CSIRO PUBLISHING

E. K. Bigg, *Environ. Chem.* **2008**, *5*, 184–193. doi:10.1071/EN07086 www.publish.csiro.au/journals/env

Trends in rainfall associated with sources of air pollution

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Environmental context. Decreasing trends in rainfall over large areas of eastern and south-western Australia have resulted in critical water shortages. Three reasons have been suggested. The first is a change in atmospheric circulation as a result of greenhouse gas forcing. The second is that changes in land usage have affected surface moisture, albedo and cloud formation. Another, the subject of this study, is that airborne particulates associated with urban areas have acted to decrease the mean efficiency of rainfall, the growth of urban areas thereby causing an underlying decreasing trend in rainfall.

Abstract. Trends in rainfall in the 35 years 1970–2004 have been calculated for all 350 available rainfall stations having sufficiently complete records that lie between latitudes 26–30°S and longitudes 150–154°E. The area contains two major urban centers, Brisbane with a rapidly growing population approaching two million and the Gold Coast with a population of ∼500 000. Statistically highly significant negative trends were found in the vicinity of Brisbane, with decreases exceeding 40% of mean daily rainfall in the 35 years, and in a smaller area inland from the Gold Coast. The spatial distribution of trends was consistent with aerosol production from human activities, the prevailing winds and losses due to the topography. A previously published observation using satellite data showed that cloud properties were affected by urban aerosols in a way that is likely to reduce precipitation. The results of this study reinforce the suggestion made then that monitoring of aerosol concentrations and properties and in-situ observations of rain formation processes in the area should be undertaken as a matter of urgency.

Introduction

Rainfall varies very widely from year to year in Australia, and known influences include the El Niño-Southern Oscillation (ENSO),[1] the 'Indian Ocean dipole' (an oscillation in sea surface temperature in the Indian Ocean[2]) and the Antarctic Oscillation or southern hemisphere Annular Mode (the difference in mean sea level pressure between latitudes 40°S and 65°S).[3] The short-term variability masks any underlying trends and unless the trends are large, they will have poor statistical significance. In spite of this difficulty, water shortages in many of the more populated parts of Australia and elsewhere in the world have led to studies of trends in rainfall[4,5] and attempts to attribute their causes. On the Australian scene, south-west Western Australia has received the most attention and explanations of decreasing trends in winter rainfall based on climate models have included changes in land usage,[6,7] circulation changes resulting from greenhouse gas forcing,[8] and a combination of these effects.[9] In parts of northern Australia rainfall shows increasing trends and an explanation has been given in terms of the effects on atmospheric circulation of increases in Asian aerosol.[10] An apparent steep decline in east coast rainfall from 1950 to 2005 is partly a result of starting the series in an unusually high rainfall period[5] but no cause of the residual decrease has yet been proposed.

In addition to the relatively large-scale effects considered in the works cited above, there have been several smaller scale rainfall trends attributed to urban effects[11–15] which may be partly dynamic, partly cloud-microphysical in origin. Satellite observations have shown clear indications of reduction in cloud drop size in polluted air that is consistent with observed decreases in precipitation of winter rainfall on downwind upslopes. Cloud microphysics effects that will alter the efficiency of precipitation have been invoked downwind from several cities,[16–19] including some in Australia.

A problem with attributing changes to aerosol intervention in the precipitation process is that in some circumstances addition of aerosols may be beneficial, in others harmful. For example, production of airborne particles on which ice will form in clouds (ice nuclei) at temperatures of about −10°C aids precipitation if the undisturbed concentration is less than that required for efficient precipitation but hinders it if that concentration is already at or beyond the optimum concentration. In clouds where the ice phase is not involved in precipitation, addition of giant (diameter, >1 μm) hygroscopic particles may initiate or increase precipitation, while adding large concentrations of smaller hygroscopic particles may hinder it. In addition to these differences, stratiform clouds with slowly cooling air may respond quite differently to vigorous cumulus clouds when a given aerosol is introduced. In Australia, studies of the rain-forming processes were abandoned 20 years ago and the present concentrations of potentially precipitation-influencing particles is not known at any site or for any season. Modelling[15] has revealed the complexity but cannot anticipate the overall result because the input parameters cannot be specified.

The aim of the present paper is to calculate a set of rainfall trends from all available sites in an area of south-east Queensland and north-eastern New South Wales that contain two rapidly expanding urban and industrial sources of aerosol to reveal their spatial distribution. The relation of this to urban areas and topography and what this reveals about causes will then be investigated.

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The dataset and its manipulation

The Australian Bureau of Meteorology has produced a comprehensive dataset of daily rainfalls from all its reporting stations. In searching for trends that may be related to human activity, neither starting years nor finishing years should have had exceptional rainfall, and the intervening period should be one of continued growth of population and industry. Also the number of stations with valid records should be as great as possible. The compromise used here was to look at trends in rainfall from 1 January 1970 to 31 December 2004. If the very dry years of 2005–2007 had been included in the analysis they would have led to greater decreases than seen in 1970–2004 but the decline of El Niño that followed might eventually offset their effect.

Fluctuations in the raw data can be reduced by combining the data into annual daily average rainfalls. Few of the records are complete and years with more than one month of missing data were omitted altogether. Of the records, 44% had one or more missing years on this basis and stations with more than five were omitted. Only 10% had more than two missing years. The quality status of each daily observation is listed in the dataset and those not quality controlled were counted as missing data. Observations of accumulated rainfall for more than one day were common (weekends for example) and pose a problem in forming daily averages because the rainfall of intervening days is left blank in the Bureau's dataset. Zeros had to be substituted for the blanks.

Linear regression lines were drawn through the annual amended averages for each station. The percentage change between 1970 and 2004 in mean daily rainfall for the 35 years, the correlation coefficient with the regression line and its statistical significance were then calculated. A complete list of these parameters for stations used, their geographical coordinates and omitted years is given in the Appendix. The area is bounded by latitudes 26–30°S and longitudes 150–154°E.

Results

Fig. 1 shows contours of trends (expressed as a percentage change in mean daily rainfall from 1970 to 2004) at 10% intervals. It is immediately apparent that at this level of spatial resolution, trends are far from uniform even in areas where very similar meteorological conditions prevail. Statistical significance at the level of 0.05 or better (red, orange and half the yellow areas) applies to all the stations with trends from −30 to −55%.

A possible cause of the very large difference in trends between those near latitude 27.5°S, longitude 153°E and those west of longitude 152°E might be that the large short-term controls such as ENSO are different in the two regions, or that changes in them are the cause of the trends.

To test this, the average daily rainfall of all the stations in district 40 shown in Appendix A1 (almost entirely east of longitude 152°E) was calculated for each year and also for all stations in district 41 (almost entirely west of that longitude). Fig. 2 expresses this mean daily group rainfall for each year as a proportion of the mean trendline rainfall for each of the two groups separately. The similarity is strong, with only a few differences such as 1974 and 1999 where the eastern groups received proportionally more rain. The correlation coefficient is 0.84, variance 0.71. This implies that influences such as ENSO apply almost equally to the two regions. Even though the statistical significance is very poor in the western group, it is evidently still

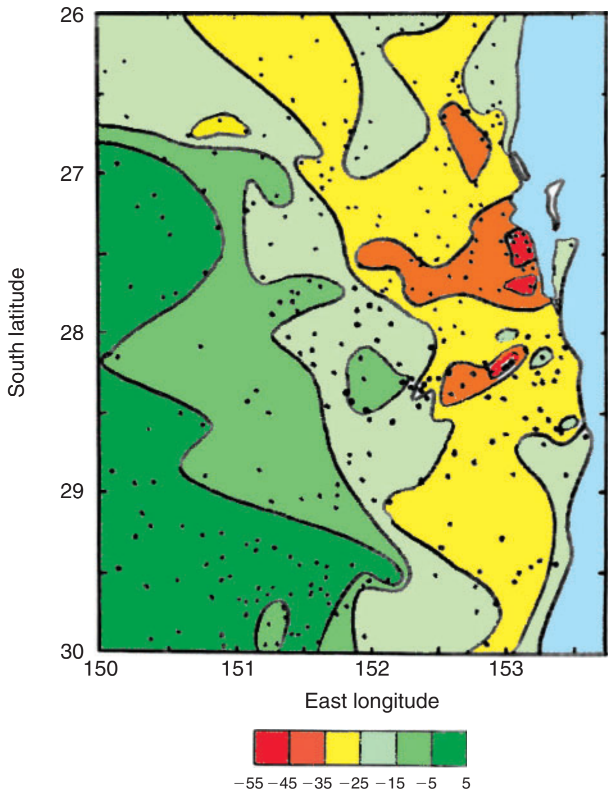

Fig. 1. Contours of the change in rainfall in 35 years (1970–2004) expressed as a percentage of the mean daily rainfall for that period at each site. The sites are listed in the appendix and are shown as dots on this diagram.

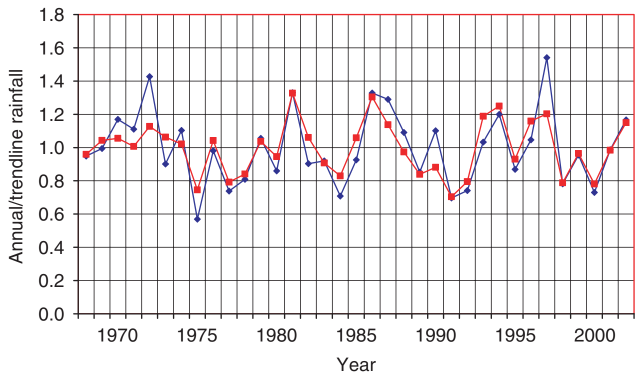

Fig. 2. Comparison of mean daily rainfalls in district 40 (blue, longitudes 152–154°E) and district 41 (red, longitudes 150–152°E) for separate years expressed as a proportion of the group's trendline rainfall at the centre of each year.

physically meaningful. The poor significance is simply a consequence of the shorter-term variations being large compared with the trend. The figure also suggests that long-term changes in ENSO (or other influence) intensity is not the main cause of the decreasing trends in rainfall.

The next question is whether these differences in trends are related to built-up areas. Rainfall is a maximum in summer, afternoon thunderstorms being the main source. About 60% of the 1500 hour winds in summer are from the east or north-east, so that effects should spread more towards the west and southwest than to the east. Time is also required for aerosol produced at the surface to enter clouds and influence rainfall so that effects

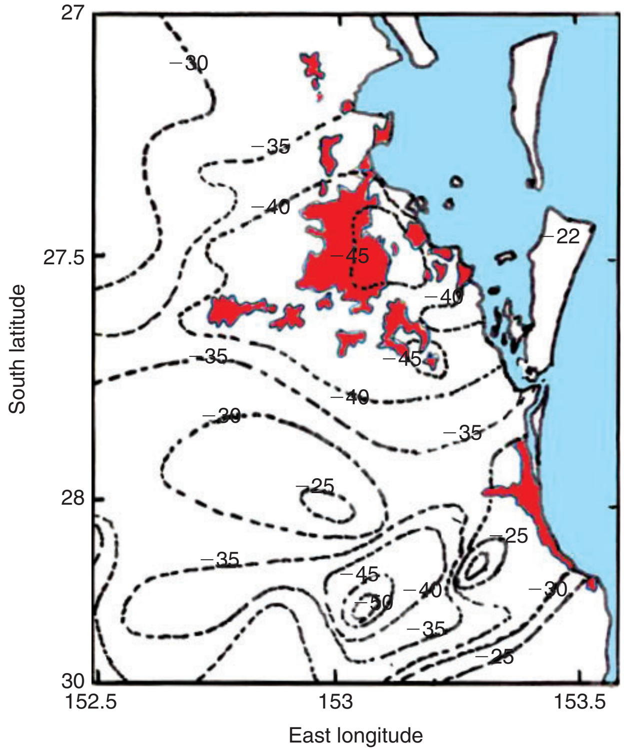

Fig. 3. Comparison of built-up areas (red) and contours of trends in precipitation.

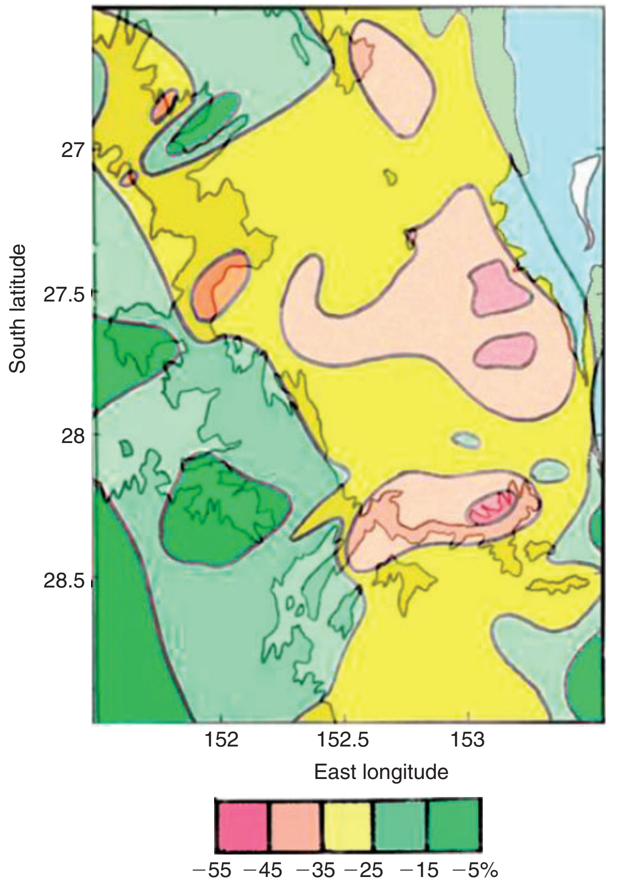

Fig. 4. Contours of 500 m are shown beneath colour-coded trends in rainfall.

may be displaced towards the west and south-west except in calm conditions.

In Fig. 3, built-up areas at the end of the period are shown in red, the two major ones being metropolitan Brisbane with a population now approaching two million and the Gold Coast to the south of Brisbane (population 500 000).

Contours of trends are shown at a spacing of 5% instead of the 10% of Fig. 1. Decreases greater than 40% in 35 years extend ~50 km to the west-south-west of Brisbane. The decrease to the west-south-west of the Gold Coast begins ~30 km from the coast, and while maximum decreases are comparable to those downwind from Brisbane, the area they occupy is far less. The direction in which the decreases occur is consistent with the most common winds in the season of maximum rainfall.

Topography can be expected to influence rainfall trends if aerosols are involved in changing precipitation efficiency because enhanced precipitation as the prevailing winds traverse mountain barriers will result in loss of the cloud-active particles. Fig. 4 examines this possibility, showing 500-m contours beneath the colour-coded trends in rainfall. Those of the main north–south Dividing Range closely parallel the contours of rainfall trends. An east–west spur of the range near latitude 28.3°S also appeared to have influenced the rainfall trends.

Discussion

While several observations[12–15] have shown that cities lead to increased thunderstorm activity in summer months, modelling has revealed[15] the complex interaction between dynamic and aerosol-induced influences on precipitation. Fig. 3 strongly indicates an urban effect on rainfall but it does not certainly point to aerosols as the main cause. Fig. 4, however, makes this seem more likely. The prevailing winds are perpendicular to the main Dividing Range and increased aerosol losses to cloud and precipitation in the rising air is to be expected. This is consistent with the orientation of the contours of trend with that of altitude contours. Where the winds are parallel to the high ground, as at latitude 28.3°S, the decreases remain large.

Modelling[15] has also shown that effects will be greatest where aerosol concentrations are least, for example, in onshore winds at the coast. In the area considered here, on or very close to the coast, the decreasing trends are least except in the vicinity of the coastal industrial area of Brisbane and the heart of the Gold Coast. Point Lookout on North Stradbroke Island (station 40175) ~50 km east of Brisbane has a trend of −22% compared with −45% over the industrial areas of Brisbane, while Tweed Heads (station 58056) at the south end of the Gold Coast has a trend of only −8%. Some urban effects would still be expected to the east of urban areas because not all rain falls from thunderstorms, not all surface winds are onshore and at upper levels in the cloud the winds are often from the west.

The apparent relationship between urban areas and decreasing trends in rainfall in this study cannot automatically be applied to other cities, where the meteorology, topography and aerosol properties may be quite different. Concentrations of both the undisturbed cloud-active particles and those produced by the cities may also differ from those in the present study. A preliminary treatment of trends in the vicinity of Sydney and Newcastle suggests very little, if any, decreasing trend in the actual metropolitan areas. There are substantial decreases inland, although smaller than those near Brisbane. In the case of Newcastle, the loss of its major industry (a steelworks) during the period may have influenced trends, while in Sydney, industry and population has tended to move further from the coast with time, possibly altering the coastal trends. In all cities, efforts to reduce aerosol emissions may have had an effect, but whether these will have resulted in an increased or decreased rainfall efficiency cannot be estimated in the absence of information on concentrations and properties of cloud-active particles throughout the study period.

Seeding thunderstorm clouds with large hygroscopic particles has had notable success in South Africa,[20] where aerosol concentrations appear to be generally much higher than in undisturbed regions of Australia. The success may have been due to the direct effects of the hygroscopic particles in initiating rainfall in a cloud that contains cloud drop concentrations too high for rainfall production by coalescence. Dynamic considerations[21] may also have been involved, but if research showed the method to be applicable in the Brisbane area, it may be possible to reduce the rainfall deficit by dispersing micrometre-sized hygroscopic particles over a wide area from ground-based generators. Assume that a concentration of $10^4\,m^{-3}$ particles of 10^{-12} g would be sufficient to initiate precipitation. The amount then required in an area of $1000\,km^2$ throughout a depth of 2 km is only 20 kg. Of course there would be logistic difficulties in obtaining the even concentration postulated, but in strongly convective situations, atmospheric mixing is rapid and this would help reduce the effects of point sources. Greater quantities than 20 kg would in fact be necessary because the size distribution of particles would inevitably be broader than the assumed diameter.

Conclusions

It seems likely that urban aerosol has affected precipitation efficiency in the region considered, although a contribution (perhaps positive, perhaps negative) from the dynamic effects of built-up areas may also be present. This strongly suggests the need for several areas of research. Measurement of in-situ aerosol concentrations and properties in rain-bearing situations in order to model their possible effects on clouds is one. Such a procedure has already been suggested[15,18] but its necessity was strongly disputed.[22] It would not be an easy task to make such observations, an undertaking that would require a considerable amount of aircraft time, and which is always difficult in built-up areas. Observations of the formation of storm and precipitation development in the clouds over built-up areas and comparison with those in nearby vegetated areas would be another necessary step to validate the models and apportion causes of changes to rainfall. This would require the use of quantitative radar measurements of precipitation.

Depending on what is found, it may be possible to alleviate the effects of urban aerosol by hygroscopic seeding of thunderstorms.

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Manuscript received 28 November 2007, accepted 13 April 2008

Appendix A1. List of stations and their statistics

Columns: A, Bureau of Meteorology's site identifying number; B, latitude, degrees; C, longitude degrees east; D, trend, change in 35 years expressed as a percentage of mean daily rain 1970–2004 for the site; E, correlation coefficient of the trend; F, statistical significance of the correlation; G, mean daily rainfall 1970–2004 (mm); H, years omitted from the analysis because of missing or bad data

A	B	C	D	E	F	G	H
40003	−26.3664	152.6236	−29	−0.26	0.14	3.41	2003, 2004
40004	−27.6297	152.7111	−41	−0.47	0.00	2.32	
40014	−28.0206	153.0131	−20	−0.23	0.20	2.41	1974, 1984, 2002
40024	−27.9925	152.6919	−30	−0.38	0.03	2.37	
40042	−28.0142	153.1664	−32	−0.3	0.08	3.22	
40056	−27.3914	152.5014	−26	−0.3	0.08	2.3	
40057	−26.1842	152.9136	−24	−0.26	0.40	4.35	
40059	−26.4181	152.9128	−15	−0.16	0.39	4.42	1990–1992
40060	−26.9833	151.8319	−12	−0.16	0.39	2.09	1985, 1988
40063	−27.1967	152.8247	−32	−0.31	0.07	3.48	
40071	−26.3828	151.1922	−30	−0.39	0.02	1.74	
40075	−27.2397	152.4225	−24	−0.26	0.13	2.37	
40079	−27.59	152.3567	−44	−0.45	0.01	2.08	
40082	−27.5436	152.3375	−31	−0.33	0.06	2.16	2002–2004
40083	−27.5425	152.2981	−35	−0.38	0.02	2.11	
40089	−26.0636	152.7739	−30	−0.32	0.06	3.14	
40090	−26.1819	152.0686	−27	−0.36	0.03	2.13	
40094	−27.8117	152.6675	−34	−0.43	0.01	2.29	
40095	−27.5675	152.4628	−28	−0.32	0.08	2.17	1970, 1974, 1984
40099	−26.4594	152.6761	−22	−0.22	0.21	3.28	1970
40100	−26.4622	152.665	−27	−0.29	0.09	3.23	
40102	−26.6656	152.4594	−23	−0.26	0.13	2.83	
40104	−27.9486	152.6236	−30	−0.39	0.04	2.41	1992–1996
40105	−26.3869	152.6767	−24	−0.25	0.17	3.32	1988, 2004
40106	−26.595	152.7236	−28	−0.29	0.09	3.41	
40108	−27.5519	152.7478	−32	−0.35	0.04	2.38	
40110	−26.9425	152.5647	−23	−0.25	0.15	2.51	2003
40111	−26.0861	152.2381	−23	−0.29	0.09	2.32	
40113	−26.6894	151.655	−33	−0.41	0.01	2.15	
40115	−27.4914	152.7519	−41	−0.42	0.01	2.45	1982
40117	−26.8081	152.9642	−25	−0.25	0.15	4.63	
40118	−26.6236	152.6839	−40	−0.39	0.02	3.28	2004
40120	−27.4622	152.575	−27	−0.34	0.05	2.27	1994
40121	−26.7528	152.8519	−31	−0.3	0.09	5.47	1993
40122	−26.4289	152.3292	−28	−0.32	0.07	2.55	1971
40123	−26.6225	152.8656	−19	−0.19	0.29	4.99	1994, 1995
40134	−26.6992	152.9039	−30	−0.29	0.09	5.04	
40135	−28.0303	152.5531	−31	−0.37	0.03	2.66	
40141	−27.6158	153.2042	−32	−0.32	0.06	3.58	
40145	−27.0675	152.7808	−34	−0.31	0.07	4.42	1971, 2002
40147	−27.4	152.7883	−31	−0.28	0.10	3.64	
40152	−26.2425	151.9425	−19	−0.31	0.07	2.03	
40158	−26.6756	151.9939	−17	−0.25	0.15	2.14	
40160	−28.0092	153.3175	−30	−0.31	0.10	3.88	1973, 1987–1991
40162	−28.1633	153.2114	−41	−0.35	0.04	3.77	
40169	−26.8447	152.8806	−35	−0.33	0.06	4.61	1992, 2004
40170	−27.3228	152.0533	−32	−0.38	0.03	2.5	
40171	−27.2692	152.9839	−37	−0.38	0.03	3.37	
40175	−27.4275	153.5219	−22	−0.27	0.13	4.51	2002, 2004
40177	−26.1639	151.6014	−28	−0.32	0.06	1.97	
40178	−28.215	152.8639	−27	−0.33	0.05	2.52	
40183	−27.8519	152.4797	−29	−0.34	0.04	2.47	
40184	−27.6361	152.5922	−35	−0.4	0.02	2.43	
40186	−27.2906	152.8214	−33	−0.33	0.06	3.28	1992
40188	−27.2675	152.6275	−31	−0.31	0.07	2.57	
40189	−27.1169	152.555	−24	−0.25	0.14	1.7	
40190	−27.9833	153.4053	−19	−0.21	0.26	4.23	1993–1997

(*Continued*)

Appendix A1. (Continued)

A	B	C	D	E	F	G	H
40196	−28.1331	153.4167	−29	−0.27	0.14	4.29	1970, 1971, 1974, 1975
40198	−27.9764	152.5117	−36	−0.4	0.02	2.75	
40199	−26.7433	151.8439	−30	−0.37	0.03	2.01	
40205	−27.0878	152.3756	−38	−0.4	0.02	2.26	
40206	−26.325	152.7867	−26	−0.25	0.17	3.59	1975, 1981–1983
40212	−27.4303	153.0669	−47	−0.44	0.01	3.2	
40222	−27.4117	153.0456	−41	−0.44	0.01	3.09	
40231	−27.4567	153.18	−47	−0.42	0.01	3.12	
40237	−27.3911	153.0628	−41	−0.4	0.02	3.32	
40246	−26.5539	151.4156	−29	−0.41	0.02	1.86	
40247	−26.8422	152.5803	−32	−0.32	0.07	2.89	
40251	−26.3172	151.8756	−29	−0.32	0.02	2.05	2004
40255	−26.41	151.815	−23	−0.32	0.07	2.09	1987
40257	−26.5603	152.9556	−22	−0.23	0.19	1.68	1975
40258	−26.8403	151.9803	−16	−0.19	0.30	2.28	2003, 2004
40259	−26.8911	151.8953	−22	−0.3	0.08	2.29	
40269	−27.6333	153.3667	−40	−0.41	0.01	4.07	
40282	−26.643	152.9392	−29	−0.28	0.10	4.62	
40287	−26.8475	151.7986	−51	−0.46	0.01	1.89	1976
40291	−27.6192	153.3056	−35	−0.35	0.04	3.74	2004
40307	−26.9664	151.7086	−28	−0.35	0.04	2.23	
40308	−27.3342	152.7717	−39	−0.38	0.03	4.44	1977
40310	−27.7239	152.3108	−37	−0.37	0.03	2.46	1979
40312	−27.7342	152.9472	−43	−0.42	0.02	2.71	1973, 1976
40314	−27.7189	152.8172	−31	−0.33	0.05	2.39	
40317	−27.7508	152.6667	−33	−0.41	0.01	2.24	
40319	−27.7347	153.3275	−40	−0.41	0.01	3.63	
40320	−27.4164	153.1556	−39	−0.36	0.04	3.33	2003, 2004
40326	−27.4433	152.975	−44	−0.42	0.01	3.36	2004
40365	−26.0544	152.3931	−20	−0.24	0.18	2.67	1988
40368	−27.5247	153.0633	−48	−0.41	0.02	3.12	1970, 1994, 2004
40374	−27.7594	152.4564	−36	−0.41	0.02	2.44	
40377	−26.2575	151.4108	−26	−0.35	0.04	2.08	
40382	−27.2711	152.0642	−29	−0.36	0.03	2.31	
40388	−27.6342	152.2203	−30	−0.36	0.03	2.12	
40389	−26.3967	152.6147	−24	−0.21	0.23	3.16	
40394	−28.2317	152.7833	−36	−0.37	0.02	2.36	
40395	−27.7181	152.1211	−24	−0.31	0.07	2.19	
40396	−26.7811	152.8211	−37	−0.38	0.03	5.14	
40397	−27.6692	152.1592	−29	−0.35	0.04	1.89	
40403	−27.3878	152.3492	−35	−0.4	0.02	2.46	
40406	−27.7094	153.2014	−46	−0.41	0.02	3.26	1994
40413	−28.1561	153.0397	−43	−0.46	0.01	2.4	2004
40417	−28.0717	153.4433	−33	−0.33	0.06	4.19	
40424	−27.755	152.0814	−21	−0.26	0.13	2.12	
40429	−27.5942	153.1181	−42	−0.41	0.01	3.34	
40435	−26.8939	151.6083	−14	−0.19	0.27	2.85	
40436	−27.5456	152.3286	−43	−0.47	0.00	2.16	
40447	−27.9906	152.4614	−34	−0.36	0.03	2.64	
40450	−27.5108	152.9975	−31	−0.3	0.08	2.96	
40460	−27.6081	153.2381	−43	−0.42	0.01	3.63	
40481	−26.5039	152.5861	−30	−0.31	0.07	3.17	
40486	−26.6167	152.5328	−42	−0.4	0.02	2.64	
40517	−27.1953	152.7539	−30	−0.3	0.08	3.24	
40523	−28.2653	152.5356	−35	−0.39	0.02	3.1	1983
40524	−28.1467	153.285	−17	−0.16	0.36	4.73	1997
40525	−26.5936	152.9036	−26	−0.24	0.17	4.43	
40534	−28.1628	153.2642	−22	−0.18	0.33	4.4	1972, 1973, 1988–1990
40550	−28.2453	153.2369	−37	−0.31	0.07	6.62	
40583	−28.2714	153.0742	−52	−0.51	0.00	2.81	1995, 2001
40635	−26.835	152.49	−19	−0.23	0.19	2.87	
40671	−26.2839	151.1897	−30	−0.37	0.02	1.88	
40695	−26.6842	152.9589	−28	−0.29	0.09	4.48	

(*Continued*)

Appendix A1. (Continued)

A	B	C	D	E	F	G	H
40721	−26.0933	152.0522	−17	−0.25	0.14	2.08	2004
41005	−26.9322	151.4503	−28	−0.38	0.02	1.8	
41011	−27.7072	151.865	−25	−0.35	0.06	1.99	1973, 1992–1995
41012	−26.6761	150.8789	−39	−0.46	0.01	1.56	2004
41014	−28.3539	151.6281	−13	−0.18	0.31	2.01	
41017	−26.7525	150.6236	−22	−0.27	0.12	1.74	
41018	−27.9317	151.9058	−19	−0.25	0.15	2.01	
41022	−28.5	151.9722	−16	−0.21	0.23	2.38	
41024	−27.2119	151.8514	−33	−0.41	0.01	1.97	
41025	−27.5742	151.0839	−16	−0.23	0.18	1.96	
41030	−28.7631	151.8483	−22	−0.32	0.06	2.14	
41033	−28.7625	151.9883	−16	−0.23	0.19	2.25	
41041	−28.2414	151.7264	−23	−0.28	0.10	1.85	
41042	−27.2242	151.8828	−23	−0.28	0.10	1.98	
41046	−28.2836	152.4161	−29	−0.36	0.03	3.16	
41047	−28.4144	151.0825	−9	−0.11	0.55	1.85	1993, 1994
41050	−26.7797	151.1111	−25	−0.35	0.04	1.81	
41052	−26.6928	151.0964	−15	−0.18	0.30	1.71	1981
41056	−28.3344	152.2953	−19	−0.26	0.13	2.05	
41058	−28.0867	150.7444	−10	−0.12	0.49	1.67	1989
41061	−27.6578	151.1986	−17	−0.21	0.22	1.73	
41062	−27.8083	151.3267	−8	−0.07	0.68	1.85	2004
41063	−28.0106	151.5856	−19	−0.22	0.20	1.88	
41069	−27.8742	151.2717	−13	−0.19	0.27	1.9	
41072	−27.4831	151.6003	−18	−0.22	0.21	1.75	1972
41075	−27.855	151.9033	−21	−0.29	0.11	2.08	1993–1995, 2004
41082	−27.7156	151.6333	−11	−0.15	0.39	1.94	
41083	−28.0694	151.7797	−16	−0.21	0.25	1.91	1982–1984
41085	−28.3253	152.3942	−23	−0.27	0.11	3.27	
41086	−26.6653	151.3969	−18	−0.24	0.16	1.92	
41087	−29.0314	151.4897	−3	−0.04	0.82	1.99	
41098	−28.2858	152.2425	−11	−0.17	0.36	2.13	1992–1995, 2000
41099	−27.2756	150.4617	−4	−0.04	0.83	1.7	2004
41100	−28.8544	151.1681	−6	−0.08	0.66	1.96	
41103	−27.5836	151.9317	−39	−0.44	0.008	1.01	
41108	−27.3797	150.5156	−2	−0.01	0.93	1.62	
41116	−28.9231	151.9306	−18	−0.26	0.14	2.16	1982, 2004
41118	−28.19	151.5758	−23	−0.26	0.14	1.77	1999
41120	−28.1897	152.2064	−18	−0.23	0.17	2.07	
41122	−28.5725	150.7542	3	0.05	0.77	1.73	1973
41128	−28.4997	150.5928	−5	−0.1	0.58	1.68	
41134	−28.3128	152.4025	−33	−0.39	0.02	3.59	
41140	−27.1864	151.2553	−7	−0.09	0.59	1.8	
41166	−27.6764	151.6022	−8	−0.1	0.58	1.86	
41182	−27.1667	151.5697	−20	−0.27	0.12	1.71	
41191	−27.2628	151.3744	−20	−0.25	0.16	1.73	
41192	−28.3692	151.7961	2	0.03	0.86	2.03	1979
41197	−27.3203	150.8725	13	0.15	0.40	1.68	1974
41198	−27.1472	151.3025	−6	−0.08	0.67	1.67	2004
41199	−27.2625	151.6297	−17	−0.22	0.23	1.86	1988–1992
41202	−27.0203	151.7114	−19	−0.25	0.15	1.92	2000–2002, 2004
41205	−28.1203	151.4725	−17	−0.23	0.22	1.81	1997
41208	−28.3542	152.3392	−27	−0.32	0.06	2.59	2000, 2001, 2004
41209	−28.4814	151.8856	−12	−0.17	0.32	2.01	
41212	−27.2156	151.6908	−19	−0.23	0.18	1.78	
41215	−26.7986	150.6708	−31	−0.35	0.05	1.53	2001
41216	−28.0333	152.0519	−18	−0.24	0.16	1.92	1973
41219	−27.6664	151.5536	−14	−0.19	0.28	1.78	
41223	−28.2928	151.9447	−11	−0.21	0.25	1.96	1971–1973
41225	−27.8394	152.0614	6	0.08	0.66	1.75	1971
41240	−27.1864	151.1419	−17	−0.21	0.23	1.76	
41242	−27.0181	151.635	−27	0.33	0.05	1.73	
41244	−27.1356	151.3967	−11	−0.14	0.42	1.52	

(*Continued*)

Appendix A1. (Continued)

A	B	C	D	E	F	G	H
41248	−27.0419	151.1406	−19	−0.23	0.22	1.72	1971–1973, 1992
41249	−28.0136	151.3947	−17	−0.18	0.35	1.83	1977, 1978
41250	−27.7894	151.4133	−10	−0.12	0.49	1.75	
41251	−28.4311	151.8228	−7	−0.1	0.58	1.8	
41256	−27.815	151.9858	−22	−0.27	0.12	1.93	
41257	−27.2314	151.1019	−26	−0.29	0.09	1.73	
41261	−27.1156	150.765	−6	−0.07	0.70	1.72	
41266	−27.0703	151.3733	−14	−0.2	0.30	1.71	1977–1981
41271	−27.0789	151.6531	−42	−0.47	0.01	1.65	2000
41275	−28.1469	151.9253	−11	−0.15	0.39	1.89	
41276	−27.9292	152.1606	−18	−0.24	0.16	1.95	
41277	−26.7667	151.2	−19	−0.29	0.09	1.69	
41285	−28.3275	151.845	−9	−0.11	0.51	1.94	
41291	−26.8631	150.8681	−11	−0.15	0.39	1.75	
41306	−27.8628	151.4536	2	0.02	0.90	1.73	
41310	−26.8886	151.2006	−11	−0.15	0.40	1.63	
41314	−27.7578	151.4483	−10	−0.14	0.44	1.77	
41315	−28.1064	151.5689	−27	−0.27	0.12	1.74	
41317	−27.0719	151.4181	−13	−0.16	0.35	1.72	
41318	−27.9683	151.3417	−13	−0.15	0.40	1.67	1993
41327	−27.7417	151.8017	−10	−0.13	0.46	1.87	
41338	−28.8	151.8433	−21	−0.3	0.09	2.1	2004
41344	−28.2075	151.5608	−12	−0.17	0.33	1.9	2002
41349	−27.73	150.5617	−2	−0.03	0.87	1.7	
41358	−27.4417	151.2567	−19	−0.27	0.13	1.85	1981, 1985, 1986
41368	−27.7161	150.2244	−1	−0.01	0.95	1.55	
41371	−28.4572	151.6817	−16	−0.24	0.17	1.98	
41388	−28.055	151.3297	−19	−0.24	0.17	1.83	
41391	−28.3611	151.1464	−4	−0.05	0.78	1.79	
41397	−28.1422	150.1319	−11	−0.11	0.55	1.61	2004
41408	−28.4992	151.2317	−9	−0.11	0.52	1.8	1972
41504	−27.7358	151.4117	−9	−0.11	0.55	1.88	1973–1975
41554	−27.7792	150.4583	−2	−0.03	0.89	1.66	1976, 1977, 1991
42002	−27.2067	150.2828	5	0.06	0.74	1.65	
42023	−26.6581	150.1844	−22	−0.28	0.10	1.81	
42033	−26.3	150.1833	−15	−0.17	0.32	1.71	
42034	−27.1689	150.0019	−1	−0.02	0.89	1.66	
42048	−26.9269	150.1419	−1	−0.05	0.78	1.71	1970
42078	−26.9186	150.4722	2	0.02	0.89	1.7	
42086	−27.1347	150.4086	1	0.01	0.97	1.64	
53004	−28.60	150.36	2	0.03	0.87	1.75	
53018	−28.99	150.02	3	0.05	0.80	1.72	
53033	−29.47	150.14	−2	−0.03	0.86	1.79	
53041	−28.87	150.09	−3	−0.07	0.70	1.71	
53047	−28.93	150.39	−4	−0.06	0.74	1.81	2003
53076	−28.95	150.26	0	0	0.99	1.73	
54002	−29.32	151.09	−4	−0.06	0.76	2.01	2001, 2004
54004	−29.87	150.57	−6	−0.08	0.64	2.07	
54007	−29.05	151.28	−11	−0.15	0.42	1.87	1995–1997
54012	−29.25	150.75	−9	−0.17	0.34	2.14	
54013	−29.65	150.83	−4	−0.04	0.80	1.99	
54016	−29.44	150.79	−15	−0.21	0.23	2.06	1988
54017	−29.58	150.34	−6	−0.09	0.61	1.9	
54027	−29.56	150.89	10	0.16	0.36	2.05	
54028	−29.96	150.92	−5	−0.07	0.67	2.34	
54029	−29.54	150.58	0	0.01	0.96	2	
54032	−29.20	150.61	−4	−0.04	0.81	1.91	
54035	−28.90	150.77	−17	−0.22	0.20	1.85	2001
54036	−29.24	150.89	−13	−0.12	0.48	2.19	
54043	−29.36	151.14	−5	−0.18	0.67	2.05	2001
54044	−29.31	151.15	4	0.06	0.73	2.03	
54045	−29.34	151.29	−1	−0.02	0.92	2.03	2004
54046	−29.40	151.41	−5	−0.07	0.70	2.11	

(*Continued*)

Appendix A1. (Continued)

A	B	C	D	E	F	G	H
54049	−29.41	150.90	9	0.12	0.51	2.09	
54057	−29.52	150.96	5	0.06	0.72	2.11	1974
54065	−29.61	151.27	4	0.04	0.82	2.16	1970, 1971, 1989, 1990
54069	−29.60	151.16	11	0.16	0.38	2.11	1970, 1971, 1976
54073	−29.64	151.24	−3	−0.04	0.82	2.16	
54074	−29.66	151.02	0	−0.01	0.97	2.26	2002, 2004
54077	−29.69	151.07	−5	−0.08	0.63	2.02	
54082	−29.64	151.41	−8	−0.11	0.52	2.43	
54124	−29.27	150.27	5	0.05	0.76	1.7	
54128	−29.89	150.90	−17	−0.22	0.20	2.25	
54129	−29.21	150.37	−7	−0.09	0.59	1.81	
54130	−29.13	150.30	5	0.06	0.75	1.76	1999–2001
56001	−29.72	151.36	8	0.12	0.49	2.16	1970
56007	−29.93	151.29	−15	−0.21	0.23	2.65	2004
56008	−29.44	151.85	0	−0.01	0.94	2.29	
56009	−29.45	151.60	3	0.04	0.84	2.21	1996
56011	−29.74	151.74	−6	−0.13	0.47	2.52	1970, 2003, 2004
56013	−29.70	151.69	−14	−0.21	0.24	2.39	
56018	−29.78	151.08	−5	−0.07	0.69	2.27	1996, 1997
56022	−28.46	152.35	−15	−0.21	0.23	2.38	
56023	−28.39	152.42	−12	−0.14	0.42	2.41	
56029	−29.46	151.48	−14	−0.19	0.28	2.21	
56032	−29.05	152.02	−29	−0.4	0.02	2.44	
56033	−29.95	151.21	−20	−0.29	0.10	2.37	2003
56038	−28.55	152.16	−22	−0.26	0.13	2.26	2004
56044	−28.95	151.76	−9	−0.14	0.47	2.34	1982, 1983, 2002, 2003
56050	−29.02	151.75	−20	−0.24	0.16	2.18	2003
56052	−29.10	151.74	−12	−0.18	0.31	2.08	
56055	−29.02	151.62	−6	−0.08	0.64	1.93	
56088	−29.53	151.67	−4	−0.07	0.71	2.23	1971
56094	−29.55	151.99	−16	−0.27	0.12	2.57	
56095	−29.58	151.56	−3	−0.03	0.88	2.3	1989–1991
56096	−29.59	151.63	−24	−0.25	0.14	1.7	
56098	−29.58	151.95	−15	−0.23	0.18	2.24	
56100	−29.63	151.56	−2	−0.03	0.84	2.44	
56102	−29.64	151.68	−2	−0.03	0.85	2.29	2004
56111	−29.78	151.35	−4	−0.05	0.79	2.16	
56115	−29.70	151.83	−19	−0.29	0.11	2.32	1991, 1992, 2004
56121	−29.88	151.41	−11	−0.19	0.29	2.33	2002
56123	−29.88	151.47	−4	−0.06	0.72	2.45	
56128	−29.83	151.52	4	0.07	0.70	2.41	
56139	−29.95	151.61	−3	−0.06	0.75	3.08	
56140	−29.47	151.67	0	0	0.98	2.26	
56163	−30.00	151.85	−14	−0.26	0.15	2.79	1979, 1980
56165	−29.81	151.23	−16	−0.21	0.25	2.18	2003, 2004
56167	−30.00	151.08	−14	−0.18	0.32	2.32	2002
56203	−29.05	152.13	−23	−0.29	0.10	2.37	1978, 1990
56205	−29.90	151.97	−17	−0.28	0.11	2.49	1977
56207	−28.54	151.99	−21	−0.29	0.09	2.28	
57003	−28.74	152.62	−37	−0.4	0.02	2.67	2004
57005	−28.93	152.38	−10	−0.11	0.52	3.09	2001, 2003
57014	−29.56	152.14	2	0.02	0.92	2.83	2003, 2004
57015	−28.65	152.60	−26	−0.27	0.13	2.73	
57018	−28.89	152.57	−29	−0.34	0.05	2.75	
57020	−28.47	152.55	−36	−0.4	0.02	2.84	2004
57024	−28.39	152.61	−36	−0.47	0.01	2.65	
57026	−28.28	152.50	−29	−0.38	0.03	3.14	
57051	−29.19	152.59	−30	−0.33	0.06	2.78	2003
57066	−29.35	152.52	−33	−0.38	0.02	3.15	
57085	−28.57	152.59	−21	−0.26	0.15	2.81	1974, 2000, 2001
57093	−29.51	152.49	−19	−0.23	0.19	3.29	
58001	−28.85	153.57	−4	−0.05	0.81	5.05	1984–1986
58004	−28.79	152.77	−27	−0.28	0.11	3.12	1988

(*Continued*)

Appendix A1. (Continued)

A	B	C	D	E	F	G	H
58006	−29.57	153.08	−33	−0.39	0.04	2.93	1975, 1992, 1995, 1996, 2004
58007	−28.64	153.59	−20	−0.26	0.13	4.84	
58009	−28.64	153.64	−23	−0.28	0.10	4.82	
58011	−28.31	153.28	−34	−0.29	0.10	4.54	1990, 1992, 2000
58012	−29.43	153.36	−19	−0.25	0.15	4.08	
58014	−29.59	152.78	−9	−0.11	0.56	2.93	1974, 2004
58015	−28.99	153.29	−26	−0.25	0.16	3.65	2003, 2004
58019	−28.53	153.32	−34	−0.32	0.06	5.74	
58020	−28.29	153.37	−25	−0.25	0.18	4.77	1972, 1996–1999
58027	−29.42	153.25	−28	−0.33	0.05	3.65	
58032	−28.62	153.00	−35	−0.38	0.03	3.21	
58033	−29.50	153.10	−28	−0.31	0.08	3.13	2004
58036	−28.31	153.22	−30	−0.28	0.10	4.74	
58038	−29.45	153.20	−27	−0.28	0.11	3.51	2002, 2004
58040	−28.55	153.49	−44	−0.49	0.005	4.87	1988, 1992, 1999, 2004
58056	−28.20	153.55	−8	−0.09	0.62	4.75	
58060	−28.60	153.38	−32	−0.29	0.11	6.38	2002–2004
58061	−29.07	153.34	−28	−0.29	0.09	3.73	1999
58063	−28.88	153.05	−35	−0.39	0.02	2.92	
58067	−28.24	153.38	−30	−0.29	0.09	5.91	1975
58070	−28.64	153.41	−29	−0.29	0.09	5.16	
58073	−29.49	152.79	−26	−0.29	0.09	3.17	
58074	−29.93	152.87	−36	−0.42	0.02	2.85	1992, 1996
58078	−28.78	153.11	−18	−0.2	0.26	3.08	
58080	−29.87	153.27	−4	−0.07	0.71	3.66	1983–1986
58088	−28.67	152.91	−31	−0.34	0.05	2.9	1986
58099	−29.28	152.99	−29	−0.32	0.06	2.99	
58102	−29.74	152.79	−21	−0.25	0.14	2.74	
58115	−28.38	152.88	−30	−0.34	0.05	3.51	2002, 2004
58127	−28.73	153.41	−16	−0.18	0.30	4.25	
58129	−28.47	153.26	−17	−0.31	0.07	4	
58130	−29.68	152.93	−17	−0.23	0.18	2.88	
58133	−28.72	153.36	−34	−0.34	0.04	4.11	
58135	−28.89	153.45	−10	−0.12	0.48	4.9	
58138	−29.84	152.90	−24	−0.28	0.10	2.69	
58141	−28.41	152.98	−31	−0.34	0.05	3.31	1984
58148	−28.53	153.15	−30	−0.34	0.05	4.26	