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

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ABSTRACT

A hypothesis that air pollution in the form of small particles has caused a secular decrease in precipitation over South East (SE) Australia was advanced by Rosenfeld (2000), who concluded that the hypothesis was proven. This paper critically reviews the experimental design used in that paper and subsequent work presented in Rosenfeld (2006). It is shown that the meteorological conditions on the single day studied were inappropriate for testing the hypothesis, as was the synoptic weather pattern. Moreover, the study failed to consider prior published work in Australia and readily available independent data such as rainfall patterns that call into question the approach used. We conclude that the experimental design was incapable of addressing the hypothesis, which therefore remains unproven.

1. Introduction

The validity of the claim by Rosenfeld (2000) to have demonstrated widespread suppression of rain and snow by urban and industrial air pollution over alpine regions of South East (SE) Australia was challenged by Ayers (2005) and subsequently defended by Rosenfeld et al. (2006). Here we review the experimental design used by Rosenfeld (2000) against a set of relevant criteria to form a view as to whether that experiment was capable of yielding such a definitive conclusion as 'Air pollution must be an important factor in determining precipitation amounts in the Snowy Mountains' (Rosenfeld, 2000).

2. Method

The evaluation criteria used here are typical of those that may be found in a plethora of texts on experimental design (e.g. Hoshmand, 2006). If we take as given that a valid hypothesis is being tested, evaluation of any experiment, including the experiment conducted by Rosenfeld (2000), can be made against the following criteria typical of good experimental design.

(1) Acknowledgement of prior work, including alternative views, to inform experimental design and provide full context for discussion of experimental results.

(2) The experimental design must be capable of addressing the hypothesis to be tested.

(3) The experiment should be able to be replicated at the time.

(4) The experiment should be reproducible, at other times.

(5) Results should be robust against testing with independent data.

(6) Alternative or confounding explanations for results should be acknowledged and discussed.

(7) Inherent experimental uncertainty should be acknowledged and discussed.

3. Prior work

The novelty claimed by Rosenfeld (2000) rests on discussion of evidence concerning three propositions: that aerosol plumes (pollution tracks) of greatly enhanced particle number concentration are emitted by human activities; that the resultant elevated levels of cloud condensation nuclei (CCN) lead to clouds having increased concentrations of smaller cloud droplets; and that reduced precipitation efficiency results. Each of these propositions had already been addressed in Australia and discussed in a large body of work to which Rosenfeld (2000) made little or no reference. Aerosol plumes from anthropogenic sources were observed, analysed and contrasted with natural sources by Warner and Twomey (1967), Twomey et al. (1978), Bigg and Turvey (1978), Ayers et al. (1979), Bigg et al. (1978), Ayers et al. (1982), Manton and Ayers (1982), Carras and Williams (1981) and Carras and Williams (1988) (indeed the city of Adelaide studied by Rosenfeld was one of the cities for which

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CN flux had been quantitatively measured); consequential effects of varying CCN levels on clouds were demonstrated by Warner and Twomey (1967) and Ayers (1981) over the continent and by Boers et al. (1994), Boers et al. (1998) and Boers and Krummel (1998) in the marine atmosphere; Warner (1968) identified a potential effect of agricultural smoke on downwind precipitation, only to follow up in a subsequent analysis with the conclusion that no such effect could be demonstrated (Warner, 1971). Set within the context of these studies the work of Rosenfeld (2000) was largely not new, nor complete in that it did not acknowledge, in particular, Warner's careful study into the possibility of precipitation suppression in Australia which failed to demonstrate a precipitation effect. The absence of reference to such a body of significant prior Australian work, including a specific prior work on the hypothesis being tested, is a major omission in the study of Rosenfeld (2000).

A limited reference to local work also occurred in Rosenfeld et al. (2006). In the 5 yr between the original paper and the Rosenfeld et al. (2006) response to the criticism of Ayers (2005), the Australian Government commissioned a review of the proposition that air pollution-suppresses rain/cloud-seeding-can-fix-the-problem. That review was carried out by Neville Fletcher, author of the first comprehensive cloud physics text, The Physics of Rainclouds (Fletcher, 1962), and was published in 2002. Notable among Fletcher's conclusions (see Fletcher, 2002) is: 'It is concluded that there is no reliable evidence that pollution plumes have actually decreased rainfall in the Snowy Mountains, the Victorian Alps, or in Western Victoria. Some such effect cannot be ruled out, and is not unreasonable on physical grounds, but may be minor and limited to certain cloud types and wind trajectories'.[1] This is a long way from a ringing endorsement of the conclusions drawn by Rosenfeld (2000), and one that we argue should be part of the story. Likewise, the paper by Nicholls (2000) demonstrating that an apparent long-term rainfall decline in the Snowy Mountains was actually a measurement artefact, and another by Nicholls (2005) demonstrating that long-term decline spring snow depth in the Snowy Mountains was driven mostly by increasing temperatures (increased melting), and less by declining precipitation, are highly relevant to the issue at hand but were not cited by Rosenfeld et al. (2006).

[1]Fletcher was only a little less sanguine about the difficulties inherent in the view that cloud seeding is the answer to rainfall decline: 'Despite these advances, it is likely that experiments could yield either no discernible result, a positive result implying a rainfall increase of order 10%, or even a negative result of similar magnitude. It is therefore necessary for a carefully designed seeding and evaluation program to be carried out if any reliable conclusions are to be reached. In view of the variability of natural rainfall, particularly in Australia, such a program would need to be carried out over at least as long as five years to achieve a reliable result. Because the cost of an experimental program is very significant, and the cost of an operational program even more so, it is important that a cost-benefit analysis be carried out in advance for the particular program contemplated'.

Evaluation: the conclusions reached by Rosenfeld (2000) and Rosenfeld et al. (2006) were not adequately set within the context of prior published work that would point a reader to possible alternative conclusions.

4. Fitness for purpose

It is straightforward to show that the experiment carried out by Rosenfeld (2000)—analysis of a single satellite image taken on 21 October 1998—is incapable of supporting the conclusions reached. There are two components to this. First, the experiment was carried out on a day of the wrong synoptic type to have any major implications for precipitation in the Snowy Mountains region or regional surface water flows. Ryan and King (1997) analysed historical rainfall records and showed that rainfall in the predominant part of the year (July–November, which includes the month of Rosenfeld's experiment) had only 11% of rainfall contributed by the synoptic type of Southwest stream that characterises Rosenfeld's experimental day. Frontal systems, not studied by Rosenfeld, were the most important, contributing 51% of historical rainfall, with deep systems next most important at 15.2%, closed lows at 8.3% and trough at 4.4%. Clearly, generalised conclusions about long-term loss of regional precipitation based on the single, less important synoptic type studied, is not possible.

Second, the specific day of the experiment is an inappropriate choice on which to test the hypothesis of rainfall suppression, as it was a day on which meteorological conditions dictated that no significant rain would fall. This was pointed out by Ayers (2005) who provided a vertical profile from Adelaide showing conditions to be inversion-limited, and devoid of any significant moisture aloft (above 3000 m), leading him to question the precipitation potential. Rosenfeld et al. (2006) quite properly corrected an error in the vertical scale in the figure drawn by Ayers (2005), but did not then go on to analyse the precipitation potential for the day of the experiment, simply offering instead the qualitative and unreferenced statement that in Hawaii 'similar clouds' can produce significant precipitation. It is unclear how the very different meteorological conditions encountered in Hawaii can provide any model for springtime rain clouds on a specific day in continental SE Australia.

More quantitative an estimate of precipitation potential is found in the output of the Bureau of Meteorology's weather forecast for the day (i.e. based on its numerical weather prediction model which assimilates all available meteorological boundary conditions). The forecast issued at 0500 on 21 October 1998 for the state of Victoria, the area of the experiment, was 'Victoria: Showers in southern and mountain areas will become more isolated today and mostly contract to the coast as a high pressure system approaches. The weather should remain generally fine on the northern plains with only isolated showers, likely in the morning. Conditions will be generally cool'. As shown by the 24-h average rainfall map for that day provided by Ayers (2005), and reproduced here as Fig. 1, that forecast was

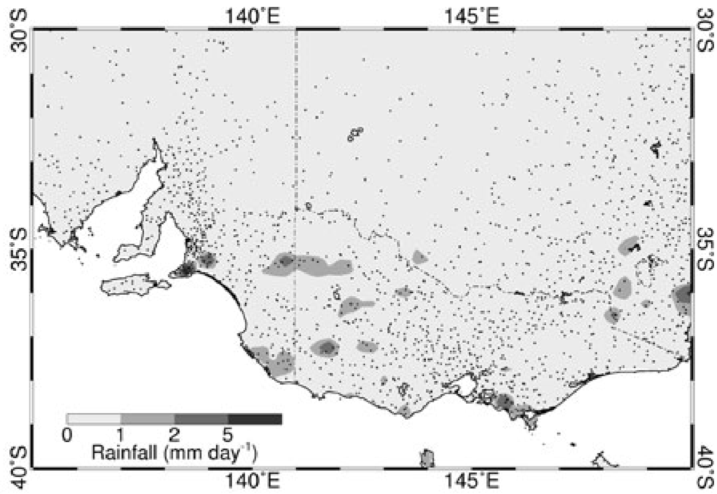

Fig. 1. Rainfall for the 24 h period to 0900 22 October 1998 (Eastern Australian Standard Time = UTC + 10 h). Each dot represents a daily rainfall measurement site. Data source: Australian Bureau of Meteorology.

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essentially perfect, with just a few light, isolated showers evident, tending to be near the coast. The vast majority of the state received no rainfall at all, consistent with the inversion-limited, dry vertical profile from Adelaide, as pointed out by Ayers (2005). Thus it is impossible to seek a pattern match with Rosenfeld's interpretation of pollutant distribution, since rainfall was not expected and did not fall over most of the region, irrespective of the pollutant distribution. Suppression of rainfall by aerosol is not a process in the numerical weather prediction (NWP) system, so this process clearly was not necessary for the Bureau of Meteorology to accurately predict the widespread absence of precipitation on the day.

Evaluation: the experiment carried out by Rosenfeld was not fit for purpose in that it focussed on the wrong synoptic type and was carried out on a day when no significant rainfall was forecast.

5. Replication at the time

In the absence of replication of the experiment by Rosenfeld (2000), Ayers (2005) processed a separate data stream from an AVHRR overpass that occurred 1 h later than the TRMM VIRS visualisation employed by Rosenfeld.[2] Ayers pointed out that there were significant differences between the images, in particular because the AVHRR image provided a larger field of view and showed cloud having low droplet effective radius (i.e. assumed by Rosenfeld to be polluted) off the south coast of Victoria and upwind on pollution sources, leading him to conclude 'None of these areas can be associated readily with upwind sources of pollution, causing doubt as to the assumption that all such areas are the result of aerosol pollution'. The response by Rosenfeld et al. (2006) was to discuss the AVHRR image shown in Fig. 2, which they referenced to Ayers (2005). However this is not the image produced by Ayers (2005). It appears to be an image produced some years earlier by one or more of these authors and used on the front page in one of a number of submissions to an Australian parliamentary committee (the Council of Australian Governments Inquiry on Bushfire Mitigation and Management, which reported in 2004). The image is cropped south of the continent, so does not show the much larger extent of the cloud field over the region shown by Ayers (2005) which had led him to question the generality of the conclusion that all clouds showing radiances interpreted as showing reduced effective radius must be polluted.

Rosenfeld et al. (2006) state that the analysis of Ayers was flawed on two counts, the first being that the NOAA-14 satellite viewing angle for clouds off the coast was such as to cause the colour coding of this cloud to be a viewing angle artefact. If indeed this is the case it actually strengthens a separate criticism made by Ayers (2005)—of the need to consider confounding explanations, such as this proposed artefact. This was not acknowledged by Rosenfeld (2000). In other words, according to Rosenfeld et al. (2006), caution should be exercised in use of this (and other) AVHRR image(s) if this artefact exists. This caveat also appears to have been omitted in submissions to parliamentary committees such as that noted above.

That said, the particular assertion of artefact by Rosenfeld et al. (2006) at location A in Fig. 2 may not be problematic, because it has not been proven. The scattering angle for area A in

[2]Colour-composite satellite visualisations of NOAA AVHRR images were produced here in the manner of Rosenfeld (2000), as described by Rosenfeld and Lensky (1998), based on prior work by Kaufman and Nakajima (1993). As summarised by Rosenfeld (2000), 'red is modulated by the visible channel; blue is modulated by the thermal infrared (IR); and green is modulated by the solar reflectance component of the 3.7 μm channel, where larger (greener) reflectance indicates smaller droplets. The composition of the channels determines the colour of the clouds, where red represents clouds with large drops and yellow represents clouds with small drops. The blue background represents the ground surface below the clouds'. Figure 2 in Rosenfeld (2000) shows that cloud top droplet effective radii of less that 14 μm are represented by yellow coloured clouds, while red coloured clouds had radii in the range above 15–30 μm.

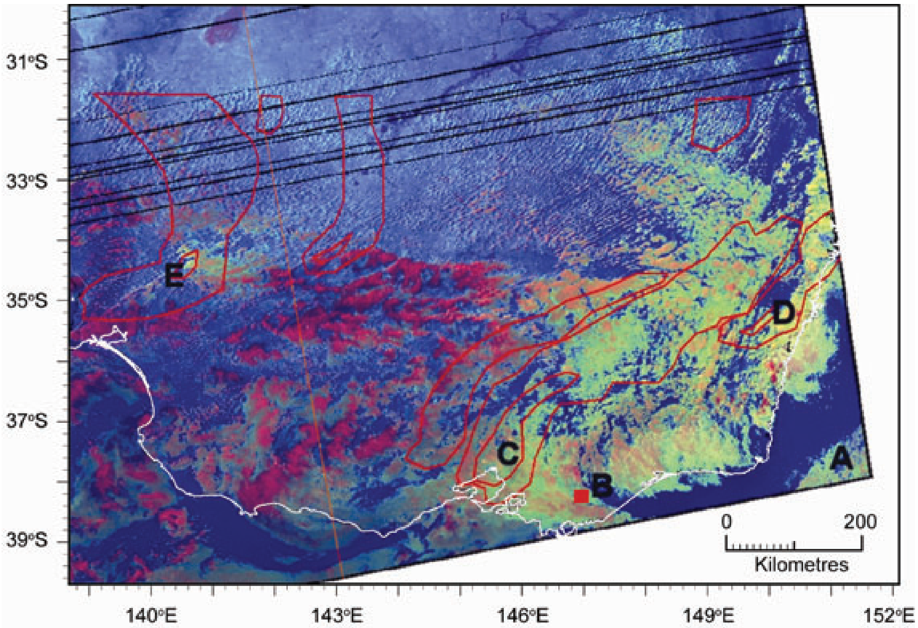

Fig. 2. Figure 2 from Rosenfeld et al. (2006). The red square, scale and white coastline have been added to the original image. The red square depicts the inland region containing the Latrobe Valley's coal-fired power stations, which are approximately 70–80 km downwind of the coast. It is evident that the cloud with low droplet effect radius (yellow-coloured) to the west, southwest, south and southeast of the red square cannot be explained by emissions from these power stations given the persistent south westerly winds at the time (see Fig. 5) which places these clouds upwind of the power stations. The letters A–E were part of in the original image and refer to comments in Rosenfeld et al. (2006). (Figure used with permission: Clean Air Society of Australia and New Zealand.)

this image is 153.3°. Typical water cloud phase functions have a fairly tight backscattering lobe—for example the one modelled by Hu et al. (2000) only increases at a scattering angle of about 170 degrees. In the angular range of relevance (140–160°) that phase function actually declines by about 30%, opposite to the increase required for the artefact argument to be valid. While a formal evaluation would require consideration of a range of phase functions and radiative transfer calculations based on them, it seems likely that there is a prima facie case to be made against the artefact argument.

The second defence by Rosenfeld et al. (2006) was that the areas colour-coded as cloud with reduced droplet effective radius (i.e. polluted) in the region labelled B in Fig. 2 was caused by the power stations in the Latrobe Valley. Such an explanation cannot be correct, since the four power stations are all located well inland as shown in Figs. 2 and 3, but the coherently yellow-coloured cloud mass extends a substantial distance upwind (to the SW) and out over the ocean. Moreover, as shown by fig. 1 in Rosenfeld (2000), strong point sources such as power stations manifest their pollution tracks in low clouds as thin isolated plumes, none of which is apparent in the AVHRR image. It is evident that the false-colour response of clouds in region B is not caused by the power stations, reinforcing the doubt expressed by of Ayers (2005) 'as to the assumption that all such areas are the result of aerosol pollution'.

Evaluation: the conclusions reached by Rosenfeld are not replicated by analysis of an alternative satellite view on the experimental day.

6. Reproducibility at other times

A singular feature of this debate is that in the years since publication of Rosenfeld (2000), that analysis has not been repeated and reported in the literature for any other day. Was it just a lucky one-off confluence of conditions that led to buoyant plumes interacting with low, thin cloud, so as to reveal the pollution tracks in Fig. 1 of Rosenfeld (2000)? Or is this common?

Rosenfeld (2000) asserted that pollution tracks in the vicinity of Adelaide were of frequent occurrence, stating that 'These pollution tracks were observed in the clouds of all 47 AVHRR images identified on different days examined in which stratocumulus and cumulus clouds with tops warmer than about –12 °C existed over the region'. This assertion was reinforced by Rosenfeld et al. (2006), but no details of these 47 d were provided to readers of either paper, so in the normal peer-reviewed sense this assertion is unsupported. To gain an independent perspective on this general assertion we carried out a small 'blind' test in which a staff member was asked to select at random and process one NOAA-14 image per month for 1999 that included

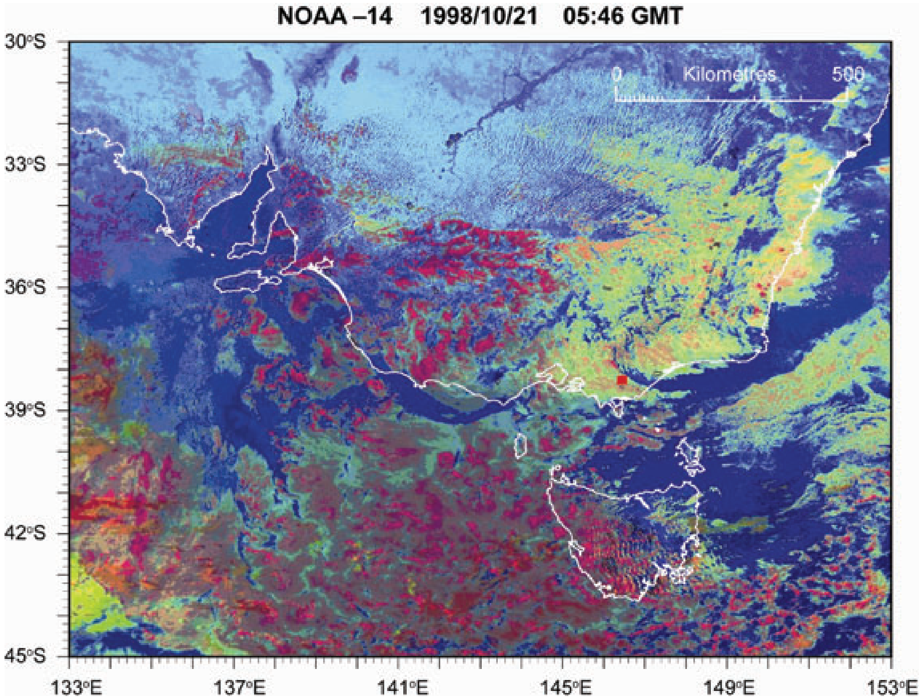

Fig. 3. AVHRR image (0546 UTC) corresponding to that of Fig. 2 showing a larger area, processed using the methodology employed by Rosenfeld (2000).

cloud over the state of Victoria, using the methodology employed by Rosenfeld (2000). Images so randomly selected were [time (UT)/day/month] : 0538/21/01; 0538/25/02; 0538/25/03; 0536/29/04; 0619/31/05; 0555/20/06; 0615/15/07; 0611/20/08; 0556/17/09; 0603/13/10; 0620/16/11 and 0625/12/12. There is no claim here that this is a representative sample, but having at least this set of 12 images enables a qualitative search for pollution tracks downwind of power stations and cities. The subjective analysis we carried out failed to identify any clear-cut pollution tracks. Figure 4 provides two of the examples (April and December 1999).

Evaluation: At this point eight years after the original publication, the reproducibility of the experiment carried out by Rosenfeld (2000) over SE Australia is yet to be demonstrated.

7. Test against independent data

Ayers (2005) pointed out that another fundamental weakness in conduct of the experiment carried out by Rosenfeld (2000) was the absence of independent data against which to verify a number of assumptions, assertions and conclusions. Ayers (2005) therefore provided independent data in the form of an alternate satellite view, a meteorological profile, simulated pollutant dispersal, and rainfall pattern at the ground on the experimental day. As we have seen above, the alternate satellite view and meteorological analysis call into question the validity of the experiment by Rosenfeld (2000) in ways that were not addressed convincingly by Rosenfeld et al. (2006). Here we briefly review the other independent information provided by Ayers (2005): modelled pollutant dispersal results and the daily rainfall pattern derived from the national surface rain gauge network.

The pollutant dispersal patterns in Fig. 5 apply to the time of the AVHRR overpass analysed by Ayers (2005), as mapped onto fig. 2 by Rosenfeld et al. (2006). Despite those authors' assertion to the contrary, it is evident as pointed out by Ayers (2005) that there is only partial overlap of clouds labelled as polluted by Rosenfeld (2000) with the simulated urban plumes (see Fig. 2). As noted earlier, this is particularly stark in region B in the figure, where neither emissions from power stations in the Latrobe Valley nor satellite viewing angle can explain the 'polluted' colour-coding of the cloud field. This remains an intractable problem with Rosenfeld's interpretation.

The rainfall map at the ground is even more problematic in terms of seeking an independent pattern match between rainfall and regions of unpolluted and polluted clouds identified either subjectively by Rosenfeld (2000) from the TRMM VIRS image, or from the AVHRR image, or from the pollutant dispersal simulations. The rainfall map is included here in Fig. 1. The observed rainfall patterns match none of the above—not surprising since there was no rainfall recorded over most of the land mass. Rainfall was detected by the TRMM radar in NE Victoria in a small area of 'unpolluted' clouds as identified by Rosenfeld (2000), and that rainfall is reflected in the map of Fig. 1. However wide areas of surrounding and equally 'unpolluted' clouds

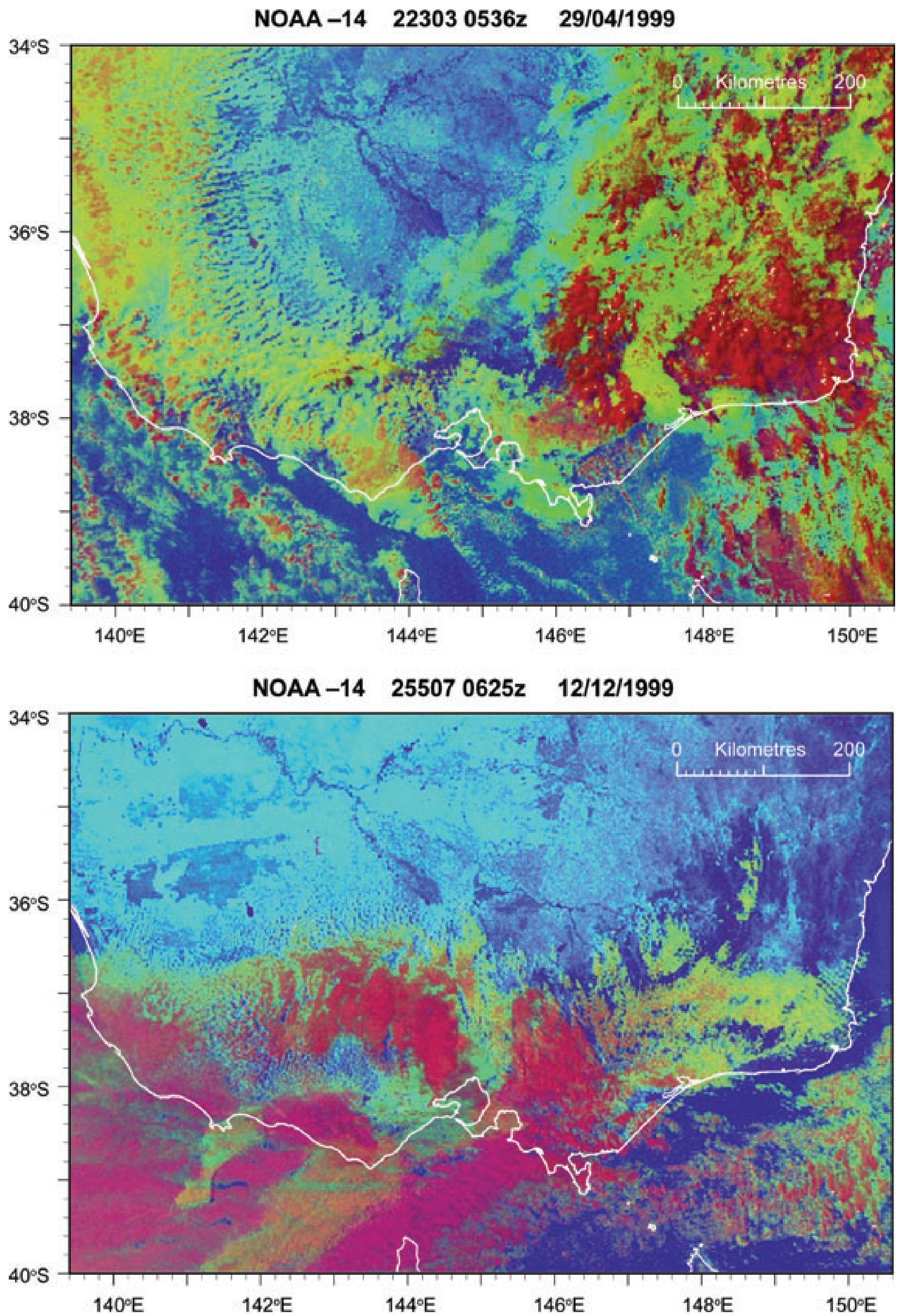

Fig. 4. AVHRR images for April and December 1999 processed as for Figs. 2 and 3.

did not precipitate, according to the raingauge network, while in contrast the clouds colour-coded as 'polluted' over coastal regions at the eastern edge of area B overlie one of the few coastal regions where surface rainfall did occur. Clearly it is not possible to support the conclusion that rainfall was suppressed by air pollution over SE Australia using the observed surface rainfall pattern.

Rosenfeld et al. (2006) did not respond convincingly to this point. The authors did not acknowledge that the experiment was carried out on a day when it was known that there would be no rainfall over most of the state, or that where it did, or did not rain, did not coincide spatially with assumed pollutant distribution. Instead they provided the surprising defence that: 'natural variability of surface precipitation has been a major obstacle

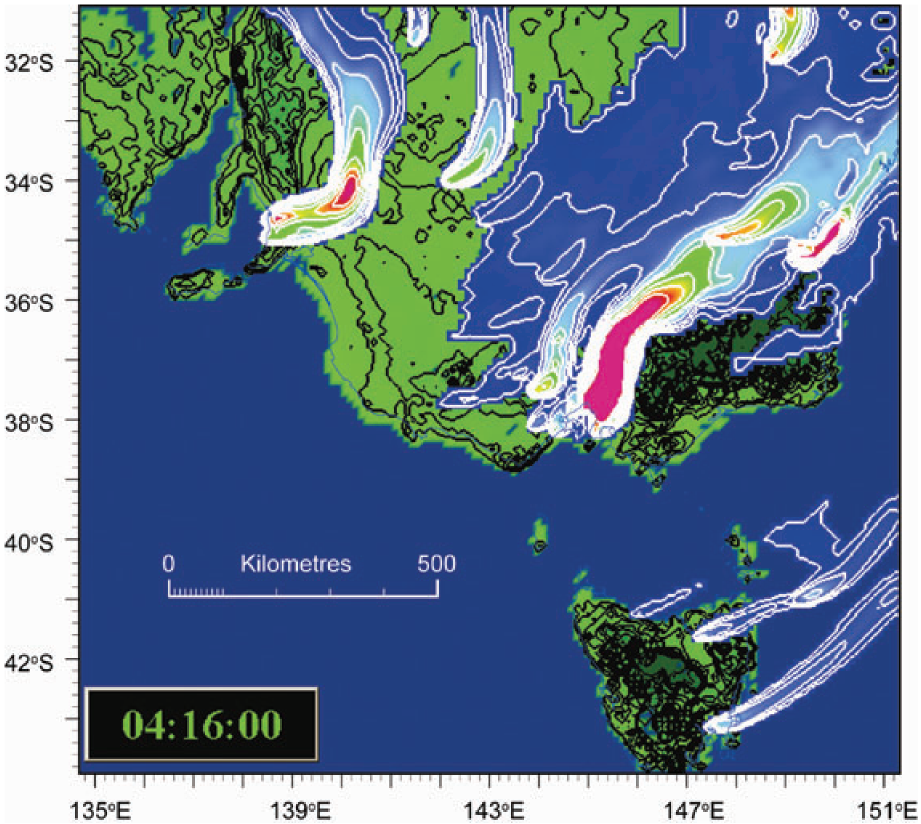

Fig. 5. Modelled primary CN concentration distribution at 500m over SE Australia on 21 October 1998 at 1600 local time. Source function used was the population–flux relationship of Ayers et al. (1982) convolved with a gridded population density database available at 1 km resolution. The chemical-transport model used for this simulation was TAPM (Hurley, 2005) run at 12 km resolution. The outermost contour is 1000 cm^{-3}, the innermost contour is 32000 cm^{-3} (individual contours are at 1,2, 4, 6, 8, 10, 16, 24 and 32 thousand per cm^3). Time scale refers to 1600 local time (0600 UTC) on day 4 of the simulation, which was initialized 4 days prior to the time of interest to ensure adequate spin-up for proper representation of plume transport. Features evident in this figure include the state capital cities of Adelaide (pop. 1 million), Melbourne (pop. 3 million) and Canberra (pop. 0.5 million) as the three largest CN sources positioned in that order west to east across the frame. The Victorian Alps are evident in the height contours shown to the east of the major Melbourne plume.

in documenting advertant or inadvertent man-made impacts on precipitation. This variability averages out at longer timescales, which is why cloud seeding experiments require several years for reaching any hope of detecting the seeding effect. Detecting the signal of precipitation suppression based on a single daily rainfall map in GA 05 is obviously not a viable proposition' (Rosenfeld et al., 2006).

In other words, the authors themselves acknowledge that any experiment carried out on a single day provides an inadequate basis from which to prove suppression of surface rainfall. It is illogical, given this statement, for Rosenfeld et al. (2006) then to go on and argue that the single-day experiment of Rosenfeld (2000) has provided proof of rainfall suppression over SE Australia.

Evaluation: independent datasets on pollutant and rainfall spatial patterns on the experimental call into question the conclusions reached by Rosenfeld (2000).

8. Consideration of other explanations (confounders)

Ayers (2005) made the generic point that in reaching one particular conclusion (that aerosols microphysically suppressed precipitation over Australia) it is important to have considered and discussed possible confounders, that is, explanations for the experimental result from causes other than those encapsulated by the starting hypothesis.

It was suggested that perhaps dynamics of cloud systems across a large region might differ, such that differences in cloud microphysical properties sensed by satellite might indeed vary spatially, but be caused by dynamical, not microphysical gradients. To illustrate this, Ayers (2005) provided a plot showing that droplet population properties could vary in a hypothetical cloud if updraft varied, even though aerosol size distribution remained constant. This was not intended to represent any particular cloud on the day of Rosenfeld's experiment, but simply to illustrate the generic point.

Rosenfeld et al. (2006) chose to criticize that hypothetical plot, rather than address the substantive issue raised by Ayers (2005), the substantive issue being whether there could be dynamical explanations for spatial gradients in the observed cloud properties. One germane example is the work of Manton (1979), which showed that variations in topography of as little as 100 m could detectably affect precipitation in the SE Australian region. It remains for future work to analyse the meteorological conditions of an experimental area in those terms (i.e. patterns of orography), or in terms of the different dynamics evident in the leading and trailing edges of a coherent weather system, or in other ways, to test the possibility that gradients in cloud properties studied over the whole of Victoria are dynamically, not microphysically determined.

A second confounder with respect to long-term rainfall trends is the need to control any microphysical experiment for effects of long-term changes in dynamic meteorology. According to Ayers and Levin (2008) this is a crucial point. Its importance has been underscored by the recent time-series analysis of Cai and Cowan (2008) that detected a long-term decrease in rainfall in the month of May (mid-autumn) over the region studied by Rosenfeld. However Cai and Cowen's analysis revealed causality not in microphysics, but in dynamic meteorology: meteorological shifts in precipitation patterns associated with long-term trends in SST variability over the Indian Ocean and changes in frequency of the ENSO cycle. The analyses by Rosenfeld (2000) and by Rosenfeld et al. (2006) were deficient in not considering the likely role of dynamics in precipitation formation and trends.

Evaluation: plausible confounding explanations were not adequately taken into account in the analysis of Rosenfeld (2000), raising doubt about the conclusions reached.

9. Inherent uncertainty

This is an essential component of any complex experiment where control of all factors of influence is not possible. Rosenfeld (2000) and Rosenfeld et al. (2006) did not provide a discussion of uncertainty associated with their conclusions.

10. Conclusion

The experimental design used by Rosenfeld (2000) is incapable of demonstrating that air pollution 'must be an important factor' in determining precipitation amounts over SE Australia. Thus this hypothesis is unproven.

11. Acknowledgments

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References

Ayers, G. P. 1981. Natural aerosols, anthropogenic aerosols and cloud properties over Australia. In: *Proceedings, Seventh International Clean Air Conference*, Ann Arbor Science, Adelaide, 375–385.

Ayers, G. P. 2005. Air pollution and climate change: Has air pollution suppressed rainfall over Australia? *Clean Air Environ. Qual.* **39**, 51–57.

Ayers, G. P. and Levin, Z. 2008. Air pollution and precipitation. In: *Clouds in the Perturbed Climate System* (eds J. Heintzenberg and R. J. Charlson). MIT Press, Cambridge, MA, 369–399.

Ayers, G. P., Bigg, E. K. and Turvey, D. E. 1979. Aitken particle and cloud condensation nucleus fluxes in the plume from an isolated industrial source. *J. Appl. Meteorol.* **18**, 449–459.

Ayers, G. P., Bigg, E. K., Turvey, D. E. and Manton, M. J. 1982. Urban influences on condensation nuclei over a continent. *Atmos. Environ.* **16**, 951–954.

Bigg, E. K. and Turvey, D. E. 1978. Sources of natural atmospheric particles over Australia. *Atmos. Environ.* **12**, 1643–1655.

Bigg, E. K., Ayers, G. P. and Turvey, D. E. 1978. Measurements of the dispersion of a smoke plume at large distances from the source. *Atmos. Environ.* **12**, 1815–1818.

Boers, R. and Krummel, P. B. 1998. Microphysical properties of boundary layer clouds over the southern ocean during ACE 1. *J. Geophsy. Res.* **103**(D13), 16 651–16 663.

Boers, R., Ayers, G. P. and Gras, J. L. 1994. Coherence between seasonal variation in satellite-derived cloud optical depth and boundary layer CCN concentrations at a mid-latitude Southern Hemisphere station. *Tellus* **46B**, 123–131.

Boers, R., Jensen, J. B. and Krummel, P. B. 1998. Microphysical and short-wave radiative structure of stratocumulus clouds over the Southern Ocean: summer results and seasonal differences. *Q. J. Royal Met. Soc.* **124**(545A), 151–168.

Cai, W. J. and Cowan, T. D. 2008. Dynamics of late autumn rainfall reduction over southeastern Australia. *Geophys. Res. Lett.* **35**, L09708, doi:10.1029/2008GL033727.

Carras, J. N. and Williams, D. J. 1981. The long-range dispersion of pollution from an isolated source. *Atmos. Environ.* **15**, 2207–2215.

Carras, J. N. and Williams, D. J. 1988. Measurements of relative σ_y up to 1800 km from a single source. *Atmos. Environ.* **22**, 1061–1069.

Fletcher, N. 1962. *The Physics of Rainclouds*. Cambridge University Press, London.

Fletcher, N. H. 2002. Advice on the impact of pollution on rainfall and the potential benefits of cloud seeding. Report to the Australian Government Department of Environment and Heritage. [http://www.environment.gov.au/water/publications/urban/cloud-seeding.html]

Hoshmand, A. R. 2006. *Design of Experiments for Agriculture and the Natural Sciences* 2nd Edition. Chapman & Hall/CRC, Boca Raton, FL, USA, pp. 456.

Hu, Y.-X., Wielicki, B., Lin, B., Gibson, G., Tsay, S.-C. and co-authors. 2000. d-Fit: A fast and accurate treatment of particle scattering phase functions with weighted singular-value decomposition least-squares fitting. *J. Quant. Spectrosc. Rad. Trans.* **65**, 681–690.

Hurley, P. J. 2005. The air pollution model (TAPM) version 3. Part 1. Technical description. Aspendale, Vic.: CSIRO Atmospheric Research. (CSIRO Atmospheric Research Technical Paper; 71). 54 p., available at: http://www.cmar.csiro.au/e-print/open/hurley_2005b.pdf

Kaufman, Y. J. and Nakajima, T. 1993. Effect of Amazon smoke on cloud microphysics and albedo – analysis from satellite imagery. *J. Appl. Meteorol.* **32**, 729–744.

Manton, M. J. 1979. Modification of rainfall by topographical variations. *Contribut. Atmos. Phys.* **52**, 58–66.

Manton, M. J. and Ayers, G. P. 1982. On the number concentration of aerosols in towns. *Boundary Layer Meteorol.* **22**, 171–181.

Nicholls, N. 2000. An artificial trend in district average rainfall in the Snowy Mountains. *Aust. Met. Mag.* **49**, 255–258.

Nicholls, N. 2005. Climate variability, climate change and the Australian snow season. *Aust. Met. Mag.* **54**, 177–185.

Rosenfeld, D. 2000. 'Suppression of rain and snow by urban and industrial air pollution'. *Science* **287**, 1793–1796.

Rosenfeld, D. and Lensky, I. M. 1998. Satellite-based insights into precipitation formation processes in continental and maritime convective clouds. *Bull. Am. Meterol. Soc.* **79**, 2457–2476.

Rosenfeld, D., Lensky, I. M., Peterson, J. and Gingis, A. 2006. Potential impacts of air pollution aerosols on precipitation in Australia. *Clean Air Environ. Qual.* **40**, 43–49.

Ryan, B. F. and King, W. D. K. 1997. A critical review of Australian experience in cloud seeding. *Bull. Am. Met. Soc.* **78**, 239–254.

Twomey, S., Davidson, K. A. and Seton, K. J. 1978. Results of five years' observations of cloud nucleus concentration at Robertson, New South Wales. *J. Atmos. Sci.* **35**, 650–656.

Warner, J. 1968. A reduction in rainfall associated with smoke from sugar-cane fires: an inadvertent weather modification. *J. Appl. Meteorol.* **7**, 247–251.

Warner, J. 1971. Smoke from sugar-cane fires and rainfal. In: *Proceedings, International Conference on Weather Modification*. American Meteorological Society, Canberra, 191–192.

Warner, J. and Twomey, S. 1967. The production of cloud nuclei by cane fires and the effect on cloud droplet concentration. *J. Atmos. Sci.* **24**, 704–706.