SOURCES OF ATMOSPHERIC AEROSOLS DURING WINTERTIME STORMS IN THE SNOWY MOUNTAINS

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Abstract

Wintertime storms in the Snowy Mountains of south-eastern Australia provide an interesting circumstance to investigate the effect of atmospheric aerosols on clouds and precipitation. This alpine region forms the catchment for the Snowy Mountains Scheme, which in addition to energy generation, is responsible for the redirection of water to the Murray river for irrigation. Severe droughts in the past decade have put significant pressure on this river system, motivating a cloud seeding research project currently being conducted by Snowy Hydro Ltd, the operators of the Scheme.

As a precursor to performing high resolution numerical modelling to investigate the sensitivity of precipitation processes in wintertime storms in the Snowy Mountains region, a climatology of the atmospheric aerosol content is performed. A back-trajectory model, in conjunction with mesoscale meteorological data is used to identify potential aerosol sources for wintertime precipitation events in the Snowy Mountains. The results of this study are to be verified by comparison with microphysical and meteorological data gathered by Snowy Hydro during cloud seeding operations since 2005.

1 INTRODUCTION

The Snowy Mountains Scheme is a hydroelectricity and irrigation complex in south-east Australia. Eastward flowing waters from the Snowy River are diverted inland through a complex of underground tunnels beneath the Snowy Mountains to the Murray and Murrumbidgee Rivers, and are used to generate hydroelectricity during national peak-load periods. Diverted waters from the Snowy Mountains region make up about five to ten percent of total inflows into the Murray River basin, and the hydroelectricity generated in the process provides about 3.5 per cent of Australia's electricity.

The most significant precipitation in the Snowy Mountains region falls in the winter months between May and September. Wintertime precipitation events in the region are generally characterised by the passage of a cold front, where a 'pristine' airmass originating from the Southern Ocean passes over south-eastern Australia. Precipitation during these events is enhanced by orographic uplift over the western slopes of the mountains. Increased lifting in these regions results in the availability of additional condensate for scavenging by precipitation at higher levels within the cloud (Reinking et al., 2000).

The amount of precipitation from these events is highly variable and depends principally on the dynamics of individual storms. It has been suggested that precipitation is being suppressed in the Snowy Mountains due to the influence of atmospheric aerosols emitted from anthropogenic sources. Rosenfeld (2000) uses observations from the Tropical Rainfall Measuring Mission satellite to deduce reduced cloud particle size in 'pollution plumes' originating from sources in south-eastern Australia. Rosenfeld infers that cloud droplet coalescence and ice particle formation have been inhibited as a result, and that this leads to suppression of precipitation in water catchments, including the catchments of the Snowy Mountains (Rosenfeld et al., 2006).

Supporting Rosenfeld's claims of precipitation suppression in orographic clouds is a modelling study (Lynn et al., 2007), in which a two-dimensional simulations performed by the Weather Research and Forecast (WRF) model were coupled to a spectral microphysics module. The study compared the effects of "clean-air" maritime and "dirty-air" continental aerosol loadings on precipitation from orographic cloud in the Sierra Nevada, and found that the increased aerosol concentration led to a downwind shift of precipitation particles compared to the "clean-air" case. Lower precipitation was accumulated in the "dirty-air" case, especially on the lower slopes of the terrain. Importantly, it was noted in particular that anthropogenic aerosols had been shown to decrease precipitation in comparatively dry environmental conditions.

Attempts have been made to correlate mountain-top cloud microphysical observations with precipitation accumulation during wintertime storms. For example, Borys et al. (2003) compare observations of two storms in the Rocky Mountains considered to be similar except for differences in cloud particle number concentration and size distribution. Dramatically different precipitation rates are attributed to inhibition of snow particle riming growth. However, a systematic correlation between aerosol concentration and precipitation was not confirmed in a statistical analysis (Hindman et al., 2006) of microphysical and precipitation records for the same site over the twenty year period between 1984 and 2004. If a subset of wintertime storm conditions susceptible to precipitation suppression by increased aerosol concentration is to be identified, Hindman et al. conclude that continuous monitoring of the chemistry and physics of cloud, snow and aerosol must be done in concert with fine-grid, meso-scale modelling to ascertain the seasonal role of aerosols on precipitation rates.

To date, suggestions of precipitation suppression in the Snowy Mountains are yet to be supported by measurement based evidence (Ayers, 2005). Substantial differences in orography and meteorology, as well as the extent of aerosol pollution between south-eastern Australian and the US south-west must be considered. As discussed by Ayers, supporting precipitation observations are required to verify a decline in rain and snowfall, and further that the anthropogenic aerosol dispersion patterns require validation. Although an intensive measurement campaign has yet to be conducted, a cloud seeding research project is being conducted by Snowy Hydro, during which a variety of microphysical and meteorological data are being collected.

2 CLIMATOLOGY OF PRECIPITATION EVENTS

2.1 Ten year climatology

A ten year climatology of wintertime precipitation events in the Snowy Mountains region was performed in order to identify some of the key features of winter storms currently affecting the region. Daily precipitation records were obtained from the Australian Bureau of Meteorology for four sites within the Snowy Mountains alpine region for the winter months (May-September) during the period 1997-2007. An automated method was used to objectively identify and distinguish between precipitation events, which were defined as a set of monotonically increasing daily precipitation readings to a peak value followed by a set of decreasing values. This was considered to be an appropriate criteria for precipitation events associated with a dominant synoptic feature, such as a cold front or extra-tropical cyclone, that typically influence a region for two to five consecutive days.

	Frequency; Rel. Contribution			
Year	Type-1	Type-2	Type-3	Other
2005	6; 41.3%	13; 42.6%	2; 4.3%	14; 11.5%
2006	7; 31.8%	10; 42.4%	3; 8.8%	7; 12.6%
2007	12; 17.5%	12; 35.3%	4; 2.4%	22; 3.1%
3-yr	8.3; 35.6%	11.6; 49.0%	3; 5.5%	14.3; 9.9%

Table 1: Wintertime precipitation statistics for 2005-2007

The one hundred most significant precipitation events, ranked by mean total precipitation accumulated over the duration of the event, were then classified subjectively by inspection of Mean Sea Level Pressure (MSLP) analyses. Precipitation events fell into three dominant categories:

- Type-1: Cold frontal passage associated with cut-off extra-tropical cyclone in Great Australian Bight and Bass Strait region.
- Type-2: Cold frontal passage associated with extra-tropical cyclone or trough in the Southern Ocean.
- Type-3: Moist flow associated with cut-off low pressure centre in Tasman Sea.

2.2 Three year climatology

Further attention was paid to the three years between 2005 to 2007, as these years coincide with the first three years of cloud seeding operations in the Snowy Mountains, marking the availability of in-situ microphysical observations during precipitation events.

Table 1 summarises the frequency of occurrence and relative importance of each of the three categories of precipitation events in terms of precipitation accumulated during the course of the event for the three years. These result show that cold frontal passages are by far the dominant precipitation producing weather systems in the Snowy mountains region in the most recent three years. This is somewhat at odds with the findings of the ten year climatology of major precipitation events, where cut-off Tasman depressions contributed a more significant proportion of the total precipitation. The most intense of these depressions, the so-called meteorological ‘bombs’, produce significant precipitation and regional flooding, but occur relatively infrequently (Leslie et al., 2005).

3 CLIMATOLOGY OF AIR PARCEL HISTORIES

Central to developing an atmospheric aerosol climatology is an understanding of air parcel histories during precipitation events. In order to present an overview of air parcel histories during the different types of precipitation events discussed in section 2.1, parcel back trajectories during the events were computed at three hourly intervals with the use of the NOAA Air Resources Laboratory Hybrid Single-Particle Lagrangian Integrated Trajectory (HYSPLIT) model. Back trajectories were computed using two different data sets. For the three years between 2005 and 2007, all precipitation events were analysed using three hourly Global Data Assimilation System (GDAS) analyses, over a one degree latitude-longitude grid, produced by the National Centre for Environmental Prediction (NCEP). For several selected case studies, 0.125 degree resolution Mesoscale Limited Area Prediction System (MLAPS) analyses produced by the BoM were used in order to resolve mesoscale features.

3.1 Preliminary Climatological Features

Subjective analysis of MSLP analyses and time series of back trajectories was used to identify the approximate time of frontal passages in the Snowy Mountains region for the type-1 and type-2 precipitation events. Back trajectories from each event were classified as pre-frontal or post- frontal according to their arrival time. In order to identify general features of air parcel histories, trajectories arriving six and twelve hours before and after the frontal passage were considered statistically. Figures 1 and 2 show mean trajectories and probabilistic envelopes of one standard deviation in position and height respectively, for 35 type-2 precipitation events between 2005 and 2007. Parcel histories are shown to an age of 36 hours.

3.1.1 General features of trajectory envelopes

General patterns of the frontal passage are captured by the statistical approach used here. A change in the orientation of the lower level back trajectory envelope of approximately 90° between pre-frontal and post-frontal trajectories at 500 m is evident. Less marked shifts are also apparent for 1000 m and 2000 m arrival trajectories. An increase in wind speed following the frontal passage is shown by the significantly longer post-frontal mean trajectories for the 36 hour duration considered here.

Significant variability within both the pre-frontal and post-frontal trajectory sets is displayed by the width of the envelopes. The lower level trajectories are particularly vari-

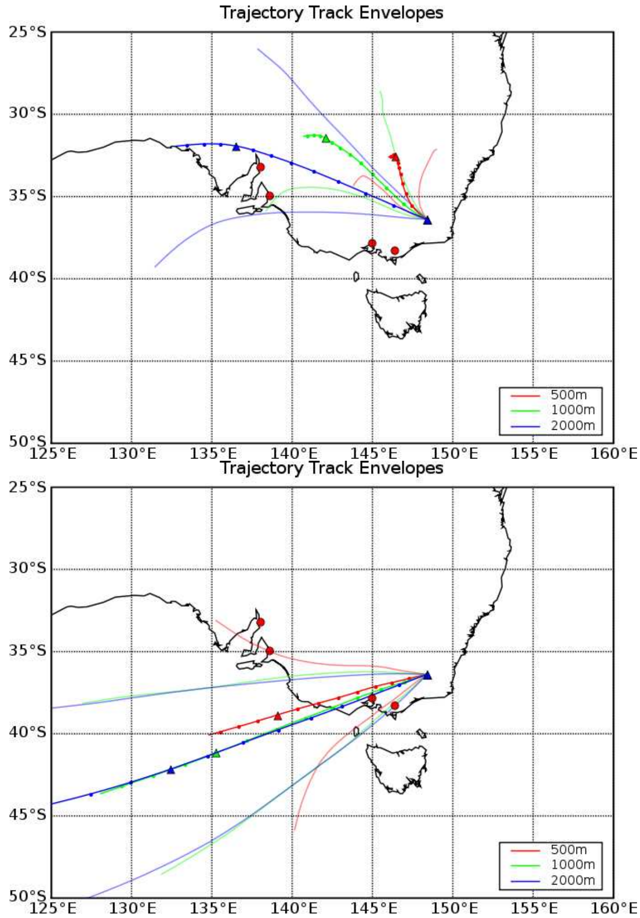

Figure 1: Mean trajectories and 1-σ envelopes for trajectories arriving six hours pre-frontally (upper) and post-frontally (lower). The trajectories are timestamped with 3-hourly (dot) and 24-hourly (triangle) markers.

able, with correlations of histories longer than 36 hours becoming very poor. The correlation between the post-frontal histories is better for the 1000 m and 2000 m, where the 500 m histories show increasing divergence before about 18 hours prior to arrival. This feature indicates that lower level parcels are 'caught' by the front as it approaches. By twelve hours prior to arrival the correlation between the lower level parcels is similar to that of the upper level parcels.

On average, trajectories arriving before the passage of a cold front pass closer to ground level than those arriving post-frontally. Vertical profiles of pre-frontal trajectories show consistent ascent for each of the three levels as they reach their endpoint in the Snowy Mountains region. This may in part be due to orographic influence, but as this feature is not apparent in the post-frontal trajectories it is also attributed to surface level convergence ahead of the cold front. In particular for upper-level post-frontal arrivals, the parcels spend the entire duration of the 96 hour

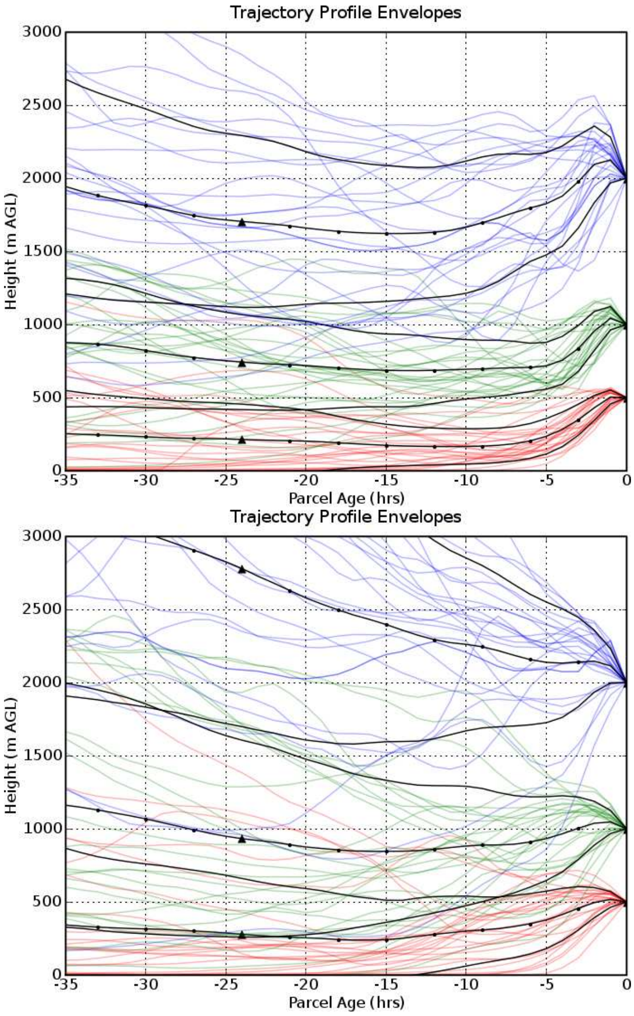

Figure 2: Same as Figure 1 but for vertical profiles of trajectories.

trajectories in the cold airmass, and a general subsiding trend can clearly be seen for these parcels.

There is significant spread within the profiles of the post-frontal trajectories in particular. Initial analyses of these have indicated that this is primarily due to the existence of some outlying trajectories that deviate far from the probabilistic envelope. There is also evidence of trends within these sets of post-frontal trajectories, with the $1000\ \mathrm{m}$ arrivals showing a sets of 'ascending' and 'descending' trajectories. The spreads may be significantly reduced if particular synoptic scale features can be identified to influence this characteristic.

As shown by the narrower envelopes, the spreads of the pre-frontal trajectory profiles are somewhat smaller. There are fewer outliers than in the post-frontal trajectories, and there do not appear to be any systematic trends within the trajectories displayed.

3.1.2 Implication for aerosol loading

The air parcel history climatology of this set of precipitation events illustrates an important point about cold frontal passages in south-eastern Australia. During the passage of the front, there is a significant change in the origin of air parcels arriving at the Snowy Mountains region, with parcel histories changing from continental to maritime over the course of about twelve hours. The exposure that these air parcels have had to different types of terrain and proximity to urban or industrial centres will have significant bearing on the atmospheric aerosol content of the airmass in the region. Results obtained to date suggest that lower level parcels arriving pre-frontally are most likely to have been isolated from major industry and in general the mid and upper level trajectories are stratified and thus unlikely to have been significantly influenced by emissions in lower levels.

During and following the frontal passage, there is potential for pollution of an otherwise pristine airmass from urban and industrial centres in the region. Emissions from several urban and industrial sites in particular have been implicated as possible sources for aerosol pollution resulting in precipitation suppression (Rosenfeld, 2000), and are plotted as red dots in Figure 1. Of these, only the Melbourne urban centre falls clearly within the envelope of influence of the lower-level trajectories for type-2 precipitation events for trajectories arriving six hours post-frontally. Further analysis will yield more information about the potential for significant impact by these sources on the aerosol loading during wintertime precipitation events under these conditions

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