Tellus SERIES B CHEMICAL AND PHYSICAL METEOROLOGY
PUBLISHED BY THE INTERNATIONAL METEOROLOGICAL INSTITUTE IN STOCKHOLM

Tellus (2009), 61B, 694–700
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TELLUS

Comment on "Air pollution and precipitation suppression over SE Australia: critical review of evidence presented by Rosenfeld (2000) and Rosenfeld (2006)" by Greg Ayers

By DANIEL ROSENFELD[1]*, JIM PETERSON[2] and ARON GINGIS[3], [1]*Institute of Earth Sciences, The Hebrew University of Jerusalem, Israel;* [2]*School of Geography and Environmental Science, Monash University, PO Box 11A Victoria, Australia 3800;* [3]*Australian Management Consolidated Pty. Ltd, Bentleigh 3204, Victoria, Australia*

(Manuscript received 18 March 2009; in final form 3 June 2009)

ABSTRACT

Rosenfeld (2000, hereafter R00), in applying new satellite methodology to analyse case studies in Southeastern Australia and elsewhere, provided evidence that urban and industrial air pollution can suppress precipitation from shallow clouds. He concluded that 'Air pollution must be an important factor in determining the precipitation amounts in the Snowy Mountains'. These satellite observations were the impetus for our proposed detailed follow-on research program to further validate and quantify these inferences, publicly offered in Rosenfeld et al. (2006, hereafter R06) and repeated here, thereby recognizing the remaining large uncertainties. In response, Ayers (2009, hereafter A09) attempts to deny the significance and validity of the observations of R00. His scientific arguments are refuted here. Furthermore, A09 wrote erroneously that 'a hypothesis that air pollution in the form of small particles has caused a secular decrease in precipitation over SE Australia was advanced by Rosenfeld (2000), who concluded that the hypothesis was proven.' But R00 did not make such a claim, although this is a viable hypothesis that warrants testing (R06). In fact, R00 wrote: 'trend analyses of snow, winter temperature, and total winter rainfall for the period 1910–1991 showed statistically insignificant decreases. . . (Duus, 1992)'.

1. Prior work

In Rosenfeld (2000, hereafter R00, a three-page paper), the argument is about the potential value of what amounts to cloud attribute mapping. Previous work, however conclusive, or not, is not about this. Clearly, the works cited in R00 rest on previous work, which is acknowledged in R00.

Satellite cloud attribute pattern mapping offers a way of testing the physical evidence derived from the field, laboratory and modelling work that shows that air pollution aerosols suppress cloud drop coalescence. The mapping reported in R00 (nearly 10 years ago) was an application of this method to full scale cloud systems: the first time, for a case study of air pollution interacting with clouds. It is worth mentioning that there has been replication in a study of the impacts of smoke on suppressing rain from convective clouds over Indonesia (Rosenfeld, 1999) and the Amazon basin (Rosenfeld and Woodley, 2003). These satellite-based results have served as the impetus for aircraft campaigns, validating, by in situ measurements, the impacts of smoke in the Amazon (Andreae et al., 2004) and air pollution in California (Rosenfeld et al., 2008a), Thus the satellite inferences are validated. The in-cloud aircraft observations showed that convective clouds that ingest greater concentrations of cloud condensation nuclei (CCN) have to grow to greater depth above their base before onset of precipitation. The notion of aerosols suppressing rainfall from shallow clouds has now become widely accepted. In their executive summary, Levin and Cotton (2009) wrote: 'Larger concentrations of CCN produce larger concentrations of smaller cloud drops that are slower to grow into raindrops. There are reports that show that reduction of cloud drop size also delays the formation of ice, which then forms at higher altitudes and lower temperatures. This may lead to suppression of precipitation in shallow and short-lived clouds, such as those that form during winter over topographical barriers.'

The other studies mentioned by Ayers (2009, hereafter A09) that failed to document the aerosol effects on precipitation were

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*Corresponding author.
e-mail: Daniel.rosenfeld@huji.ac.il
DOI: 10.1111/j.1600-0889.2009.00434.x

not limited to shallow clouds, but included clouds for which aerosol effects can go either way (Rosenfeld et al., 2008b; Levin and Cotton, 2009).

Accordingly, and given the focus of R00 (it was not a review paper) and Rosenfeld et al. (2006, hereafter R06) (a defence of R00) on shallow clouds, we reject the conclusion in A09 that 'The conclusions reached by Rosenfeld (2000) and R06 were not adequately set within the context of prior published work that would point a reader to possible alternative conclusions.'

2. Fitness for purpose

A09 states that the analysis of a single satellite image taken on 21 October 1998 is incapable of supporting the conclusions reached. This would have been a valid statement if A09's assertion was not erroneous, ascribing to R00 the conclusion that 'a hypothesis that air pollution in the form of small particles has caused a secular decrease in precipitation over SE Australia...was proven'. But, in fact, R00 stated, that 'such results might indicate that human activity may be altering clouds and natural precipitation on a global scale'.

The main outcome from R00 was in showing that conditions do exist where aerosols can suppress precipitation from shallow clouds. This was reported for 47 cases over Southeastern Australia, and exemplified for a single case. R00 clearly stated that pollution tracks have been found in 47 AVHRR images on different days examined over eastern and Southeastern Australia. These cases do exist and documentation of them was provided to the Editor of *Tellus.* The list of the cases is provided in Table 1. The suppression effects would be mostly notable during marginal conditions for precipitation, where the added aerosols make the difference between rain/snow fallout or not. Such was the case for Southeastern Australia on 21 October 1998, and therefore the satellite image documenting that situation was perfectly suitable for the reported experiment. A09 dismisses the climatological importance of the shallow clouds that were documented by R00. However, pristine clouds of similar (shallow) depth can contribute large amounts of rainfall. For example, Hawaiian orographic clouds of similar depth produce most of the rainfall in one of the rainiest locations in the world. Here we have to remind ourselves that Levin and Cotton (2009) state in the executive summary of their book that aerosols 'may lead to suppression of precipitation in shallow and short-lived clouds, such as those that form during winter over topographical barriers'. This is important when considering the global perspective of R00's observations. When pristine, there is no reason why shallow clouds cannot rain significantly also over the hills in Southeastern Australia. In fact, R00 referenced Harasymiw and McGee (1993) in which it is shown that most of the winter precipitation events in the Snowy Mountains come from clouds with temperature at the tops between −4 and −13 °C.

A09's conclusion for this section states '*Evaluation:* the experiment carried out by Rosenfeld was not fit for purpose in that it focused on the wrong synoptic type and was carried out on a day when no significant rainfall was forecast'. This statement is again unfounded. The considerations above show that the cloud conditions were perfectly suitable for unequivocal demonstration of the impacts of the pollution plumes on suppressing precipitation from the clouds on that day.

3. Replication at the time

A09 questions the validity of the inferences of R00, 'because of the colours'. However, the colour coded display of the spectral data used for this kind of cloud mapping, varies for the same cloud composition depending on the viewing angles which is why interpretation of the displays must be carried out in reference to the metadata. Only the calculated effective radius takes the effect of the viewing angle properly into account, and so it should be used during objective assessment of the evidence. For example, A09 highlights the yellow colour of point A of his fig. 2 and its similarity to the colour over the Latrobe Valley. This is tested here with a cloud top temperature—effective radius (T-Re) analysis for area A (over ocean) and for the eastern Latrobe Valley (area B), shown as Fig. 1. The figure demonstrates that the clouds over the ocean at the far eastern part of the image have a large drop size despite being displayed as yellow. The cloud drop size there is much larger than over the eastern Latrobe Valley, but not as large as is typical of highly pristine clouds of the Southern Ocean. This might be due to some pollution from Tasmania (see eastern Tasmania in fig. 3 of A09; See also the pollution sources from Tasmania as simulated in fig. 5 of A09) and/or from the Latrobe Valley. The strong yellow colour patch mentioned by A09 in this context is due to the geometry of observation and illumination angle, with the target area being at the eastern margin of the satellite swath. Such illumination effects have been also clearly explained in R06, but A09 chose to ignore this explanation.

The strong yellow colour over the sea just to the south of the Latrobe Valley is not sufficiently far from the centre of the satellite ground track to be explained by invoking a large viewing angle, as for point A in fig. 2 of A09. The effective radius of these 'yellow' clouds south of the La Trobe Valley is small, indicating that these clouds, despite being over the Tasman Sea, are polluted. A09 claims that pollution is impossible there due to the regional southwesterly flow at the time. A09 goes on to claim that the whole analysis of R00 and R06 should therefore be discredited. However, a close examination of the cloud motions (see Fig. 2) shows that the clouds moved slowly from the metropolitan region of Melbourne and Geelong towards the Latrobe Valley. A local northwesterly component of the flow drove the clouds from the Latrobe Valley to be lying over Bass Strait to the south by the time the image was taken. This

Table 1. The 47 cases of pollution tracks that were identified by R00, all based on the NOAA-14 satellite

	Time UT (yymmdd hh:mm)	Description
1	970531 05:21	Melbourne, Latrobe Valley. Diffused
2	970608 05:34	Adelaide, Melbourne, diffused.
3	970618 05:25	Melbourne, diffused and tracks. Brisbane, tracks.
4	970629 05:05	Adelaide and Melbourne, diffused
5	970701 04:43	Brisbane Cu diffused.
6	970702 04:32	Melbourne Latrobe Valley diffused.
7	970708 05:07	East Australia, tracks
8	970710 04:45	West Victoria and Adelaide, diffused and focused. Latrobe stalks!!!
9	970715 05:32	Port Augusta, Port Pirie and Adelaide tracks
10	970715 05:32	Port Augusta, Port Pirie and Adelaide weak tracks
11	970717 05:09	Adelaide and Melbourne diffused and tracks
12	970719 04:47	Brisbane and Sydney diffused
13	970719 04:47	Adelaide and Melbourne diffused and tracks
14	970720 04:36	Brisbane and Sydney diffused
15	970720 04:36	Melbourne diffused
16	970724 05:33	Port Augusta, Port Pirie and Adelaide diffused and tracks
17	970727 05:00	Melbourne diffused
18	970727 05:00	Port Augusta, Port Pirie and Adelaide weak tracks
19	970729 04:38	Melbourne and Latrobe valley diffused.
20	970812 05:26	Port Augusta, Port Pirie and Adelaide strong tracks
21	970812 05:26	Tracks everywhere
22	970813 05:15	Port Augusta, Port Pirie and Adelaide tracks
23	970813 05:15	Port Augusta, Port Pirie and Adelaide diffused
24	970823 05:06	Port Augusta, Port Pirie weak tracks
25	970824 04:54	Port Augusta, Port Pirie and Adelaide strong tracks
26	970824 04:54	Melbourne and Latrobe valley weak tracks
27	970909 05:20	Melbourne diffused.
28	980607 05:54	Port Pirie and Adelaide diffused tracks
29	980626 05:44	Victoria tracks
30	980722 05:58	Port Augusta, Port Pirie and Adelaide diffused
31	980723 05:47	Port Augusta, Port Pirie and Adelaide diffused tracks. Melbourne diffused.
32	980809 06:00	Melbourne diffused.
33	980819 05:50	Sydney track.
34	980905 06:03	Port Pirie and Adelaide tracks. Melbourne diffused.
35	980906 05:51	Port Augusta, Port Pirie and Adelaide diffused tracks. Melbourne diffused.
36	980923 06:04	Port Augusta, weak tracks.
37	980924 05:53	Port Augusta, and Adelaide diffused tracks. Melbourne diffused.
38	981003 05:53	Melbourne diffused.
39	981021 05:55	Port Pirie and Adelaide diffused tracks. Melbourne diffused.
40	981117 05:56	Melbourne diffused.
41	981214 05:57	Adelaide diffused
42	981214 05:57	Melbourne diffused.
43	990313 06:08	Melbourne diffused.
44	990322 06:08	Gippsland diffused.
45	990331 06:08	Victoria diffused
46	990426 06:18	Adelaide diffused
47	990531 06:27	Adelaide diffused

calculated cloud movement is supported by the Melbourne radiosonde data (Fig. 3). The confluence of the northwesterly wind over the LaTrobe Valley with the west–southwesterly wind over Bass Strait is evident in Fig. 2. The confluence of the polluted continental air with the pristine maritime air is also evident from the colour-coded display in fig. 3 of A09, where the yellow clouds grade into red clouds some distance south of the coast line, to the south of Latrobe Valley.

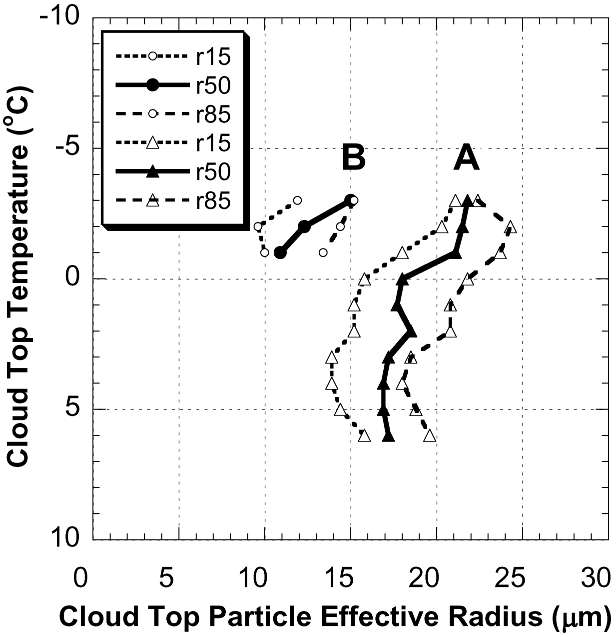

Fig. 1. T-Re analysis, as done in R00, for: (A) the ocean to the southeast of the SE corner of Australia (Point A of Fig. 2 in A09) and (B) over the land part of the SE corner of Australia.

This analysis indicates that before these clouds arrived over the Latrobe Valley, they had already become polluted from passage across the Melbourne and Geelong metropolitan areas. Therefore, the locally added pollution could not be discerned against the background of the already highly polluted clouds.

A09's conclusion for this section states: '*Evaluation:* the conclusions reached by Rosenfeld are not replicated by analysis of an alternative satellite view on the experimental day'. In contrast to this unfounded statement, here we show that additional, more in-depth analysis of the case offers strong support to R00's findings and explains the observed fine details.

4. Reproducibility at other times

A09 claims 'that analysis has not been repeated and reported in the literature for any other day'. Such a statement ignores the large number of publications reporting results in which this kind of analysis using TRMM satellite data has been applied elsewhere around the world (Rosenfeld, 1999; Rosenfeld et al., 2001 and 2002; Rosenfeld and Woodley, 2003). Furthermore, these satellite inferences have been validated by in situ aircraft measurements already discussed in Section 2. In addition, A09 states that he failed to identify pollution tracks. This is despite R00 having stated that he found 47 AVHRR images of pollution tracks in clouds over Southeastern Australia. These cases do exist and have been provided to the Editor of *Tellus.* The list of these cases giving times and locations is presented in Table 1.

A09's conclusion for this section states: '*Evaluation:* At this point 8 yr after the original publication, the reproducibility of the experiment carried out by Rosenfeld (2000) over SE Australia is yet to be demonstrated'. The evidence provided here shows multiple replications in Australia and for many other parts of the world: Therefore this A09's statement has no factual basis. Despite our efforts to do follow up research as has been done in other places where pollution tracks were observed (Andreae et al., 2004; Rosenfeld et al., 2008a), the proposals for detail analysis of Southeast Australian clouds microphysics and effects of aerosols on precipitation have been publicly opposed by Ayers as not having any merit. Thus funding for further research and application has been blocked.

5. Test against independent data

In this section, A09 reprocesses his previous arguments, which we have shown to be erroneous in the previous sections and in R06. Specifically, the AVHRR analysis is shown here to replicate and support the TRMM analysis, rather than otherwise as claimed by A09. The main new insight is that portions of the urban plume from Melbourne and Geelong flow into the Latrobe Valley, where the urban pollution mixes with the heavy emissions from the brown-coal power plants.

A09 claims that the fact that rain did not occur under either 'polluted' or 'pristine' clouds invalidates the suggestion that pollution was the cause of lack of rain. By making such a claim A09 ignores the naturally large variability of rainfall distributions. Natural variability of surface precipitation has a notoriously masking effect on attempts to measure the impact of aerosols and of cloud seeding on rainfall. For example, the detection of impacts of cloud seeding experiments requires many tens to hundreds of experimental units for a signal to be detectable. Therefore, the lack of correspondence of surface precipitation to the pollution track is not indicative of anything. R00 never suggested that the impacts of aerosols can be detected in surface precipitation based on a single case study.

A09's conclusion for this section states: '*Evaluation:* independent datasets on pollutant and rainfall spatial patterns on the experimental call into question the conclusions reached by Rosenfeld (2000).' But rainfall distribution cannot possibly be indicative for the single case study addressed here by A09. The rest of the evidence provided here shows that the contrary to this claim is true.

6. Consideration of other explanations (confounders)

The impact of updrafts on cloud drop concentration is much smaller than the variability in aerosols (see fig. 3 of Rosenfeld et al., 2008c). Furthermore, the pollution track occurred over a flat area without any obvious dynamical feature. In addition, the effects of topographic features are not evident in the observed

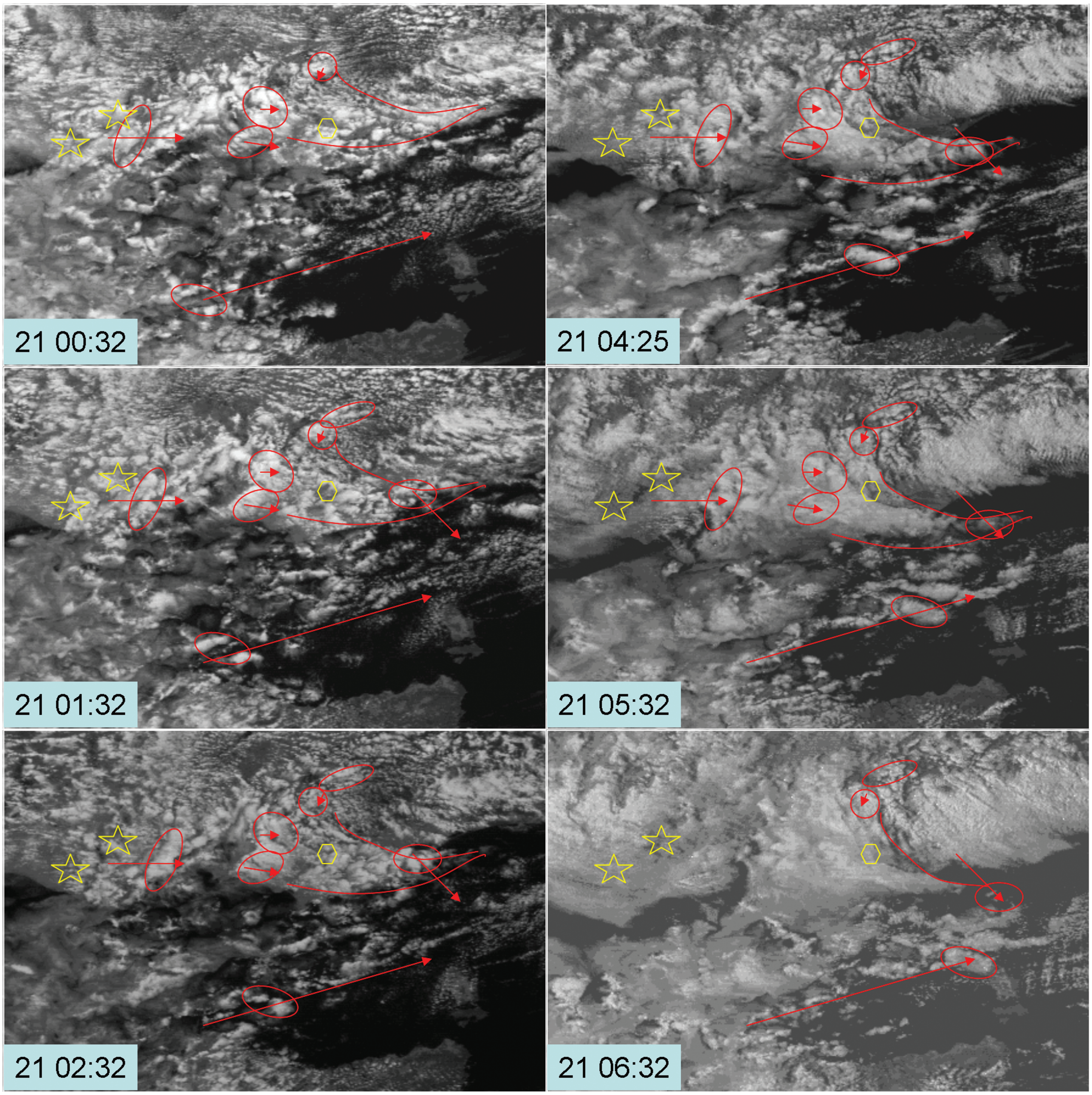

Fig. 2. An image sequence of GMS geostationary satellite provides the cloud movement over southern Victoria and the adjacent seas. The times are day in October 1998 and GMT hour. The two yellow stars are Melbourne and Geelong. The yellow hexagon marks the location of the coal power plants. The red ellipses and arches mark traceable features in the clouds. The arrows mark the trajectory of the tracked features. Note the weak flow from the urban area of Melbourne and Geelong towards the Latrobe Valley, and the northwesterly component of the flow driving the clouds from the Latrobe valley into the ocean.

field of cloud microstructure. This demonstrates the fact that possible differences in cloud base updraft due to change in topography are much weaker than those caused by other factors. In the homogeneous cloud field, with no detectable dynamic features of synoptic forcing over nearly flat land, updraft changes in cloud base greater than changes induced by the variability in topography over the Victorian Alps would be unlikely to happen. Therefore, the aerosols remain as the only viable explanation for most of the microphysical spatial variability of the clouds in the case study of R00.

A09 states that secular trends in precipitation in Australia were documented to be connected to changes in sea surface temperature and global circulation. However, the existence of such trends does not exclude the possibility that aerosols might also

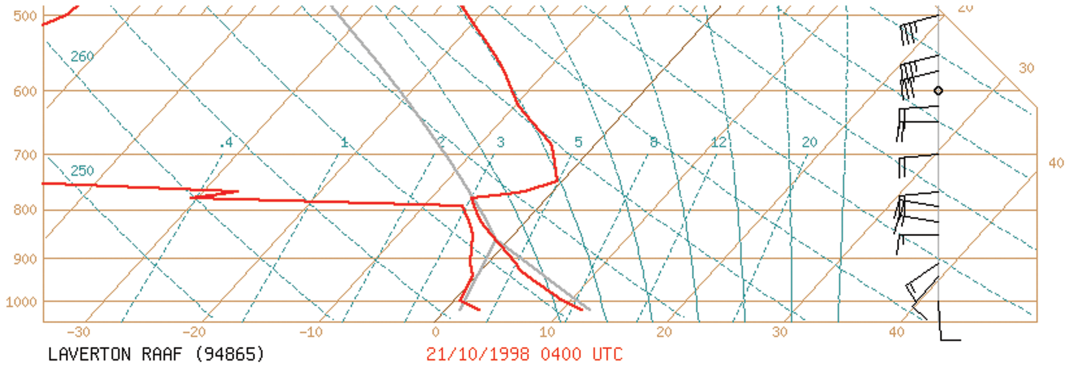

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Fig. 3. The radiosonde from Melbourne at 21 October 1998 04:00 GMT. Note the westerly winds with slight northerly component within the cloudy layer below the strong inversion.

have impacts on precipitation trends. Obviously, the relations between such trends and aerosols cannot be possibly proved by a single case study designed primarily to demonstrate the feasibility of detecting from space the presence of aerosols capable of suppressing precipitation from shallow clouds.

A09's conclusion for this section states: '*Evaluation:* plausible confounding explanations were not adequately taken into account in the analysis of Rosenfeld (2000), raising doubt about the conclusions reached'. This statement is incorrect: the evidence demonstrates that variability in cloud base updraft cannot serve as a viable alternative explanation in this case. Moreover, rainfall trends are not relevant as alternative explanations for a case study.

7. Inherent uncertainty

R00's case studies were selected such that air pollution could make the difference between the occurrence of rainfall or the lack of it. This selection was made so as to avoid the need for quantitative assessment of the changes in rain intensity and the error of the rain intensity measurement that comes with that. With cloud attribute mapping, clouds can be classified and those uncertainties associated with not knowing the extent and the attributes of polluted and pristine clouds is avoided.

8. Conclusion

The conclusions of R00 have been strengthened by this more in-depth analysis. We showed that all the claims of A09 are unfounded, and that R00 has indeed demonstrated that air pollution is potentially an important factor in determining precipitation amounts over SE Australia. The quantitative determination of this potential effect awaits additional study, such as has been taking place in California (e.g. Rosenfeld et al., 2008a). The proposed study plan over Southeastern Australia was comprehensively outlined in R06, but ignored by A09.

We conclude by repeating our open call that was previously made in R06.

Having clarified the issues that A09 raised, it is the opinion of the authors of this paper that the gravity of the findings in Australia and elsewhere in the world warrants instigation of an investigation of the potential role of air pollution in suppressing precipitation to the extent that water and hydroelectric energy resources of Australia are diminished.

The main elements of the proposed research program are as follows.

(1) Combined satellite and radar analyses of cloud top microstructure and precipitation with respect to potential aerosol sources.

(2) Aircraft measurements of the aerosols and cloud microstructure, with emphasis on validating the satellite retrievals.

(3) Hilltop monitoring stations of aerosol composition, CCN and ice nuclei properties, cloud drop size distribution, hydrometeor types, cloud water and hydrometeor chemical content. Two or three locations on the Victorian Alps and the Snowy Mountains will provide useful data of cloud properties in and out of the pollution plumes.

(4) Analyses of the historical record of precipitation for identifying possible trends in the orographic precipitation enhancement factor in conjunction with the study of trends in the production of submicron aerosols. Included, should be analyses of meteorological factors that can explain changes in the orographic precipitation due to natural variability.

(5) Application of aerosol chemistry and dispersion models.

(6) Application of cloud models with incorporation of explicit microphysics that will simulate the cloud-aerosol integration. This would be used as the tool to assimilate and extend the significance of the observations to the fundamental understanding of the microphysical processes.

The outcome of such a program can lead to benefits not only in enhancing the water and energy resources, but also to fundamental understanding of the anthropogenic impact on the climate system through the aerosol effects on clouds and precipitation.

9. Acknowledgments

The authors are grateful to Australian Management Consolidated Pty. Ltd. for encouraging the research on the potential impacts of air pollution on rainfall and snowfall, water availability for the Murray and the Snowy Rivers and hydroelectric power generation in the Snowy Mountains and the Victorian Alps in Australia. The geostationary satellite images were originally processed by the Bureau of Meteorology from the Geostationary Satellite GMS-5 operated by the Japan Meteorological Agency.

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