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The solar Resource Assessment in Mexico: State of the Art

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Abstract

In the mid 70's of the last century, the first attempts were initiated in order to know precisely the Solar Climatology of Mexico. For this, data from heliographs and actinographs were used. Latter, in the 90's models based on the use of satellite images were employed. Currently a number of maps and databases describing spatially and temporally the solar resource distribution in the country can be found on the Internet, but in none of them confidence intervals of data are provided. This is due to a simple reason: historically there were only a handful of weather stations in the country that measured solar radiation over a long period of time. In the last two decades several automatic weather station networks have been established, which include radiometers. However, only very recently the radiometers from these stations have started to be systematically calibrated, and assessment of the quality of the previously measured data initiated.

Keywords: Solar Energy Assessment; Solarimetric Network; Solarimetric Database

1. Introduction

The evaluation of solar radiation in Mexico was started by Dr. Ladislao Gorcziñsky, who carried out measurements at different locations between 1911 and 1917 [1, 2]. A few years later, between 1923 and 1928, the *Servicio Meteorológico Nacional* (SMN; National Weather Service) continued this work at the Astronomical Observatory of Tacubaya, under the direction of Dr. Gorcziñsky. The results of these measurements were published in several reports, some of which still exist in the archives of the SMN, although others have been lost..

In 1957, with occasion of the International Geophysical Year, the Institute of Applied Science and the Institute of Geophysics, both from Universidad Nacional Autónoma de México (UNAM; National Autonomous University of Mexico) resumed the task. Five solarimetric stations were installed in: Ciudad

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Universitaria (UNAM main campus in Mexico City), Distrito Federal; Altzomoni, Estado de Mexico; San Cristobal de las Casas, Chiapas; Veracruz, Veracruz; and Chihuahua, Chihuahua. In 1959 the Altzomoni station was moved to Tlamacas, Estado de Mexico. Also, in 1960 a station was installed in the city of San Luis Potosi. Of these original stations, only two operated for a long time period: Chihuahua, for fifteen years, and Ciudad Universitaria, which is still in operation. Since December 1967, the Institute of Geophysics of the UNAM began operating a station in Orizabita, Hidalgo, which also continues in operation to date. Other attempts to install stations in other places have been unsuccessful. Therefore, the only long term historical data available for Mexico in the World Radiation Database (WRDB) is that from the three stations Ciudad Universitaria, Chihuahua, and Orizabita.

Several government agencies have installed weather station networks in the country, some of which have had solar radiation sensors:

- The main involved agency has been SMN, which currently belongs to the *Comisión Nacional del Agua* (CONAGUA; National Water Commission). In the 70s, the SMN installed bimetallic piranographs and heliographs in about 60 weather stations of its network. However, the piranographs were not systematically recalibrated and the information was not processed.
- In the 80s, The *Comisión Federal de Electricidad* (CFE; Federal Electricity Commission) created a Solarimetric network with about 20 stations equipped with piranographs, located in hydrological basins. This network did not have calibration or information processing programs. In recent years CFE set up 6 stations with modern equipment. It is not known if solar radiation sensors are kept calibrated.
- In the first decade of XXI century, the SMN installed a network with 133 automatic weather stations (EMAS), with real-time transmission of data every 10 minutes; these stations have a pyranometer to measure horizontal global solar radiation.

2. Current solarimetric networks

Currently, solarimetric networks that belong to government agencies are:

- The SMN operates a network of 187 automatic stations (http://smn.cna.gob.mx/-productos/emas/emas.html), measuring global solar irradiance with at least good quality pyranometers according to World Meteorological Organization (WMO) [3]. More than half of these pyranometers have already achieved the age of 5 to 10 years depending on the site they were installed. Although they were factory calibrated, a program for recalibration has not been followed subsequently. This network has a quite broad coverage of the national territory, even though it was designed taking into account only hydrological criteria, leaving aside other relating to land use, topography, and the different climates that exist in the country.
- The CFE continues operating the above mentioned network of about 20 pyranographs and 6 pyranometers, also without recalibration.
- The *Secretaría de Marina* (the Mexican Navy) has a network of about 10 pyranographs and 10 heliographs. It has also installed 22 automatic weather stations with pyranometers. However, the collected information is not public.
- The *Secretaría del Medio Ambiente del Distrito Federal* (Mexico City´s Environmental Secretariat), through the Automated Environmental Monitoring Network (RAMA), has 3 referenced pyranometers. This network also makes measurements of solar UV radiation in 7 of its stations and photosynthetically active radiation in 2 of them. (http://www.sma.df.gob.mx/simat/pnrama2.htm)
- The *Instituto de Investigaciones Eléctricas* (IIE; Electrical Research Institute), through a CONACYT research grant, installed between 2008 and 2010, a network with more than 10 stations for solar and

wind resource assessment, which include pyranometers for measuring global horizontal solar radiation. However, data from these stations is not widely accessible.

- The *Instituto Nacional de Investigaciones Forestales, Agropecuarias y Pecuarias* (INIFAP; National Institute for Forestry, Agriculture and Livestock) has a network of about 993 weather stations and most of them have a global radiation pyranometer in operation. These data have been used for local solar resource assessment; however, solarimetric data from these stations is not easily accessible. (http://clima.inifap.gob.mx/redinifap).

Several universities have measured solar radiation specifically for the solar energy resource assessment, for instance, UNAM's Renewable Energy Institute, since 1990 [4], the Energy Group at the University of Sonora, from 1993 to 2001[5], and the Laboratory for Energy and Environment of the department of Architecture and Design of the University of Sonora. Other institutions which have been involved in such measurements at different periods were: the *Universidad Autónoma de Yucatán*, the *Universidad de Colima*, the *Universidad Autónoma de Baja California*, the *Instituto Politécnico Nacional*, the *Universidad Veracruzana*, the *Univeridad de Zacatecas*, and more recently the Graduate School of Architecture of the UNAM.

Under the project "Calibration of a national network of solar radiation sensors and its database (recovery, validation and calibration of 133 stations)", with financial support from CONACYT, the pyranometers from each of the EMAS stations from the SMN, are being replaced [6]. The removed sensors will be recalibrated and will be reinstalled after a year of its substitution. The project's goal is to have reliable data on 133 points in the country for a period of 4-5 years.

This year, the installation of a network of 10 pyranometers will be started in the basin of Mexico, for solar resource assessment of Mexico City and its surroundings. The project is financed by the *Instituto de Ciencia y Tecnología del Distrito Federal* (Mexico City´s Council for Science and Technology).

Figure 1. Location of EMAS from the SMN in Mexico.

3. Solarimetric Database for Mexico

The World Solar Radiation Data Center (WRDC), located St. Petersburg, Russia, serves as central repository for data of solar radiation measured in over a thousand sites around the world. It was established in 1964, by a resolution of the World Meteorological Organization (WMO). Its aim is to centralize and publish the world's solar radiometric information, to ensure the availability of such information to the international scientific community. From all information stored in the WRDC, now you can get on their website data from the years 1964 to date. (http://wrdc-mgo.nrel.gov/, maintained by the National Renewable Energy Laboratory of the U.S., NREL)

In the case of Mexico in the WRDC website, there is information from three measurement points: Ciudad Universitaria, Mexico, DF (1967-2012); Chihuahua, Chih. (1967-1976); and Orizabita, Hidalgo. (1968-2004).

As mentioned previously, the SMN operates a network of 187 stations that measure global solar radiation. Data from the last 90 days can be consulted on the website of SMN, in the form of daily global solar irradiance. For longer-term data is necessary to communicate directly with the staff of the SMN. (http://smn.cna.gob.mx/productos/emas/emas.html)

Some universities in the country have made public on the Internet, their information on solar radiation; e.g., Solar Radiation Observatory IGF-UNAM, with data for Ciudad Universitaria, in Mexico City, and Orizabita, Hidalgo. (http://www.geofisica.unam.mx/ors/ors-red.html) and the Renewable Energy Institute, UNAM (http://xml.cie.unam.mx/xml/se/cs/ meteo.xml).

Currently there is an ongoing project in the IGF-UNAM for the development of models of solar radiation in the Mexico from data generated by the SMN. An analysis of the SMN data was made last year [7], and currently those stations that passed the first analysis filters are being processed to assess their validity.

4. Solar radiation estimated from models

Several maps and tables of solar radiation to Mexico have been published by different authors. As relatively few measured data have been available for the preparation of these maps, all of them are based on estimating methods of different types, with presumably high uncertainties.

In 1975 Almanza and Lopez [8] obtained the first monthly solar radiation maps in the form o isolines of daily irradiation. Insolation was estimated from sunshine data of 38 sites, covering periods of 10-30 years. For that work the model from Reddy was used [9]. Almanza, Estrada-Cajigal and Barrientos [10] conducted in 1992 an update of the irradiance maps, by using meteorological data collected from 1941-1980 in 54 locations. The results were isolines presented for each month of the year and the year average (Figure 2).

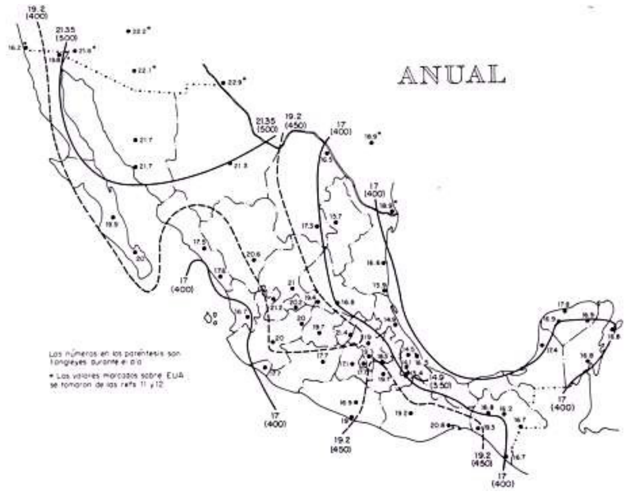

Figure 2. Contourlines of the average annual insolation for Mexico, in MJ / m² / day; taken from [10].

The works of Galindo and Valdes [11], in 1992, and Cifuentes, Galindo, Estrada, and Nava [12], in 1996, used data from the VISSR radiometers, with a detection range between 550 and 750 nm wavelength, mounted on board of the geostationary satellites SMS-2 and GOES-2. The files used consisted of seven daily images, with a one degree resolution in latitude and longitude, wich were translated into irradiance values according to the Tarpley method, modified by Galindo et al in 1991 [13]. The modification of the correlation coefficients of the model was done by comparing with the measured data in Ciudad Universitaria (CU), Mexico, D. F., by the Institute of Geophysics of the UNAM, in the year 1984. With this method isoline maps were generated for monthly averaged daily irradiation [11], as illustrated in Figure 2, and tables of this parameter were given for each month for every state capital in the country [12].

As is apparent from examination of the examples shown in Figs. 2 and 3, it is possible to find large differences between irradiation estimates by different authors. Renné et al. [14] made a comparison of the different results available in the literature as for year 2000 and found that the differences between them were as high as 20%. In particular the works of Galindo & Valdes [11], Hernandez et al. [15], Almanza et al. [10], Galindo & Chavez [16] were compared.

Figure 3. Contour lines of the average annual insolation for Mexico, in MJ / m² / day. Colors represent the altitude above sea level at the surface. Adapted from [11].

The big differences that can be seen in the results from different authors are attributable to the empirical nature of the method used, but also to the lack of surface measurement sites to calibrate the models. For instance, in the works of Almanza et al. [10] and Galindo & Valdes [11], the model was tested against only two or three sites in Mexico which had radiation data available at the time. To compensate for this limitation some data were also used from measurement points in the United States near the Mexican border.

In their work Renné et al. [14] also present some results obtained with the CSR model (Climatological Solar Radiation Model). They estimated that this method was more accurate than those previously used. However, no additional comparisons with measured data in Mexico were available to confirm this opinion.

Recently there have been other efforts to carry out the assessment of the solar resource in the country, with more complex satellite based models. CFE performed, in 2010, a public tender for the elaboration of maps of solar radiation in Mexico. The evaluation was carried out with a resolution of 10 km x 10 km using the SUNY model [17], but the results have not been made available to the public. Also in 2010 a national inventory of renewable energy (Figure 4) was published by the IIE on its web site, summarizing the results of the project "National Laboratory for Renewable Energy Assessment in Mexico", funded by CONACYT and IIE (http://evaluarer.iie.org.mx/genc/evaluarer/lerm/inicio.htm). Very little information was given about the scientific methods of this project, which makes very difficult to assess the quality of the results.

Figure 4. Average annual horizontal insolation for Mexico, kWh / m² / day. Taken from Renewable Resource Explorer of IIE (2013).

There are other internet servers, where data can be found for Mexico. For example, the National Renewable Energy Laboratory (NREL) maintains a web server with support of a geographic information system to display worldwide information from global horizontal solar radiation (Figure 5). For the case of Mexico, this server provides monthly average and annual average daily solar resource, with a resolution of 40 km by 40 km in size. The Solar resource value is represented as watt-hours per square meter per day for each month. The data were developed from NREL's Climatological Solar Radiation (CSR) Model [18]. In This server also other components like DNI radiation can be obtained.

Figure 5. Yearly averaged daily global insolation for Mexico from the CSR, kWh/m²/day; from NREL (http://maps.nrel.gov/swera).

5. Conclusions

As discussed before, differences above 20% can be observed between the different solar radiation maps that have been published for Mexico, and the differences with respect to measured data available in some cases may reach up to 40%. This contrasts with the error achievable by satellite models, which has been estimated at between 7 and 13%, and indicates that there is significant potential for improvement.

The current state of development of solar energy technologies is increasing the need for more detailed radiation information. It is clear that the publication of maps of monthly averaged daily global radiation fulfills only the bare minimum needs of the users. In that sense, the efforts for establishing a National Database of Solar Radiation [19] are very relevant. This database will store a larger amount of information, with short time steps (one hour, 10 minutes, etc.), and with more than one solar parameter, where they are available. However, is very important to ensure the quality of data that is integrated into the database.

To ensure the quality of the data, is necessary for the various institutions to establish programs for calibration of its solar radiation sensors at least every two years. This could be carried out through the regional centers of the World Meteorological Organization (such as the Solar Radiation Observatory from IGF -UNAM), established to calibrate radiometers with respect to the World Radiometric Reference.

The failure of models is attributable, to a high degree, to the historical lack of ground measured data for Mexico. This situation is improving with the increasing utilization of automatic weather stations equipped with pyranometers. However, due to the complex orography of the country, it is necessary to establish new stations in strategically chosen sites, according to solar resource assessment criteria. Also systematic assessment of the quality of old measured data is necessary before trying to calibrate models against it.

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Appendix A. Stations from the SMN

The following table presents the currently operating automatic weather stations from Servicio Meteorológico Nacional (from http://smn.cna.gob.mx/emas/).

State	Station Name	Latitude (deg)	Longitude (deg)	Altitude (m)	State	Station Name	Latitude (deg)	Longitude (deg)	Altitude (m)
AGS	Calvillo	21.849	102.712	1618	MEX	Presa madín	19.524	99.268	2364
AGS	Presa 50 aniv.	22.189	102.465	2063	MEX	Atlacomulco	19.799	99.877	2570
AGS	Sierra fria	22.270	102.609	2976	MEX	Nev. de Toluca	19.126	99.771	4139
BC	P. A. Rodriguez	32.447	116.908	156	MEX	Cemcas	19.480	98.974	2176
BC	P, E. L. Zamora	31.891	116.603	32	MEX	Parque Izta-Popo	19.096	98.640	3682
BC	Mexicali	32.667	115.291	50	MEX	Altzomonil	19.119	98.655	4007
BC	San quintín	30.532	115.937	32	MEX	Valle de Bravo	19.376	100.085	2476
BC	B. de los Angeles	28.896	113.560	10	MEX	L. de Zempoala	19.053	99.313	2820
BC	Cataviña	29.727	114.719	514	MICH	Angamacutiro	20.125	101.723	1730
BC	La Rumorosa	32.272	116.206	1262	MICH	Apatzingan	19.083	102.372	282
BC	Const. de 1857	32.042	115.922	1576	MICH	Uruapan	19.381	102.029	1606
BCS	Santa Rosalía	27.338	112.269	53	MICH	M. Monarca i	19.671	100.278	3255
BCS	Cd. Constitución	25.010	111.663	28	MICH	M. Monarca ii	19.539	100.290	2970
BCS	Cabo San Lucas	22.881	109.926	224	MICH	Presa Zicuiran	18.922	101.931	265
BCS	G. Diaz Ordaz	27.643	113.458	37	MOR	IMTA	18.882	99.157	1355
BCS	San Juanico	26.258	112.479	36	MOR	Tepoztlan	18.951	99.079	1384
BCS	Bahia de Loreto	26.010	111.354	1	MOR	Tres marias	19.051	99.249	2839
BCS	Cabo Pulmo	23.445	109.424	1	MOR	Sierra de huautla	18.541	98.936	1330
BCS	Sierra la laguna	23.555	109.999	1949	NAY	Ixtlan del rio	21.039	104.298	1163
CAMP	Cd. del Carmen	18.648	91.823	8	NAY	Acaponeta	22.466	105.385	29
CAMP	Campeche	19.836	90.507	11	NAY	Marismas Nales.	22.221	105.331	1
CAMP	Calakmul	18.365	89.893	28	NL	Presa el cuchillo	25.733	99.321	134
CAMP	Escarcega	18.608	90.754	60	NL	C. de monterey I	22.560	100.390	1455
CAMP	Yohaltum	19.014	90.311	80	NL	C. de monterey II	25.401	100.308	1437
CAMP	Monclova	18.057	90.821	100	OAX	Puerto ángel	15.671	96.497	91
CAMP	Calakmul II	18.094	89.462	256	OAX	Pinotepa Nal.	16.350	98.053	195
CAMP	Los Petenes	19.943	90.374	2	OAX	Matias romero	16.883	95.036	186
CHIS	Palenque	17.526	91.990	52	OAX	Nochistlan	17.437	97.249	2040
CHIS	Escuintla	15.298	92.676	42	OAX	Miahuatlan	16.344	96.580	1588
CHIS	Cañon Sumidero	16.828	93.095	1253	OAX	Benito juarez	17.164	96.740	1950
CHIS	El triunfo	15.656	92.808	1974	OAX	Laguna chacahua	15.967	97.688	6
CHIS	La encrucijada	15.068	92.755	1	PUE	Tecamachalco	18.866	97.722	2047
CHIS	L. de Montebello	16.114	91.730	1492	PUE	Izucar de M.	18.617	98.452	1353
CHIS	Montes azules	16.812	91.525	325	PUE	Tezuitlan	19.888	97.391	1578
CHIS	Volcan tacana	15.091	92.147	1492	PUE	Huauchinango	20.099	98.153	2193
CHI	Chinipas	27.393	108.536	431	PUE	La malinche ii	19.141	98.032	2748
CHI	Guachochi	26.813	107.073	2390	PUE	Tehuacan	18.314	97.617	1736
CHI	Urique	27.216	107.917	577	QRO	Huimilpan	20.390	100.283	2280
CHI	Maguarichi	27.858	107.994	1663	QRO	Presa jalpan	21.206	99.472	773
CHI	Chinatú	26.229	106.771	1982	QRO	Sierra gorda I	21.499	99.169	1111
CHI	Basaseachi	28.199	108.209	1973	QROO	Cancún	21.029	86.852	1
CHI	Ciudad Delicias	28.170	105.500	1188	QROO	Chetumal	18.501	88.328	14

CHI	Jimenez	27.111	104.907	1360	QROO	Sian ka'an	20.128	87.466	8
CHI	Cd. Cuauhtemoc	28.397	106.839	2100	QROO	Cozumel	20.477	86.907	5
CHI	Ojinaga	29.534	104.476	790	QROO	Nicolas bravo	18.455	88.924	104
CHI	Villa Ahumada	30.616	106.505	1931	QROO	J. Ma. Morelos	19.752	88.704	56
CHI	El Vergel	26.473	106.390	2800	QROO	La union	17.897	88.879	11
CHI	Janos	30.839	108.427	1398	QROO	Arref. Xcalak	18.280	87.835	2
CHI	C. de Majalca	28.803	106.486	2088	SLP	Matehuala	23.648	100.658	1627
COAH	Nueva rosita	27.920	101.330	366	SLP	Cd. Valles	21.980	99.031	58
COAH	Santa cecilia	28.399	101.213	595	SLP	Cd. Fernandez	21.936	100.022	1009
COAH	Cuatro Cienegas	27.002	102.073	556	SLP	Gogorron	21.811	100.940	1809
COAH	Venustiano Carran.	27.519	100.950	264	SIN	Obispo	24.251	107.188	4
COAH	Morelos - Muzquiz	28.013	101.711	492	SIN	San Juan	25.486	107.843	112
COAH	Ocampo	28.825	102.525	1662	SIN	El Fuerte	26.411	108.618	82
COL	S. de Manantlan I	19.463	103.917	2490	SON	Nogales	31.298	110.914	1269
DF	ENCB, IPN	19.454	99.171	2389	SON	Alamos	27.022	108.938	409
DF	ENCB II, IPN	19.499	99.145	2240	SON	Yecora	28.367	108.917	1531
DF	Ecoguardas	19.271	99.204	2200	SON	Hillo-B. Kino	29.013	111.137	150
DF	Tezontle	19.385	99.100	2358	SON	Caborca	30.775	112.435	188
DGO	Las Vegas	24.186	105.466	2398	SON	Sonoyta	31.865	112.847	369
DGO	Agustin Melgar	25.263	104.066	1226	SON	S.L.Rio Colorado	32.424	114.798	39
DGO	La Flor	26.550	104.000	1164	SON	El pinacate	31.680	113.305	99
DGO	Villa Ocampo	26.441	105.502	1657	TAB	Paraiso	18.423	93.156	4
DGO	S. Juan de Gpe.	24.638	102.783	1526	TAB	Centla	18.406	92.646	2
DGO	La michilia	23.388	104.247	2464	TAB	C. Usumacinta	17.290	91.229	123
DGO	Mapimi	26.686	103.747	1157	TAMPS	Matamoros	25.886	97.519	4
GTO	Presa allende	20.848	100.825	1915	TAMPS	San Fernando	24.843	98.158	45
GTO	Sierra gorda II	21.321	99.831	2216	TAMPS	Ciudad Mante	22.744	98.983	85
GRO	Acapulco	16.763	99.749	7.5	TAMPS	Villagran	24.471	99.489	390
GRO	Cd. Altamirano	18.351	100.658	251	TAMPS	Jaumave	23.408	99.375	750
GRO	Petacalco	17.984	102.123	53	TAMPS	Barra del Tordo	23.052	97.772	5
GRO	Iguala	18.360	99.524	780	TLAX	Huamantla	19.386	97.966	2222
GRO	Zihuatanejo	17.645	101.555	5	TLAX	La Malinche I	19.298	98.044	2931
GRO	Atoyac	17.209	100.440	120	VER	Tuxpan	20.960	97.417	5
GRO	Tlapa de Com.	17.549	98.563	1060	VER	Alvarado	18.715	95.633	113
GRO	El Veladero	16.884	99.907	302	VER	Cd. Aleman	18.189	96.098	107
HGO	Pachuca	20.097	98.714	2423	VER	P. la Cangrejera	18.106	94.331	34
HGO	Huichapan	20.389	99.664	2080	VER	Citlaltepec	21.334	97.879	211
HGO	Huejutla	21.155	98.369	115	VER	Cordoba	18.890	96.923	852
HGO	Zimapan	20.740	99.391	1788	VER	Acayucan	17.977	94.901	106
HGO	Zacualtipan	20.665	98.672	2056	VER	Perote	19.545	97.268	2410
HGO	El Chico	20.186	98.716	3004	VER	Presa Tuxpango	18.846	97.039	965
HGO	Los Marmoles	20.873	99.220	2577	VER	Los Tuxtlas I	18.584	95.074	117
JAL	Chapala	20.290	103.202	1493	VER	Los Tuxtlas II	18.375	94.931	915
JAL	Tizapan	20.169	103.044	1503	YUC	Celestún	20.858	90.383	10
JAL	Jocotepec	20.283	103.416	1506	YUC	Río lagartos	21.571	88.160	5
JAL	Los colomos	20.707	103.393	1571	YUC	Tantaquin	20.030	89.047	30
JAL	Río Tomatlan	19.998	105.133	141	YUC	Dzilam	21.391	88.904	2
JAL	Chamela-Cuix.	19.498	105.045	84	YUC	Oxkutzcab	20.291	89.394	28
JAL	La primavera	20.726	103.644	1468	YUC	Tizimin	21.161	87.989	19
JAL	Nev. de Colima	19.592	103.591	3461	ZAC	Zacatecas	22.747	102.506	2270
JAL	S. Manantlan II	19.554	104.148	2882	ZAC	La florida	22.686	103.603	1870
MEX	Cerro catedral	19.542	99.519	3754					