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The impact of wind shear on observed and simulated trajectories during the ACE-1 Lagrangian experiments

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As part of the first Aerosol Characterization Experiment (ACE-1), two Lagrangian experiments were conducted with the intent of observing the evolution of boundary layer air over the course of 24 hours. Smart tetroons, which adjust their internal pressure to maintain a fixed elevation, were used to mark an ideal air mass. During both Lagrangians, however, the smart tetroons were observed to artificially lose elevation overnight; they dropped to near the ocean surface as a result of liquid-water loading from condensation. First we use the tetroon trajectories to assess the accuracy of numerical trajectories based on the analysis of four global numerical weather prediction models. Comparable to other studies, the computed trajectory errors range from 12-34% of the travel distance in heterogeneous flow and 5-15% in homogeneous flow. The vertical motions, however, do not show a strong agreement. We then use numerical simulations to assess the sensitivity of the trajectories to the meteorology. Vertical wind shear was observed for both Lagrangians and had a major impact on the tetroon trajectories when coupled with the overnight decrease in altitude. We also find that the trajectories are more sensitive to the initial position in the first Lagrangian than in the second. This sensitivity is probably due to the presence of a nearby cold front. Finally, we assess the impact of the liquid-water loading on the tetroon trajectories through the use of composite numerical trajectories in which the altitude is prescribed hourly. The error over the entire time period was reduced to 15-23% if the trajectories were lowered to 100 m altitude overnight, and 5-15% if they were lowered to 10 m. This suggests that the tetroons interacted with the surface layer throughout the night. Budget and evolution studies of the ACE-1 Lagrangians must take this into account.

Introduction

Numerical trajectories are a commonly used tool in the analysis of atmospheric chemistry observations, even though they suffer from uncertainties inherent in the underlying meteorological analysis or prognosis. These caveats are usually unavoidable, as the trajectories are often the only tool available that shed some light into the history of a sampled air mass. When

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greater resources are available, Lagrangian field experiments (or simply Lagrangians) may be undertaken in which the evolution of an ideal air mass is observed directly over an extended period of time. In addition to providing richer observations, Lagrangians do not depend on numerical trajectories and their inherent uncertainties. A more complete description of the scientific principles and motivations of Lagrangian experiments can be found in Bretherton and Pincus (1995), Bretherton et al. (1995) and Businger et al. (1996).

As part of the first Aerosol Characterization Experiment (ACE-1), two marine boundary layer (MBL) Lagrangians were carried out over the remote Southern Ocean south of Tasmania, Australia (Bates et al. 1998). Ideally, the MBL would be well-mixed with the entire column of air moving at a uniform horizontal velocity. For both Lagrangians, however, the MBL was observed to be vertically sheared (Wang et al. 1999a). Under these conditions, the ideal motion of an air mass within the MBL follows the mass-weighted average horizontal velocity of the entire column of boundary-layer air. For meaningful budget and evolution studies, considerable horizontal uniformity must exist for the tracked air mass. Wind shear across the top and bottom of the mixed-layer also complicates any analysis as it promotes mixing with the overlying free troposphere and the underlying surface layer.

While the concept of an ideal air parcel moving with the mass-weighted average velocity of the MBL air may be straightforward, tagging such a parcel is difficult from a practical perspective. Marker tetroons have been successfully employed for this purpose (Businger et al. 1996) although their motion is only an approximation. To help assure that the tetroons would stay in the middle of the MBL during the ACE-1 Lagrangians, smart (pressure-adjusting) tetroons were used. Unfortunately, these smart tetroons were observed to suffer a relatively sharp loss of altitude overnight as a result of liquid-water loading from condensation. GPS-based observations placed the tetroon heights within 100 m of the ocean surface, possibly in the surface layer below the mixed layer. In comparison with the MBL, the surface layer is characterised by a weaker horizontal velocity and stronger vertical shear. If the tetroons did descend into the surface layer, then their trajectories would be a biased average over both layers. Strictly speaking, this violates the assumptions of a MBL Lagrangian experiment, and budget and evolution studies need to account for this. Our primary aim is to assess the impact of these sharp elevation changes on the observed trajectories and, accordingly, on the validity of the Lagrangian framework.

To assess the impact of this vertical motion we employ numerical trajectories. Numerical trajectories have a rich history in the literature. Kuo et al. (1985), Kahl and Samson (1986) and Rolph and Draxler (1990) have studied the sensitivity of forward trajectories to variations in the spatial and temporal resolution of meteorological observations. Typical trajectory errors, relative to a base simulation, were found by Rolph and Draxler to be on the order of 20 - 25 per cent of the travel distance when the meteorological data were available at a spatial and temporal resolution comparable to the rawinsonde network. When the spatial and temporal resolution was greater the errors approached 10 per cent. Some investigators (e.g. Clarke et al. 1983; Reisinger and Mueller 1983) compared calculated trajectories using a variety of meteorological data with positions of tetroons. Errors for these studies ranged from 14 per cent of the travel distance when the flow was relatively simple and well-defined up to 46 per cent in more complex flow patterns. A third technique employed to assess accuracy has been the use of atmospheric pollutants as tracers. Long-range trajectories have been compared with the paths implied by surface concentration measurements of non-depositing inert gases by Haagenson et al. (1987), Kahl and Samson (1988), Draxler (1987), Lee (1987), Stunder and Draxler (1989) and Shi et al. (1990). Most of the trajectory errors ranged from 20 - 25 per cent of the travel distance for these studies. Similar results were found during the ANATEX experiment (Draxler 1991) where trajectory errors ranged from 20 per cent to 30 per cent over all trials (in more homogeneous flow regimes the errors were about 15 per cent). The positions of the smoke plumes arising from the Kuwait oil fires were used by McQueen and Draxler (1994) to determine the accuracy of back trajectories based upon global numerical weather prediction (NWP) models. They found errors of about 10 per cent of the travel distance using the NOAA fine grid model output, and 14 per cent when using the NOAA coarse grid model output.

In this paper numerical trajectories are calculated from the analysed or forecast dynamics and thermodynamics of four different NWP models. For a description of this technique see Warner et al. (1983) or Draxler (1991, 1996). Given the remote location over the Southern Ocean, only global NWP models were routinely available for ACE-1. This paper has three main aims. First, we assess the accuracy of numerical trajectories made over the remote Southern Ocean for ACE-1. Second, following the advice of Kahl (1993) and Pickering et al. (1996), we explore the sensitivity of the Lagrangian numerical trajectories to perturbations in the initial vertical and horizontal position. This provides an insight into how important the meteorology is in interpreting the trajectories and Lagrangian observations. Finally, we assess the impact that the liquid-water loading had on the tetroon trajectories. We begin with a brief description of the synoptic meteorology to put this research in context.

Summary of the logistics and synoptic meteorology

The logistics and meteorology of the Lagrangian experiments have been described in detail in Wang et al. (1999a, 1999b) and Businger et al. (1999). We briefly summarise the relevant points. For clarity, the two Lagrangians of ACE-1 have been labelled LA and LB. LA began at 45.0°S, 141.1°E with the release of a single tetroon (T10) around 13:00 UTC on 1 December 1995; it was monitored for the next 21 hours. LB involved the release of three tetroons (T00, T06 and T08) near 45.6°S, 144.1°E with the first one (T08) being released about 2300 UTC on 7 December 1995, and the latter two being released near 0200 UTC the following day. These tetroons were monitored for approximately 24-27 hours. Only tetroon T00 is used for analysis in this paper.

Tetroons were equipped with limited meteorological instrumentation and a GPS transmitter. Their positions were transmitted to a receiver aboard the NCAR (National Center for Atmospheric Research) C-130 research aircraft. Details of the instrumentation, operation and performance of the tetroons can be found in Businger et al. (1999). The trajectory labelled T10 in Fig. 1 shows the horizontal advection of the tetroon over the course of 21 hours. Elevation records were observed to fluctuate as a consequence of both the inaccuracy of the GPS measurements (~100 m) and the turbulent motions within the boundary layer. These rapid fluctuations in elevation were not averaged out, as one of the goals of this paper is to understand the effect of the vertical shear. Unfortunately the trajectory code used throughout this paper only allowed for hourly adjustments. For the numerical trajectories to be run, a composite elevation history (labelled COMP in Fig. 2) of T10 was created by taking the hourly values and ignoring any interim values; no averaging was undertaken.

Tetroon T10 of LA was launched in the middle of the night into the upper part of the marine boundary layer. Its elevation was recorded to fall to within 200 m of the ocean within three hours of its release (Fig. 2). The limitations of GPS measurements prevented the altitude being known with any greater accuracy (Businger et al. 1999). The elevation for T10 remained low for the remainder of the night (~5 hours). After sunrise its air pressure was recorded to decrease, and T10 returned to the middle of the MBL. Later that day its pressure was recorded as low as 880 hPa, placing T10 near the top of the MBL as observed from the NCAR C-130.

Fig. 1 **The horizontal trajectory of tetroon T10 for Lagrangian A and the numerical trajectories based on GASP, ECMWF, AVN and FNL data. Asterisks indicate six-hour intervals. The heavy line indicates the overnight time period for T10.**

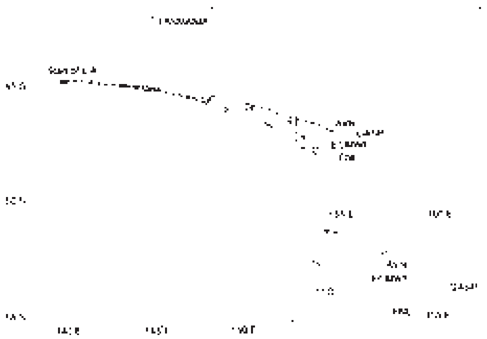
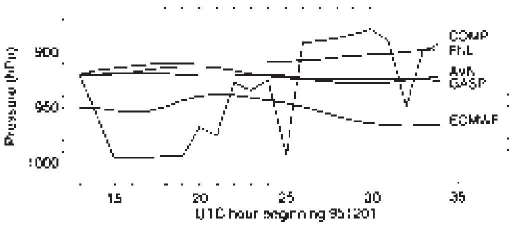


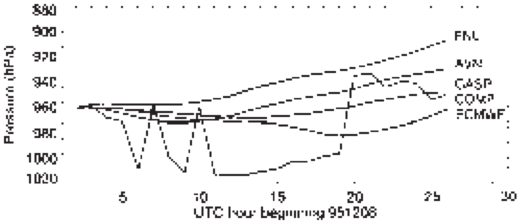
Fig. 2 **The altitude trajectories of T10 and the numerical trajectories based on GASP, ECMWF, AVN and FNL data. The T10 altitude trajectory is a composite of the hourly observations and is labelled COMP.**



The trajectory labelled T00 in Fig. 3 shows the horizontal advection of that single tetroon for Lagrangian LB. All three tetroons of LB were observed to lose elevation sometime near sunset (similar to observations from LA), about eight hours into the experiment. Approximately nine hours later, near sunrise, all three tetroons were observed returned to the middle of the boundary layer. The pressure and tetroon surface-wetness data suggested that condensation from water loading was responsible for the overnight loss of altitude (Businger et al. 1999). Figure 4 shows the composite elevation history of tetroon T00 of Lagrangian B.

Fig. 3 Same as Fig. 1 for tetroon T00 of Lagrangian B.

Fig. 4 Same as Fig. 2 for tetroon T00 of Lagrangian B.



The local meteorology at the beginning of both LA and LB had many similarities. The scientific objectives called for the tetroons to be launched into the middle of a cloud-free boundary layer with the hope that it would remain cloud-free for the duration of the experiment. Observations and theory suggested that the relatively cloud-free air found in post-frontal patterns best met these criteria. Typically the passage of a cold front is followed with a surge of subsiding cold air from higher latitudes. Initially this subsidence allows for only very shallow convection to exist, inhibiting the formation of clouds.

Ideally the horizontal advection of the tetroons should reflect the nearly geostrophic winds found in the MBL. Figures 5(a) and 5(b) show the 1200 UTC mean sea-level pressure (MSLP) for the days 1 and 2 December 1995 of LA as calculated by the Australian Bureau of Meteorology regional forecasting model referred to as RASP. The initial displacement of T10 was consistent with a nearly zonal, post-frontal pattern. At the time of the release, however, the front was ahead of the long wave trough suggesting that it was weakening. This front was not analysed to extend much further to the north.

In the ensuing 24 hours, the long wave trough progressed slowly to the east, while the location of the anticyclone moved from over the Australian Bight to over the Tasman Sea, off the East Coast of Australia. As Lagrangian A progressed, T10 gradually took on a more southerly heading as a consequence of this high over the Tasman. The northern edge of the front was observed to decay throughout LA, with its remains having an east-west orientation by the end of the Lagrangian.

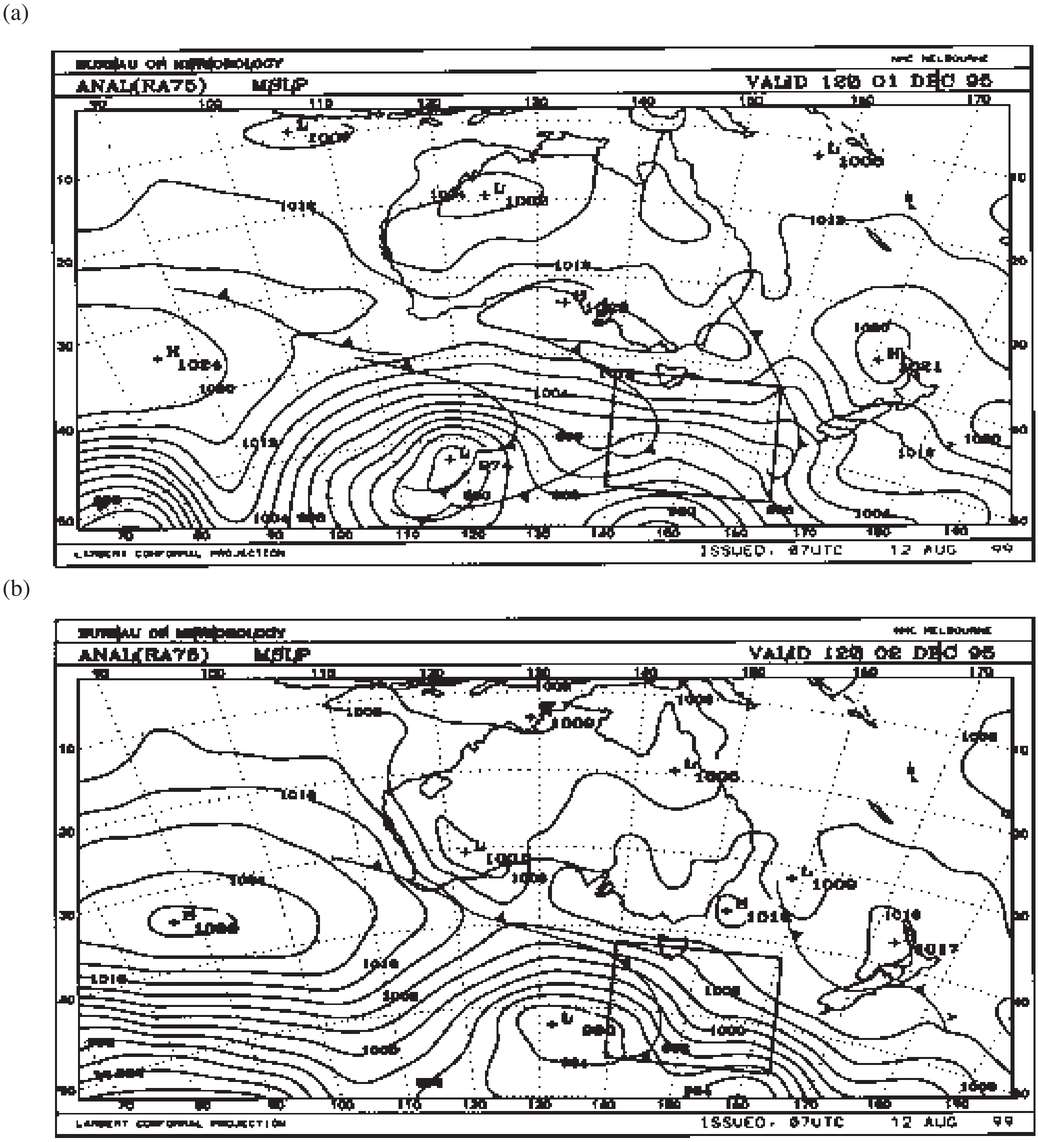
Figures 6(a) and 6(b) show the 0000 UTC MSLP for 8 and 9 December 1995 during LB and reveal many similarities with LA. The tetroons were launched behind a weak cold front with limited northern extent. Similar to LA, the front was coming off a long-wave trough. This time, however, an anticyclone was already located over the Tasman Sea, and the synoptic evolution was vastly different to that of LA. Over the 24 hours a cut-off low crossed the Australian Bight and joined the long wave trough, now located to the west of the tetroons. The anticyclone over the Tasman Sea strengthened and began to resemble a blocking pattern. Accordingly, the surface winds underwent a major shift from westerly to northerly. There was no indication of a front in the later stages of LB.

The structure of the lower troposphere was observed to be complex for both LA and LB with multiple stable layers existing between the surface layer and the free troposphere. A detailed discussion of these observations may be found in Wang et al. (1999a, 1999b). In LA the horizontal winds were nearly zonal in the free troposphere and exceeded 20 m s^{-1}, increasing slightly as the experiment progressed. High wind speeds in the free troposphere are common at these latitudes. In LB, the wind speeds in the free troposphere were initially much weaker (~ 12 m s^{-1}) but increased steadily to over 20 m s^{-1} over the 24 hours. Russell et al. (1998) discuss the existence of a buffer layer between the MBL and the free troposphere in LB. The wind speeds in the MBL were weaker than in the free troposphere with jumps across the numerous layers. The greatest shear occurred between the mixed layer and surface layer.

Assessment of the accuracy of the numerical trajectories

Our first aim is to establish the accuracy of the numerical trajectories used in the interpretation and analysis of ACE-1 observations. We initially envisioned the tetroons as an ideal basis for this assessment. Consistent with the literature, we define the relative error of a numerical trajectory as the ratio of the final

Fig. 5 **The Australian Bureau of Meteorology RASP mean sea-level pressure analyses for (a) 1200 UTC 1 Dec 1995 and (b) 1200 UTC 2 Dec 1995 (Lagrangian A).**

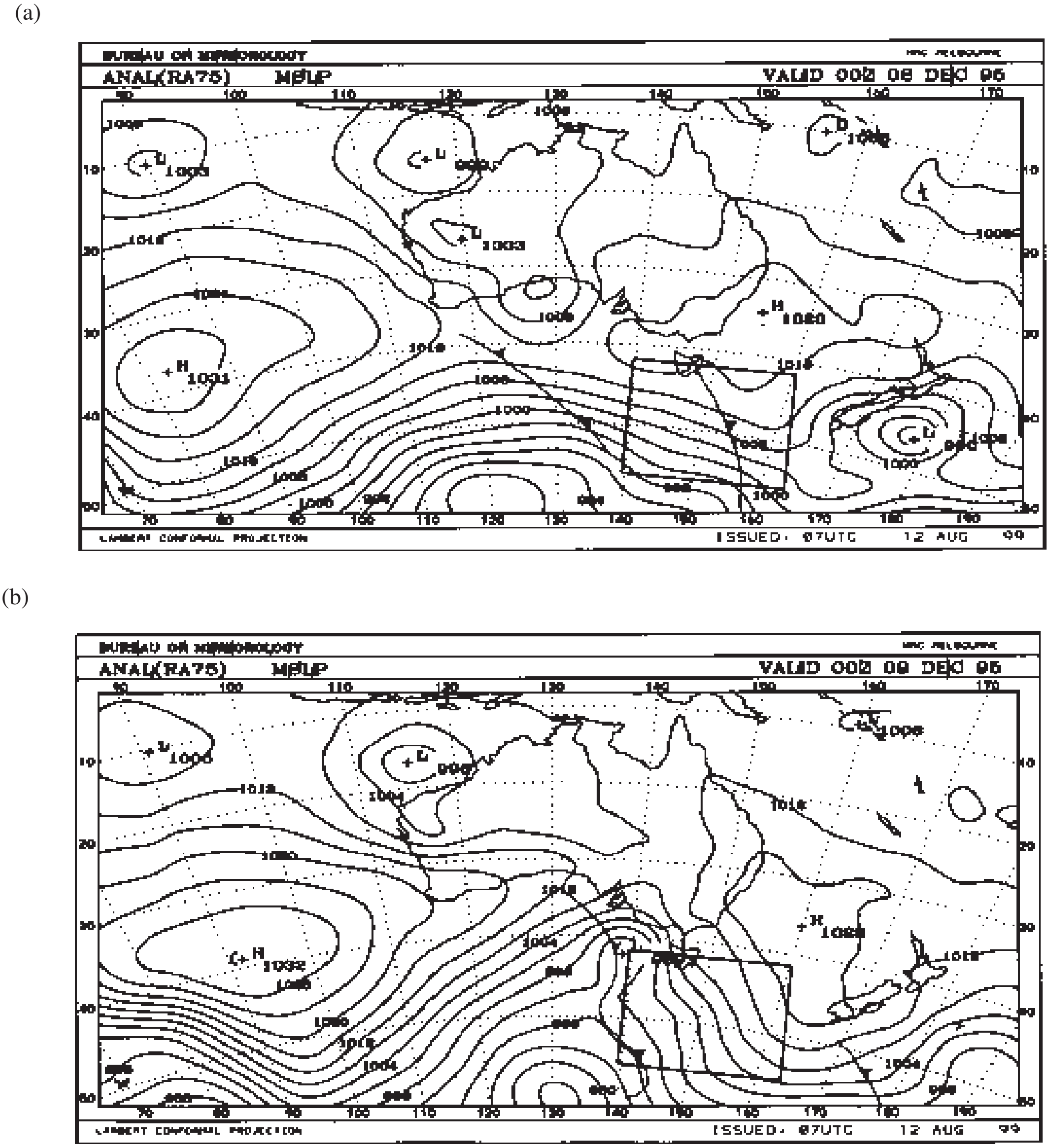


distance between the numerical trajectory and tetroon to the total distance travelled by the tetroon. No account of heading error is made.

The numerical trajectories were produced by the HYSPLIT code (Draxler 1992). They are based on the analyses and prognoses of four different numerical weather prediction models: GASP, the Australian Bureau of Meteorology model (Bourke et al. 1995), the European Centre for Medium-range Weather Forecasts (ECMWF) model, the National Oceanic and Atmospheric Administration (NOAA) aviation (AVN) model and the NOAA medium range forecast (FNL) model. Only global NWP models were routinely available as a consequence of the remote setting.

During ACE-1 GASP was run twice daily. As the temporal resolution plays a major role in determining the accuracy of trajectories (Doty and Perkey 1993; Stohl et al. 1995), we followed the suggestion of

Fig. 6 **The Australian Bureau of Meteorology RASP mean sea-level pressure analyses for 0000 UTC 8 Dec 1995 and 0000 UTC 9 Dec 1995 (Lagrangian B).**



Maryon and Heasman (1988) of using the short-period (six hour) forecast fields to interpolate between model-analysed (12 hour) fields. GASP data fields were post-processed to a horizontal resolution of 2.5 degrees. The vertical resolution was defined in terms of 19 pressure sigma levels with the lowest level above the surface at the 0.991 sigma level – approximately 110 m. The surface winds, however, were not available for these calculations. If a trajectory descended below the 0.991 pressure sigma level, the dynamics and thermodynamics were assumed to remain constant and therefore tended to be overestimated.

The ECMWF model was run with a T213 spectral resolution with data available on a 0.5 by 0.5 degree grid. The model had 31 vertical levels with eight levels below 3000 m. A surface scheme gave winds at 10 m elevation. We only used the six-hour analyses to calculate the trajectories. Similar to the GASP-based trajectories, the AVN model was run twice daily with forecasts at 0600 and 1800 UTC included with the analyses. The post-processed resolution was 190 km horizontally and 13 levels vertically. It had a pressure sigma level at 0.995 (~ 50 m) as well as winds at 10 m generated by a surface scheme. The FNL dataset had a greater temporal resolution than the AVN dataset with four analyses per day, but a poorer horizontal (381 km) resolution. It was post-processed to 12 vertical levels in addition to the 10 m level.

The trajectory calculations used the full three-dimensional wind fields. Arguably, this is more appropriate for Lagrangian studies than maintaining a constant elevation. The tetroons attempted to maintain a constant elevation, however, as they had to respond to updraughts and downdraughts caused by turbulence.

Figures 1 and 3 compare the horizontal tetroon and HYSPLIT trajectories for T10 (LA) and T00 (LB), respectively. For T10, the relative errors of the numerical trajectories range from 12-25 per cent of the total trajectory length. The ECMWF and FNL trajectories are the most accurate while the GASP trajectory fares the worst. All four numerical trajectories overestimate the distance travelled by T10. Draxler (1991) found relative errors to be on the order of 15 per cent in a region of homogeneous flow. Assuming that T10 stayed in the mixed layer the entire 21 hours, we would conclude that these numerical trajectories suffer large relative errors in comparison to previous studies. In LB (Fig. 3) we see that the four numerical trajectories also overestimate the distance travelled by T00 with errors ranging from 18-34 per cent. The ECMWF trajectory is the most accurate while the FNL trajectory is the least.

Directly comparing the numerical trajectories with the tetroon trajectories is misleading. Figures 2 and 4 show the altitude trajectories of T10 and T00 and the numerical trajectories at hourly intervals (labelled COMP, short for composite), respectively. Clearly the numerical trajectories and the tetroon trajectories have vastly different altitude histories. The composite altitude trajectories account for the overnight loss of altitude experienced by the tetroons while the numerical trajectories do not.

The altitudes of the tetroons actually were observed to have variability on a much finer time scale than one hour (Businger et al. 1999) as a consequence of the variability of the GPS readings and turbulent motions within the boundary layer. The numerical trajectories, however, were limited to one-hour time steps. These composite tetroon altitudes will be employed in later sections to help investigate the impact of the vertical fluctuations on error.

The altitude trajectories can be used to calculate the averaged divergence rate over the Lagrangian. Such calculations are of fundamental importance for analysis of the boundary layer evolution (Lenschow et al. 1999). Figure 2 shows that after 21 hours the pressure along the GASP trajectory increased only 7 hPa, the average large-scale divergence is 0.9×10^{-6} s^{-1}. Figures 2 and 4 indicate that the numerical trajectories have vastly different vertical motions amongst themselves, even though they are reasonably consistent for horizontal advection. The divergence rates calculated from these numerical trajectories will vary in magnitude and sign suggesting that little confidence can be placed in any one of them.

We also note that the ECMWF trajectory for T10 (LA) was actually initialised at a lower elevation (~ 30 hPa) than the other numerical trajectories (Fig. 2). (The initial altitude was rather arbitrary as the tetroon was experiencing pressure fluctuations.) In the next section it will be seen that this 30 hPa offset is largely responsible for greater accuracy of the ECMWF trajectory.

Turning to LB (Fig. 4), the numerical trajectories are not observed to approach the ocean surface like T00. All four numerical trajectories show a slow initial descent followed by a steady ascent. Based on the GASP trajectory, the air subsided over the first 15 hours at an average divergence rate of 1.3×10^{-6} s^{-1}. After this time the trajectory turned to the south and began to rise quickly with the divergence giving way to a strong convergence of 3.3×10^{-6} s^{-1}. The four numerical trajectories have large differences between their final altitudes, which again indicates that the derived divergence rates vary considerably.

The overnight altitudes of T10 and T00 prevent a meaningful direct comparison of the numerical trajectories against the tetroon trajectories. It is still possible to use the tetroon observations directly by limiting the comparison to the daylight hours only. For T10 of LA, additional numerical trajectories (not shown) were based on the GASP, AVN and FNL data initialised at 2200 UTC and run for 12 hours. The errors were less than 12 per cent for all three models with the GASP trajectory in error by only five per cent. All three numerical trajectories still overestimated the final position of T10, which likely reflects that T10 spent time in the slower moving regions of the MBL due to turbulent fluctuations.

For T00 (LB) numerical simulations of the initial 8 hours before sunset may be considered (Fig. 3). The ECMWF and AVN simulations both have errors of less than five per cent while the FNL and GASP simulation overestimate distance travelled by ~15 per cent. Comparisons of the GASP, AVN and FNL trajectories re-initialised for the final six hours (not presented) find that the GASP trajectory performed best in the later times with an error of three per cent. Both the AVN and FNL trajectories went too far to the east with errors of about 10 per cent.

In summary, we believe that the numerical trajectories suffer from an error of five to 15 per cent for homogeneous flow patterns. This is comparable to previously reported values (e.g. Clarke et al. 1983; Reisinger and Mueller 1983; Draxler 1991).

Sensitivity of the numerical trajectories to initial position

As discussed in Kahl (1993), it is a common mistake to over-interpret a numerical trajectory as the direct path that an air parcel follows. This mistake applies to tetroon trajectories as well. A simple path does not consider mixing processes in the atmosphere and fails to reveal the possible meteorological influences.

Both Kahl (1993) and Pickering et al. (1996) suggest that perturbing the initial position of the numerical trajectory, both horizontally and vertically, may reveal such insight. The horizontally perturbed trajectories give an indication of the deformation of the flow. When combined with the synoptic meteorology, these trajectories reveal which different air masses can be mixing with the observed air mass. The vertically perturbed trajectories give an indication of the shear. Such insight is particularly important here in understanding the impact of the overnight loss of altitude experienced by the tetroons. Such analysis is now undertaken with GASP-based trajectories only.

Figure 7 shows the effect of perturbing the initial altitude of the trajectories during LA to near the top (889 hPa) and bottom (992 hPa) of the MBL (as observed by the NCAR C-130 aircraft.) The initial surface pressure is 1004 hPa. Ideally, if the MBL were well-mixed, the horizontal velocity would be near-uniform, and all three trajectories would roughly coincide. The observations of Wang et al. (1999a), however, reveal a shear of over 10 m s^{-1} over the MBL indicating it is not a single well-mixed layer. The upper two trajectories show little difference, indicating only weak shear between these levels. The lower trajectory covers less distance and is directed furthest to the south. The southern turn may be in response to Ekman pumping in the surface layer. This turning may be overstated, as the NWPs cannot resolve sharp gradients at the top of the surface layer to resolution limitations.

A re-examination of Figs 1 and 2 suggests that T10 did not travel as far as the numerical trajectories as a consequence of its low overnight altitude. Moreover, it is likely that the ECMWF trajectory was one of the most accurate because it was initialised at a lower altitude. This allowed it to be slowed more by the shear. An ECMWF-based trajectory initialised at a higher elevation trajectory (not shown) is very similar to the GASP top trajectory. Figure 8 shows the original GASP trajectory of T10 and four trajectories generated by perturbing the initial position by 1° in each direction. As the GASP data has a resolution of 2.5°, there is a relatively smooth strain evident in the trajectories. The synoptic meteorology of LA revealed a front just to the north of T10, which is likely to be the cause of this deformation. Research on the evolution of the LA air mass must be particularly careful to consider the potential deformation along the front and the mixing that it will induce. Figure 9 shows the impact of vertical shear during LB by comparing trajectories initialised near the bottom (994 hPa), middle (960 hPa) and top (892 hPa) of the MBL (the initial surface pressure was 1006 hPa.) Again, the difference between these three trajectories reflects the considerable shear in the westerly component of the wind. Consistent with Wang et al. (1999a), this initial difference is weak but becomes much stronger later in the integration. After 24 hours, we find the trajectories to vary by ~ 6° longitude.

Figure 9 provides new insight into the trajectory of T00 (Figs 3 and 4). Initially the motion was nearly zonal as dictated by the geostrophic wind, but as night approached T00 descended to near the surface. The trajectory actually has a kink at this time as the tetroon slowed and took on a more southerly heading. Again, the strong southern turn is likely to be in response to Ekman pumping in the surface layer. After nine hours the tetroon rose, and the trajectory reflects this with a second kink. The heading of T00 becomes more easterly as it ascends into the MBL.

Finally, the sensitivity of the numerical trajectories to 1° perturbations in the initial latitude and longitude is considered for T00 of LB (Fig. 10). The five trajectories, initialised in the middle of the MBL, reveal that the flow experienced rotation but little strain over 24 hours. This is consistent with the synoptic meteorology in which the initial nearby front decayed quickly and was not evident at later stages. Analysis of the evolution of the LB air mass probably does not need to consider horizontal mixing resulting from deformation. Figure 10 also reveals that while the advection in LB is being dominated by the cyclonic system to the south, the local rotation of the five trajectories is anti-cyclonic at a rate of approximately 1.6×10^{-5} s^{-1}.

A second comparison of the numerical and tetroon trajectories

The previous section suggests that the response of the tetroons to their low overnight altitudes is consistent with the synoptic meteorology during both LA and LB. While we know the GPS-based measurements of

Fig. 7 Three numerical trajectories for LA with bottom (992 hPa), original (920 hPa) and top (889 hPa) initial pressures. T10 indicates the observed trajectory as in Fig. 1. Asterisks indicate six-hour intervals.

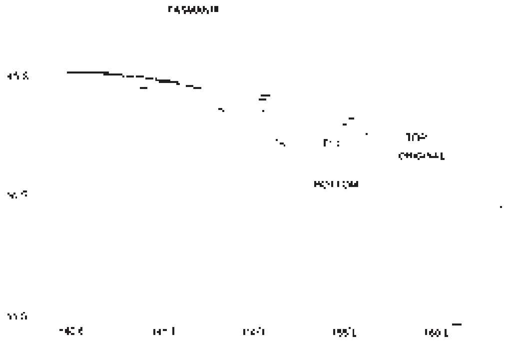


Fig. 8 Five numerical trajectories for LA with initial pressures of 920 hPa and initial position offset 1° in each direction, north (N), south (S), east (E) and west (W), from the original position (C).

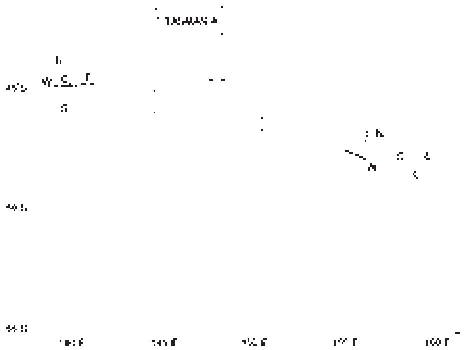


Fig. 9 Three numerical trajectories for LB with bottom (994 hPa), original (960 hPa) and top (892 hPa) initial pressures. T00 indicates the observed trajectory as in Fig. 3. Asterisks indicate six-hour intervals.

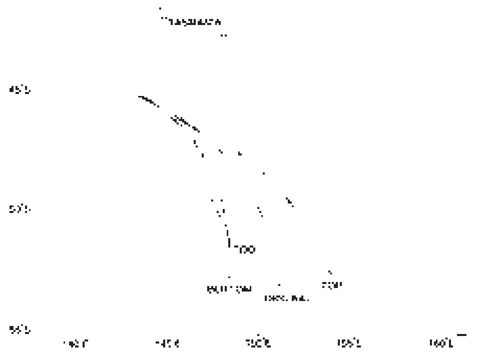
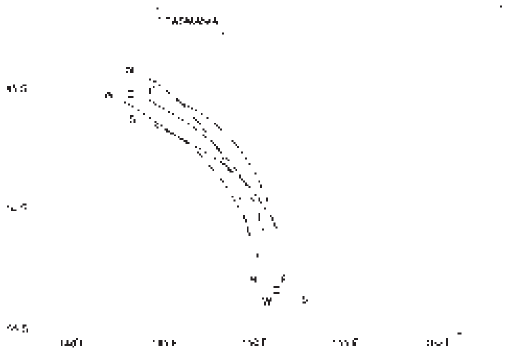


Fig. 10 Five numerical trajectories for LB with initial pressures of 960 hPa and initial position offset 1° in each direction, north (N), south (S), east (E) and west (W), from the original position (C).



the tetroons' altitude placed them to within 200 m of the ocean surface, we do not know the precise elevation. This is a very important question in analysing the evolution of the air masses. A height of 100 m above the ocean typically extends beyond the surface layer and into the bottom of the MBL; it determines whether the Lagrangian framework is valid or not. Numerical trajectories, based on global NWP fields, cannot definitively answer this question either, although they can provide some fresh insight.

Consider numerical trajectories in which the altitude is prescribed to match the tetroon records, i.e. the composite (COMP) altitudes of Figs 2 and 4. Such trajectories have been made with the GASP, AVN and FNL datasets. The ECMWF dataset was not available for these calculations. As stated earlier, the GASP dataset is limited in the surface layer; winds from ~110 m to the surface are set to the ~110 m value. The AVN and FNL datasets include 10 m wind speeds, which are derived by mixing length theory with a prescribed surface roughness length for the ocean.

Starting with numerical trajectories for T10 of LA, the altitude is set to 70 m two hours into the simulation. After two hours at 70 m, the altitude is set to 10 m for the remaining three hours before sunrise. After sunrise, the prescribed altitudes are set above the surface layer and the numerical trajectories are no longer sensitive to small changes. The prescribed altitude trajectories of Fig. 11 are more accurate than in the original numerical trajectories of Fig. 1. The error in the GASP-based trajectories is reduced from 25 per cent to 15 per cent, the AVN error is reduced from 14 per cent to eight per cent, and the FNL error is reduced from 15 per cent to five per cent.

Focussing on the overnight time period in Fig. 11, the trajectories appear to be too strongly to the south.

One might conclude that the altitudes were set too low, but this is unlikely. Additional AVN and FNL based trajectories which have minimum altitudes prescribed to 100 m for the five overnight hours (not shown), show that the initial headings remain too strongly to the south, while the errors in the distance travelled grow to over ten per cent. AVN and FNL based trajectories which have minimum altitudes prescribed to 200 m for the five overnight hour period (not shown) show an improvement in heading, but the errors in distance travelled increase to 12 per cent and 13 per cent respectively. These trajectories suggest that tetroon T10 descended well below 100 m altitude.

Figure 12 shows the altitude prescribed trajectories for T00 of LB. Overnight, the altitudes were set at 10 m for seven hours and then 40 m for the final two hours before sunrise. Again, all three adjusted trajectories show much less error than those in Fig. 3. The GASP error is reduced from 31 per cent to 23 per cent, the AVN error is reduced from 25 per cent to 5 per cent and the FNL error is reduced from 34 per cent to 15 per cent.

Focussing on the nine hour overnight time period, the orientation is not an issue for LB. The absolute distance travelled, however, remains a problem for the GASP based trajectory; the error is still 33 per cent for these nine hours. This is primarily due to the limitation of ~110 m winds overnight. The AVN based trajectory slightly overestimates the total distance travelled while the FNL based trajectory slightly underestimates total distance. Both perform considerably worse (~ 20 per cent error) when the minimum altitude is prescribed to 100 m overnight (not shown). This suggests that T00 also descended well below 100 m overnight.

Fig. 11 **The observed trajectory of tetroon T10 and prescribed-altitude numerical trajectories based on GASP, AVN and FNL data. Asterisks indicate six-hour intervals. Heavy lines indicate the overnight period of the trajectories.**

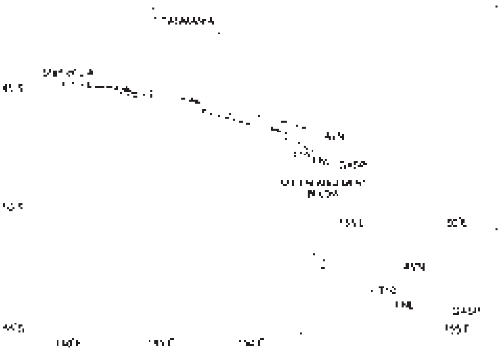
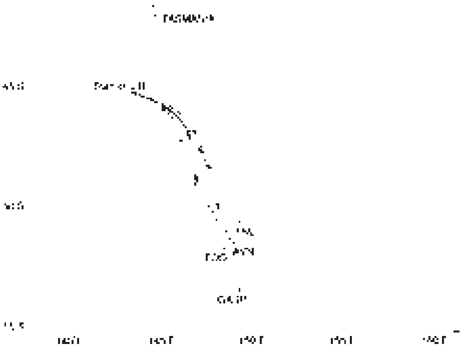


Fig. 12 **Same as Fig. 11 for tetroon T00 of Lagrangian B.**



Summary

The Aerosol Characterization Experiment (ACE-1) performed two Lagrangian experiments over the remote Southern Ocean in which pressure-adjusting smart tetroons were tracked for approximately 24 hours. The scientific aim was to determine the physical and chemical processes controlling the formation and fate of aerosols and how these processes affect the number size distribution. These smart tetroons, however, experienced liquid-water loading overnight due to condensation and descended from the upper part of the MBL to within 100 m of the ocean surface. It is not clear just how close to the surface the tetroons dropped.

Numerical trajectories based on global NWP output suffer greater errors (12-34 per cent) than reported in the literature for homogeneous flows. This is because the low overnight altitudes prevented the tetroons from staying within a mixed layer; the flow is not homogeneous. Using the daylight portions of the trajectories, we found the accuracy (5-15 per cent) to be consistent with the literature for homogeneous flow patterns. The daytime error was greater in LA when a poorly resolved front was present throughout. While all four trajectories showed consistent patterns of horizontal movement, their vertical motions were not consistent. We do not have much confidence in either the divergence rates or subsidence velocities derived from global NWP analysis.

Following the suggestion of Kahl (1993) and Pickering et al. (1996) we performed a sensitivity study to perturbations in the initial coordinates of the numerical trajectories to give an indication of the importance of the synoptic meteorology. Both LA and LB exhibited strong vertical shear consistent with the observations of Wang et al. (1999a). The response of the tetroons to the overnight loss of altitude is consistent with the observed shear. The tetroons were slowed and took on a more southerly heading. The horizontal sensitivity studies suggest that the flow during LA was vulnerable to a strain, which most likely reflects the nearby front. Air mass evolution studies undertaken by the ACE-1 community should take this into account.

The combination of the overnight loss of altitude and the vertical shear is likely to be the greatest source of error between the observed tetroon trajectories and the numerical trajectories. Numerical trajectories which had their altitude prescribed hourly, had greatly reduced errors. If numerical trajectories were prescribed to descend to 100 m overnight, their errors were in the range of 10-23 per cent. If the trajectories were set to 10 m elevation overnight, the errors were reduced to 5-15 per cent. This suggests that the tetroons descended to an altitude of order 10 m overnight. Strictly speaking, the MBL Lagrangian framework was violated during both LA and LB. Special consideration should be given in making budget and evolution studies for these experiments.

Notwithstanding the shortcomings of the model data, the sensitivity studies presented highlight the limitations of the Lagrangian framework in a MBL characterised by moderate vertical wind shear. Our studies show that this approach depends on the homogeneity of the air mass and the degree of vertical mixing present.

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