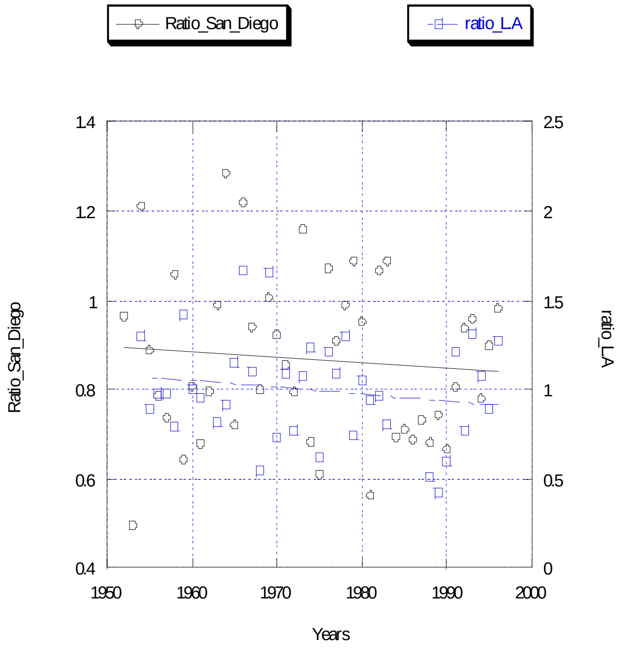


Fig. 11: The ratio between measured daily precipitations at Cyumaca and Lake Arrowhead, on days with rain in the coast, to the predicted daily precipitations. Each point is the ratio of the yearly average of the daily rainfalls at the two stations.

Model area	***N***	***Starting/end rain ratio***	***R***
San Diego	1825	0.9/0.8 = -1.12	0.80
Los Angeles	515	1.10/0.92 = -1.18	0.75
Monterey	2036	1/1.11=+1.01	0.86

Table 1: correlation between the predicted yearly average of the daily rainfalls to the measured yearly average of the daily rainfalls in the polluted areas of San Diego and Los Angeles, and in the clean areas of Monterey county.

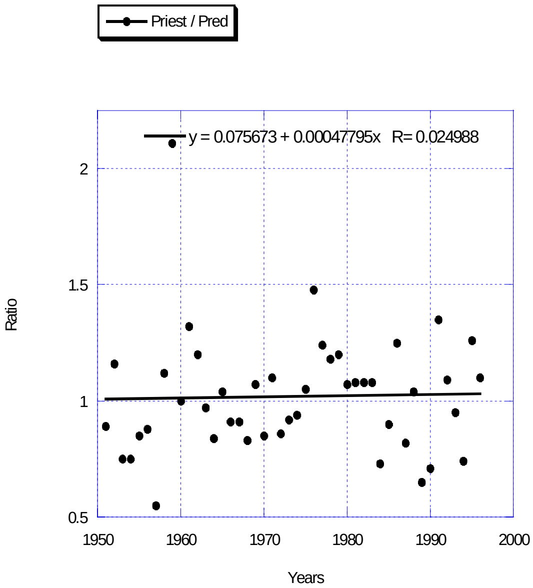


Fig 12 :ratio between the predicted rain and the measured rain in unpolluted area in Santa Barbara and Monterey counties. Unlike the polluted area of San Diego and Los Angeles, here no decrease *accrued between the measured daily rain and the predicted daily rain.*

5. CONCLUSIONS

All time series of rain gauges data that were tested from metropolitan areas in California show a decrease in the ratio between the mountain and coastal stations along the years. Similar trends founded also in Israel.

Since 1970 a sharp decrease started in the emission value of SO_2 and NO_2 and the ratio started to recover.

On the other hand, in the control areas, where the emission values are negligible, no change at all in the orographic enhancement factor was detected, both in California and in Israel.

However, while In Los Angeles and San Francisco areas the ratio start to increase since the 80th the San Diego / Cuyamaca (fig.1) is still falling. This trend in San Diego mountains can be explain by the fact that the Mexican city of Tichuana, which it's population reached to 10 millions, keeps contributing increasing levels of air pollution, that with the prevailing surface south-west wind on rainy days reaches to the mountains.

Based on the soundings analyses, no evidences where found that can explain natural trends in the orographic enhancement factor in California. This is still not checked in Israel. The radiosonde model predicted for the mountain that are being located downwind to pollution sources more rainfall than it was actually measured. The likely explanation to the decreasing orographic rainfall is the air pollution.

According to that we can say that due to the air pollution effects on the orographic rain, We lost around 15% rain in the mountains since 1945, which equal to 115 mm/year in the California mountains and 105 mm/year in the Judea and Samaria hills**.**

6. REFERENCES

Alpert P. and H. Shafir, 1989 :Meso- scale distribution of orographic precipitation: numerical study and comparison with precipitation derived from radar measurements. *J. Appl. Meteor*., 1105-1117.

Alpert P. and H. Shafir, 1991: On the role of the wind vector interaction with high-resolution topography in orographic rainfall modeling. *Quart. J.R.Meteor. Soc*., 117, 421-426.

Collier. C.G., 1975 : A representation of the effects of topography on surface rainfall within moving baroclinic disturbance. *Quart. J.R.Meteor. Soc*., **101**, 407-422.

Khain A. P., D. Rosenfeld and A. Pokrovsky, 2001: Simulation of deep convective clouds with convective clouds with sustained supercooled liquid water down to – 37.5 using a spectral microphysics model. *J. Geophys. Res. Lett*. **28,** 3887

Neiman J.N ., Ralph P.J., White A.B., Kingsmill D.E., Persson P.O.G., 2002: The statistical relationship between upslope flow and rainfall in California's coastal mountains:observations during CALJET. *AMS*. **130,** 1468-1492.

Pandey G.R., Cayan D.R and Georgaakakos K.P., 1999 : Precipitation structure in the Sierra Nevada of California during winter.*J. Geophys. Res*. **104**, 12 019-12 030.

Rosenfeld D., 2000: Suppression of rain and snow by urban air pollution. *Science* **287**, 1793-1796.

Rosenfeld D., Woodley W.L., Lahav.R and Khain.A.P,2003: On Natural and Artificial Hygroscopic Cloud Seeding. On review at*. J. Appl. Meteor.*

Rosenfeld D., and H. Farbstein, 1992: Possible influence of desert dust on seedability of clouds in Israel. *J. Appl. Meteor,* **31***,* 722-731*.*

The 2002 California Almanac of missions and Air Quality, Current Quality, Chapter 2. http://www.arb.ca.gov/aqd/almanac/almanac02/pdf/chap202.pdf

SO_2: What is it? Where does it come from? http://www.epa.gov/air/urbanair/so2/what1.html

The southland's war on smog: Fifty years of progress toward clean air, http://www.aqmd.gov/news1/marchcov.html