Objective Analysis of Constant Altitude Aircraft Measurements in Thunderstorm Inflow Regions

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ABSTRACT

Objective numerical techniques are applied in analyzing constant altitude aircraft measurements obtained from coordinated research flights in thunderstorm inflow regions. The approach combines meteorological and flight track data from dual or single aircraft missions in a common frame of reference and transforms the observations from original analogue format to horizontal two-dimensional Cartesian coordinates. Operational procedures guiding the data collection, intercomparison techniques for refining instrument calibrations and corrections for aircraft navigation errors are all considered.

Results of the interpolations are judged in the context of the storms' associated radar echo features. Primary applications include calculation of water vapor influx in cloud base updrafts. Evidence indicates that the fullest exploitation of the inflow mapping will come through combining kinematic fields observed concurrently by aircraft and multiple Doppler radars.

1. Introduction

Nearly all of the major branches of thunderstorm circulation can be observed effectively through application of some form of radar or other remote sensing technology. One notable exception is the cloud base inflow sector where the number and/or size of radar targets do not consistently provide detectable signal. In this important region it is necessary to obtain direct measurements of airflow and moisture content through systematic aircraft observation. Techniques in the use of aircraft for this purpose were developed in the 1960's (Auer and Sand, 1966; Auer and Marwitz, 1968; Auer *et al.*, 1970; Marwitz, *et al.*, 1972) and used extensively in the National Hail Research Experiment (Fankhauser, 1976, 1982; Wade and Foote, 1982).

In the mature thunderstorm investigations conducted in the Cooperative Convective Precipitation Experiment (CCOPE), coordinated inflow-mapping was performed by two similarly equipped Beechcraft Queen Airs operated by the Research Aviation Facility of the National Center for Atmospheric Research (NCAR). An outline of the scientific objectives of CCOPE, a description of the experimental approach, and a list of available observing facilities are given by Knight (1982). This paper describes operational flight plans specific to the mature storm inflow studies; quality control and calibration procedures; the development of objective analysis routines for transforming

the aircraft data, observed in analogue format, into storm-relative two-dimensional Cartesian space; and some potential uses for the interpolated kinematic and thermodynamic fields.

The requirement for spatially continuous distributions of wind and thermodynamic quantities in the thunderstorm inflow sector guided the development and application of objective analysis techniques. Vertical flux of water vapor is a major component in the total water budget of convective storms, and the evaluation of the latter was a specific objective of the mature storm studies in CCOPE. We, therefore, use examples of the shape, position, and coverage of calculated fields of moisture flux to access the validity and utility of the analysis results. The paper concludes with a comparison of aircraft wind components produced by objective interpolation with those observed concurrently by a multiple Doppler radar network, and with suggestions for combining the two to improve cloud base inflow coverage.

2. Operational procedures

Idealized flight patterns designed to measure vertical air mass and moisture flux in clear air a few (one to three) hundred meters below cloud base are shown schematically in Fig. 1. The stippled region represents radar echo corresponding to the visible precipitation shaft. Broad arrows designate mean storm and relative air motion, as indicated, and the thin solid lines are updraft isotachs. Dashed and dotted lines distinguish the paths of the two aircraft which were to be flown simultaneously at constant altitude while maintaining

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FIG. 1. Research flight patterns designed for dual-aircraft cloud base inflow studies in CCOPE. The stippled region represents cloud base radar echo. Broad arrows designate mean storm and air motion vectors as indicated, and thin contours are updraft isotachs. Dashed and dotted lines differentiate the aircraft flight tracks flown simultaneously.

visual contact as much as possible. The double race-track pattern, designated as A-1, was designed to send each of the aircraft through the updraft core on opposite headings with a minimal time delay. Variations in Pattern A-2 include a short segment where one aircraft was flown in-trail of the other until the lead aircraft received indications that it had passed through the strongest updraft. At that time word was passed by radio to the trailing aircraft that it should

make a 90° turn and proceed outbound, ideally passing through the heart of the updraft. Pattern A-2 not only extended the areal coverage of the inflow sector but also provided an opportunity to compare the output from the aircraft data systems during the overlapped portions of the pattern.

The position and orientation of the flight tracks were usually determined by using the sub-cloud rain shaft as a reference, but information on radar echo configuration and evolution was also available through radio communication with a ground-based operations center (Biter and Johnson, 1982). Leg length, which was to begin outside and extend beyond the region of updraft ($w > 0 \text{ m s}^{-1}$), was determined from on-board digital readout of vertical air velocity.

Pattern A as outlined in Fig. 1 was flown with varying degrees of success on 10 to 15 occasions during the 1981 CCOPE summer field program. When flown beneath an average-sized storm (10 to 20 km diameter), the combined tracks (A-1 and A-2) typically consumed 15 to 20 min of flight time. It was best suited for investigating isolated storms or selected inflow segments in a larger convective cluster. When convection took the form of squall lines, the patterns were altered somewhat to exploit the two-dimensionality of the lines. Occasionally only one Queen Air was available for cloud base surveillance. In such cases attempts were made to alternate between Patterns A-1 and A-2. The analysis scheme to be described was developed using the data from a well-flown two-aircraft mission but it has been successfully applied to several single-aircraft missions and to some cases where the actual flight patterns departed significantly from those illustrated in Fig. 1.

3. Instrument calibrations and data reprocessing

Since measurements from different aircraft platforms were to be combined in subsequent analyses, it was necessary to apply the best possible refinements to the instrument calibrations. Two types of tests were conducted in CCOPE to insure data quality in the field—periodic low-level flights past instrument standards mounted on a temporary tower (Tower Fly-bys) and routine inflight Aircraft Intercomparisons (AICs). These checks were essential for verifying proper instrument performance during the experiment and for identifying appropriate calibration refinements to be incorporated in the archive produced for research use.

a. Tower fly-bys

Tower fly-bys were performed to help determine the absolute accuracy of measured state parameters, such as pressure, air temperature and dew point temperature, and to verify that dynamic effects of flight upon these measurements are properly compensated in the data reduction software. During a fly-by test, an aircraft made several straight-and-level passes

at different air speeds by the instrumented tower platform, which in CCOPE was approximately 20 m above ground level. Typically, six passes were made at each of three flight speeds bracketing the normal research range.

Tower instrumentation included a digital pressure sensor, a surveyor's altimeter, and redundant temperature and moisture sensors. In addition to recording the meteorological readings and the time when the aircraft was abeam of the tower, a transit was used to determine the flight level departure from the height of the tower. If this exceeded ± 3 m, the pass was rejected.

Table 1 gives a representative example of tower fly-by results. When atmospheric conditions were conducive to acceptable comparisons (i.e., a stable well-mixed surface boundary layer), the departures of the NCAR Queen Air measurements from the tower standards were at most times well within the specifications and required tolerance for the aircraft instrumentation (CCOPE Data Inventory, 1982).

b. Aircraft intercomparisons (AIC)

The CCOPE Operations Plan called for aircraft with compatible flight speeds to fly in close formation at opportune times during research missions for the purpose of comparing the observed meteorological variables under actual flight conditions. These intercomparisons between two or three aircraft were flown ideally in relatively uniform atmospheric conditions usually to and from the area of primary research. For effective comparison straight-and-level flight legs of

at least 2-min duration were to be flown at normal research flight speed and altitude ranges. If the intercomparing aircraft had the capability for measuring horizontal winds (as the NCAR Queen Airs did), a second 2-min leg flown on a reverse heading was considered desirable. This was not always possible, especially with the NCAR Queen Airs, because of limited on-station time and restricted fuel capacity caused by weight limitations.

Table 2 shows typical results from a 2-min flight leg during an intercomparison between the NCAR Queen Airs (N304D and N306D). Where redundant instrumentation exists (i.e., temperature, dew point, pressure, and true air speed), data from primary (PRI) and secondary (SEC) sensors are specified. Since there is no basis for establishing an absolute standard in flight, the choice of a reference platform is somewhat arbitrary. For the NCAR Queen Air comparisons, N306D was designated as the reference aircraft. The 2-min average of differences obtained by subtracting 1-s values from the N306D data system from those of N304D are listed in the first column of Table 2. Once again, all of the departures between aircraft are within instrument specifications, but here, of course, they must be judged in a relative sense.

c. Combined results

The instrumentation performance analysis is enhanced by combining results from the tower fly-bys and aircraft intercomparisons. This merges the absolute tower comparison results which are generally unrepresentative of normal research flight conditions

TABLE 1. Tower fly-by results from NCAR Queen Air N306D on 5 August 1981. Time recorded on an instrumented tower is given in column 2. Column 3 lists the aircraft's true air speed (TAS) during each pass. Columns labelled pressure, temperature and dew point give the 5-s average aircraft measurement (A/C) and its departure (-Twr) from the tower standard.

Pass	Tower time (MDT)	TAS (M/S)	Pressure		Temperature (°C)		Dew point (°C)	
			A/C	-Twr	A/C	-Twr	A/C	-Twr
1	0608:25	66.1	930.3	-0.4	15.9	0.0	14.3	0.7
2	0612:47	65.9	930.2	-0.4	15.9	0.0	14.3	0.6
3	0617:14	74.0	930.4	-0.2	15.4	0.1	14.2	0.6
4	0621:17	73.4	930.5	-0.3	15.0	0.0	14.2	0.6
5	0625:18	83.4	930.8	-0.2	15.1	0.1	14.2	0.5
6	0629:11	83.8	930.7	-0.2	15.3	0.0	14.2	0.6
7	0633:18	65.7	930.3	-0.6	15.2	0.2	14.3	0.5
8	0737:17	66.0	930.3	-0.6	15.5	0.2	14.3	0.6
9	0641:10	75.2	930.5	-0.2	15.8	0.0	14.3	0.7
10	0645:12	75.0	930.6	-0.3	15.9	0.0	14.3	0.8
11	0649:14	85.9	931.0	0.0	16.2	0.2	14.2	0.5
12	0653:14	85.6	931.0	-0.1	16.3	0.2	14.1	0.7
13	0657:10	66.4	929.9	-1.1	16.3	0.1	13.7	0.2
14	0700:05	66.7	930.6	-0.7	16.2	0.1	14.1	0.6
15	0703:17	66.7	930.9	-0.4	16.2	0.0	14.1	0.7
16	0706:15	73.8	931.2	-0.4	16.1	0.0	14.2	0.7
17	0709:06	74.2	931.0	-0.3	16.1	0.1	14.3	0.8
18	0712:07	85.2	931.2	-0.2	16.1	0.2	14.3	0.5
19	0715:12	84.6	931.6	0.1	16.1	0.2	14.5	0.7
Mean value				-0.3	0.1		0.6	
Standard deviation				0.3	0.1		0.1	

TABLE 2. Results of a 2-min (1731:00–1733:00) intercomparison between the NCAR Queen Airs (N304D and N306D) during a research mission on 12 July 1981. The first column (Delta) is the average difference between the 1-s value of a parameter from N304D and the reference aircraft, N306D. Columns 2 and 3 give means for the 2-min legs. Standard deviations of parameters for both aircraft are given in columns 4 and 5.

	Delta	Mean		Standard deviation	
		N304D	N306D	N304D	N306D
Rosemount temp (°C)	0.48	18.91	18.44	0.08	0.08
Reverse flow temp (°C)	0.19	18.65	18.45	0.08	0.08
Dew point-primary (°C)	-0.51	3.78	4.29	0.43	0.35
Dew point-secondary (°C)	-0.57	3.44	4.01	0.45	0.45
Pressure-primary (mb)	-0.19	799.25	799.44	0.35	0.41
Pressure-secondary (mb)	-0.28	799.19	799.47	0.37	0.37
Mixing ratio (g/kg)	-0.23	6.29	6.52	0.19	0.16
Potential temperature (k)	0.53	311.39	310.86	0.08	0.09
Virtual potential temperature (k)	0.49	312.56	312.07	0.07	0.07
Equivalent potential temperature (k)	-0.10	330.66	330.75	0.52	0.42
Wind direction (deg true)	-4.43	160.38	164.80	5.01	5.07
Horizontal wind speed (m/s)	0.62	6.17	5.55	0.58	0.58
Vertical wind speed (m/s)	-0.58	0.01	0.59	0.22	0.22
Aircraft heading (deg true)	-0.40	135.44	135.85	0.98	1.06
TAS-primary (m/s)	0.63	79.68	79.05	1.32	1.12
TAS-secondary (m/s)	1.06	79.68	78.62	1.32	1.11
Ground speed (m/s)	0.30	74.08	73.78	1.17	0.98

with relative comparisons obtained during actual research flights.

Table 3 gives the seasonal intercomparison profiles for two basic thermodynamic variables—air temperature and dew point temperature. Between 1 June and 1 August 1981 the instrument systems were compared on ten different research flights. Three of these involved only one leg so that there is a total of 17 flight legs. Throughout the season the discrepancy in air temperature is consistent with the tower fly-by results wherein N304D showed little departure from the tower standards, while N306D displayed a consistent bias of -0.3°C . Differences in dew point temperature, however, display considerably greater day to day fluctuation throughout the season. The approach adopted here was to use those intercomparison results nearest in time to the research interval of interest and to apply all of the correction to the N306D dew point data since its tower fly-by performance and intercomparisons with other project aircraft indicated a consistent positive bias. This was a fairly sound recourse for research data collected on dates when AICs were available, but less so for days when they were not. In any event, the correction applied to dew point never exceeded -0.8°C .

d. Renavigation

Accurate positioning of the aircraft data is essential, particularly if measurements from several aircraft are merged, otherwise false gradients will be introduced. The NCAR Queen Airs were instrumented with an inertial navigation system (INS) that uses an orthogonal triad of accelerometers mounted on a gyro-

stabilized platform to measure the aircraft attitude angles and accelerations along three orthogonal axes. Aircraft velocity is computed by integrating the accelerations and aircraft position by integrating the velocity; thus, any acceleration errors accumulate with time and yield corresponding velocity and position errors. Due to the nature of the INS acceleration errors introduced by an accelerometer bias or gyro drift result in velocity and position errors that oscillate with an 84-minute period known as the Schuler oscillation (Beck, 1971). While additional errors exist in velocity and position, the ones induced by acceleration predominate. These can be approximated by a function of the form

$$f(t) = a_0 + a_1 t + a_2 \sin \omega t + a_3 \cos \omega t \quad (1)$$

where ω is the Schuler period, t is time, and the a_i coefficients are constants that are solved to yield a least-squares fit to the INS errors. Equation (1) includes a monotonically increasing time dependent error and an oscillating error with the Schuler frequency. Figure 2 shows an example of INS position errors (or corrections) and the least-squares fit using (1).

e. Data reprocessing

A special software package was designed to incorporate the calibration refinements and renavigation results described in preceding sections. The system was written to reprocess data from the NCAR aircraft and is dynamic in its ability to operate on data from other aircraft obtained in a variety of experimental modes. Data are processed at low rate (one sample

TABLE 3. Results of all 2-min intercomparisons between the NCAR Queen Airs during CCOPE for temperature and dew point. Column format is the same as Table 2. Flight code is two digit flight and two digit leg numbers.

Date (1981)	Flight code	Delta	Mean		Standard deviation	
			N304D	N306D	N304D	N306D
Rosemont temperature (°C)						
4 June	0101	0.12	4.14	4.02	0.22	0.19
12 June	0101	0.23	14.44	14.21	0.19	0.17
12 June	0102	0.28	14.55	14.27	0.21	0.13
19 June	0101	0.22	6.71	6.49	0.08	0.08
19 June	0102	0.25	6.94	6.70	0.13	0.13
20 June	0101	0.22	15.55	15.32	0.13	0.12
20 June	0102	0.27	15.75	15.48	0.14	0.12
20 June	0201	0.22	9.81	9.59	0.21	0.21
12 July	0101	0.48	18.91	18.44	0.08	0.08
12 July	0102	0.50	19.22	18.72	0.29	0.30
13 July	0101	0.23	20.16	19.93	0.36	0.38
13 July	0102	0.21	20.38	20.17	0.24	0.27
21 July	0101	0.20	5.69	5.49	0.10	0.11
21 July	0102	0.20	5.77	5.58	0.08	0.07
23 July	0101	0.30	12.40	12.10	0.12	0.13
23 July	0102	0.30	12.40	12.10	0.16	0.16
1 August	0101	0.11	24.12	24.00	0.06	0.06
Dew Point (°C)						
4 June	0101	-0.97	0.96	1.93	1.58	0.28
12 June	0101	-0.26	11.71	11.96	0.73	0.38
12 June	0102	-0.44	10.57	11.01	1.69	1.09
19 June	0101	-0.10	3.44	3.54	0.39	0.35
19 June	0102	-0.11	2.62	2.73	0.46	0.40
20 June	0101	-0.06	5.15	5.21	0.42	0.38
20 June	0102	-0.08	4.95	5.04	0.51	0.33
20 June	0201	-0.48	2.23	2.71	0.36	0.30
12 July	0101	-0.51	3.78	4.29	0.43	0.35
12 July	0102	-0.47	3.43	3.89	0.85	0.81
13 July	0101	-0.23	12.75	12.98	0.55	0.51
13 July	0102	-0.10	13.19	13.29	0.86	0.81
21 July	0101	-0.86	-0.12	0.75	0.11	0.10
21 July	0102	-0.86	0.02	0.85	0.18	0.16
23 July	0101	-0.82	4.17	4.99	0.10	0.08
23 July	0102	-0.83	4.10	4.93	0.10	0.08
1 August	0101	-0.34	10.35	10.69	0.17	0.17

per second) and a capability exists for reducing high rate data (twenty samples per second) to low rate.

Corrections to the state parameters (temperature, dew point, and pressure) are straightforwardly applied as incremental adjustments to the observed values. These corrected variables are then used to recompute such conservative thermodynamic parameters as mixing ratio, potential temperature, and equivalent potential temperature. Adjustment of the vertical component of air motion is also applied as a bias, determined from the AIC results and typically amounting to only a fraction of a meter per second. (See e.g., column 1, Table 2.)

An important function in the data reprocessing is the systematic correction of the horizontal air velocity vectors based on the resolved navigational errors. The trigonometric function (1) described in the foregoing

section is used to recompute aircraft position and velocity; the latter is differentiated to obtain corrected scalar components of the horizontal air motion (u , v).

After refinements and adjustments have been applied to all parameters requiring correction, the results are written to tape in a standard low rate (1 s^{-1}) data format for input to the objective analysis algorithm. The newly processed data files can also be read by the GENPRO software system (Lackman and Friesen, 1983) to produce revised graphics and 1 sec^{-1} listings of the corrected data.

4. Objective analysis of aircraft measurements

Once a rigidly calibrated set of constant altitude aircraft measurements has been positioned properly with respect to a fixed reference location, these data can be remapped to a two-dimensional Cartesian coordinate grid. Conversion of these measurements to a regular grid facilitates the construction of contoured displays, the evaluation of kinematic quantities such as divergence, vorticity, and moisture flux and it also provides a mechanism whereby aircraft information can be physically merged with conventional and Doppler radar analyses.

Constant altitude aircraft data can be successfully remapped to a two-dimensional coordinate system in a storm relative framework provided the following conditions have been fully satisfied:

1) All input measurements, particularly the aircraft positioning information, must be clean, continuous,

FIG. 2. Aircraft position corrections determined by comparing x , y locations recorded by an airborne Inertial Navigation System with those from a ground based Multiple Aircraft Positioning System, MAPS (Johnson and Fink, 1982). The long-term accuracy of the MAPS is used to identify drift and bias in the INS as described in the text.

and accurate. The incorporation of even a single "bad" (i.e., out of range) datum will have a significant adverse effect on the analyzed field although it may not be apparent in the final product. Furthermore, when data from more than one aircraft are utilized in an analysis, any intersystem biases must first be removed to avoid generating fictitious gradients in two-dimensional space. Details regarding the procedures employed to ensure the integrity of the input measurements have been outlined in the previous section.

2) The observed region of interest must not exhibit any significant evolution or differential motion during the 10 to 20 minute time period that was typically required to complete the flight patterns illustrated in Fig. 1. The temporal stability of the airflow and thermodynamic fields can best be assessed by comparing original aircraft measurements at points where the storm-relative tracks overlap or intersect. Independent sources such as radar, surface mesonet and cloud photography can also be used to assess the temporal stability of the observed storm.

3) Selection of relevant flight segments is crucial to the successful retrieval of the measured fields. For reasons of safety and other logistical constraints, not every pattern flown results in a representative mapping of the observed region. Plotted displays of storm-relative tracks are the primary tool for determining which flight segments will provide the best spatial coverage during the period of investigation. Care should be exercised to avoid analyzing track patterns that contain long unbounded legs or large data void regions perpendicular to the flight paths.

A software package called ACANAL (AirCRAFT ANALysis) has been developed on the CRAY-1A at NCAR for the objective analysis of aircraft measurements which satisfy the foregoing criteria. The first step in this remapping procedure is the identification of time series data segments that can be used as input in deriving two-dimensional fields at some fixed analysis or "anchor" time. Figure 3a shows the actual ground tracks flown by two NCAR Queen Airls during a 16-min period of inflow research on 23 July 1981. The paths are distinguished by plus and Y symbols plotted at 12-s intervals along the tracks. Circles represent 1-min positions.

In order to reposition the aircraft data properly within the framework of a moving storm, it is necessary to select a fixed analysis time and to advect each individual 1-s report either forward or backward in space with respect to the observed storm motion. Since the position and orientation of the flight tracks were largely determined by using the visual sub-cloud rain shaft as a reference, the most straightforward approach for calculating storm speed and direction is to examine the displacement of the cloud-base echo pattern during the data collection period. Although

this is the preferred method, other storm motion indicators that may be used include Doppler radar derived winds, tracking the movement of the down-draft-outflow boundary through the surface mesonet and the systematic analysis of cloud photography. After examining these criteria it was concluded that the storm of interest was moving from 280° at a speed of 11 m s^{-1} . An analysis time of 1603 MDT was chosen because it lay near the middle of the collection period and because it coincided with the time of a full volume scan taken by the primary research radar (CP-2) whose coordinates are given on the grid boundaries. The results of advecting the aircraft positions in Fig. 3a with respect to this storm motion vector are illustrated by the tracks in Fig. 3b. Earth referenced horizontal winds, as measured by the two aircraft, are plotted at 12-s intervals along the tracks. These vectors, derived from the measured (u , v) wind components, are scaled so that 5 km of length represents 20 m s^{-1} .

The basic processed data rate for the aircraft acquisition systems was one sample per second. With an average ground speed of $\sim 80 \text{ m s}^{-1}$, the spatial

FIG. 3. (a) Ground tracks of the two NCAR Queen Airls (plus and Y) flown near cloud base (3.2 km MSL) in the inflow sector of an isolated thunderstorm over southeastern Montana on 23 July 1981 during the period indicated at top center. Tracks begin at upper left and circles designate 1-min positions. (b) Flight tracks in (a) re-positioned to storm location at 1603 MDT using the velocity vector (V_s) indicated at upper-left. Earth-referenced wind vectors are plotted at 12-s intervals along the tracks. Vectors originate on the track and are oriented in the direction of flow with a magnitude scale of $5 \text{ km} = 20 \text{ m s}^{-1}$. Grid boundaries show x , y position (km) relative to research radar.

separation of data points is approximately 80 m. Although this and higher frequency information is of considerable scientific interest, it is preferable to obtain a data density along flight tracks that is comparable to the cross track resolution. For this reason the time series of all input parameters are smoothed using a low pass filter with a selectable lower threshold. For the case illustrated in Fig. 3b, where typical intertrack distances vary from 1 to 5 km, a 30-s cutoff was chosen to effectively dampen any spatial scales along the tracks below 2.5 km.

The orthogonal wind components (u , v , w) measured by NCAR Queen Air 304D are shown plotted as analogue time series in Fig. 4. The effects of low pass filtering using a 30-s threshold can be observed by comparing the traces before (dashed) and after (solid) its application. For each of the wind components high frequency variations have been successfully removed without altering the larger scale characteristics contained in the original trace. For input to the objective analysis, data are extracted from the filtered time series at 12-s intervals (~ 1 km). These incre-

FIG. 4. Calibrated orthogonal wind components (u , v , w) obtained from NCAR Queen Air N304D during indicated time interval. Data correspond to track delineated by Y symbols in Fig. 3. Dashed traces represent raw 1-s values and solid curves show results from a low-pass filter with a 30-s threshold. One minute tick marks are given on the abscissa.

ments correspond to the locations of the symbols (plus and Y) in Fig. 3. The earth referenced horizontal wind vectors in Fig. 3b were constructed using filtered u and v components depicted in Figs. 4a and 4b, respectively.

Comparison of data from two aircraft platforms and at different times for a particular aircraft can be made whenever the tracks overlap or intersect in the storm relative framework. As discussed earlier, agreement between co-located reports provides a basis for judging the calibration adjustments and for assessing the relative stability of airflow and thermodynamic patterns over time. Although the horizontal wind field in Fig. 3b exhibits considerable spatial variability, we note with satisfaction that wind vectors at coincident positions are in close agreement.

The objective analysis scheme developed by Barnes (1973) has been employed for remapping the irregularly spaced input reports to a uniform two-dimensional Cartesian grid. The weight assigned to an input datum at distance D from a specific Cartesian coordinate location is given by the exponential function:

$$W = \exp[\ln(c)(D^2/R^2)] \quad (2)$$

where R defines a selectable "radius of influence" at which W has a value equal to c .

For a specific grid point every input value is multiplied by its calculated weight, all weighted values are accumulated and the resultant normalized estimate is assigned to that location. The variable c is fixed in the program so that the user specified radius of influence R uniquely determines the shape of the transfer function. Figure 5 illustrates the shape of this function for $R = 2, 3, 4, 5$ with c set at 0.1. As a rule, the radius of influence should be no smaller than the minimum spatial scale retained in the filtered time series which in turn should be no less than the cross track spacing. With due regard for the character of the aircraft input data and recalling that the typical diameter of convective cells is 2 to 5 km (see e.g., Knight *et al.* 1982), our initial choice of R was 3 km.

Another selectable parameter is the number of iterative passes to perform on the interpolated field. Each pass reduces the difference between the original input values and their Cartesian space counterparts by applying the same weighting function to the current set of residuals. Barnes (1964) has demonstrated that this iterative improvement algorithm is mathematically convergent and our experience with aircraft remappings suggests that for this particular application little additional accuracy is gained after five iterations.

Upon examination of the aircraft tracks in Fig. 3b it is evident that the advected input data do not completely cover the full grid of x, y locations. Since interpolation is performed for every point in the grid, it is necessary to specify the maximum distance that grid point estimates will be accepted beyond the

FIG. 5. Shape of the weighting function W (Eq. 2) for a radius of influence, $R = 2, 3, 4$, and 5 with c set at 0.1 .

bounded region of aircraft observations. In general this distance should not exceed $R/2$ which in our examples represents one-half the wavelength of the smallest resolvable scales. The capability for two-dimensional filtering of the remapped Cartesian space estimates using the Leise (1981) Multi-dimensional Telescoped Filter is also available. Each iteration of this filter will reduce the retained scales by a factor of 2. Additional filtering in the Cartesian space domain is rarely necessary if the objective analysis procedure has been properly parameterized.

Although the Barnes (1973) objective analysis scheme is a well documented and widely accepted tool for remapping meteorological measurements to a regular Cartesian coordinate system, it is nonetheless useful to examine the validity of this technique when applied to aircraft observations acquired in the inflow region of convective storms. The issues to be resolved are whether an appropriate weighting function is being utilized for remapping these types of measurements and whether the density and configuration of the input data are sufficient to resolve the actual airflow and thermodynamic patterns at the scales we wish to preserve. Kyle, *et al.* (1976) have demonstrated that updraft profiles in convective storms can be modeled using the following relationship:

$$W_{up} = W_0 \exp\left[-a\left(\frac{r}{R_{up}}\right)^2\right], \quad (3)$$

where W_0 is the maximum updraft velocity, R_{up} is the updraft radius, r is the distance from the updraft core and a is a constant given as 2.35.

Using Eq. (3) we can generate a two-dimensional vertical velocity profile of any size, resample it using actual aircraft tracks, and remap the resampled input data to the same x, y grid using the objective analysis scheme. Figure 6a contains the contoured profile of a simulated updraft with a maximum vertical velocity $W_0 = 8 \text{ m s}^{-1}$ centered at (69, -27) which tapers off to a minimum value of -1 m s^{-1} over a 15 km distance. The actual tracks of two aircraft in typical research mode are superimposed in the same coordinate system. At locations marked with plus and Y symbols data are extracted from the modeled field for interpolation using Eq. (2). The results of the objective analysis with R set at 3 km and c set at 0.1 are given in Fig. 6b for comparison with the initial field. As a result of this and other simulations, we are confident that our data reduction and analysis procedures have been properly designed to retrieve representative two-dimensional fields from the aircraft observations.

With careful attention given to the selection of the radius of influence, the number of iterative improvement steps and the limits of extrapolation, Eq. (2) appears to be an appropriate interpolator for all cases when criteria given at the beginning of the section are satisfied. Although alternative techniques (i.e., linear interpolation, least-squares approximation, etc.) could be easily implemented within the framework of the ACANAL software, a comparative study of their relative merits in effectively dealing with irregularly spaced input data is beyond the scope of this paper.

The analysis software is currently capable of processing any time series parameter measured by the following aircraft flown during the CCOPE experiment: the Canadian Twin Otter, the University of Wyoming King Air, both NCAR Queen Airls, and the NCAR Sabreliner. A user guide is available which contains all the necessary information for understanding and running the program including sample decks and tables of all parameters associated with the aircraft listed above. Interpolated fields that are routinely produced include:

- u, v, w the orthogonal components of air motion
- q the water vapor mixing ratio
- θ the potential temperature, and
- θ_e the equivalent potential temperature.

A variety of graphical displays are also generated as a by-product of the analysis. These include ground-relative and storm-relative (advected) flight tracks, advected tracks with actual and relative horizontal wind vectors, analogue plots of raw and filtered time series and contour plots of all objectively analyzed fields.

FIG. 6. (a) Updraft contours (thin solid, dashed, and lightly dashed) modeled from Eq. 3. Heavy lines give actual flight tracks used to sample the modeled updraft at locations marked by plus and Y symbols. (b) Results of interpolation using Eq. 2 and input from modeled updraft in (a). Grid boundaries are in kilometers east and north of the CCOPE research radar.

Perhaps the most powerful feature of the program is the ability to create a Cartesian space dataset containing the analyzed fields that is physically compatible with analogous output generated from Doppler radar analyses. This capability not only facilitates the blending of measurements from the two systems but also enables us to take advantage of an existing Cartesian space analysis and display processor called CEDRIC (Mohr and Miller, 1983) which can be used

to further manipulate and examine the interpolated fields. Specific examples of computer graphics generated by the CEDRIC processor are presented in the following section.

5. Interpretation and applications

In order to assess the validity of the results it is useful to view the interpolated meteorological fields in the context of a storm's radar reflectivity pattern. Figure 7a gives the radar echo intensity contours near cloud base altitude corresponding to the anchor analysis time (1603 MDT) for the earth referenced vector field in Fig. 3b. The gridded storm-relative vector field in Fig. 7b was generated by applying the interpolation routines outlined in the preceding section to the scalar (u , v) components of the observed winds.

FIG. 7. (a) Cloud base PPI at 1603 MDT, 23 July 1981. Echo intensity contours are given at 10 dB increments beginning at 10 dBZ. Arcs of constant elevation are drawn for 2.5 and 3.0 km MSL. Streamlines are generated numerically from corresponding storm-relative vector field in (b), which in turn was derived by interpolating the u , v components of the horizontal winds plotted in Fig. 3b. Long dashed line delineates outward extent of 20 dBZ echo overhang in the 8–10 km altitude range. Grid boundaries as in Fig. 3. Vector scale is at lower right.

To obtain the airflow relative to the moving storm, as illustrated, a constant storm motion vector of 280° at 11 m s^{-1} has been subtracted uniformly from the interpolated field. The relationship between the relative airflow and the precipitation at cloud base is obtained by superimposing the streamlines calculated numerically from the vector field in Fig. 7b upon the radar echo in Fig. 7a.

The heavy dashed line on the southern flank of the storm (Fig. 7a) defines the outer limits of 20-dBZ echo overhang in the 8 to 10 km range aloft. Nearly everywhere beneath this boundary the relative airflow is directed from the south-southeast and toward the storm, thus defining the region of primary inflow. An interesting vortex signature is seen on the storm's right-rear flank where inflow air, having risen in the boundary layer from below, apparently interacts with the relative environmental airflow at flight altitude.

Contours of interpolated vertical velocity w , corresponding to the area mapped in Figs. 3b and 7b, are shown in Fig. 8a in relation to the cloud base radar echo as in Fig. 7a. Isotachs are analyzed at increments of 1 m s^{-1} using a repeating, solid (0, 3, and 6 m s^{-1}) heavy dashed (1, 4, and 7 m s^{-1}), and lightly dashed (2, 5, and 8 m s^{-1}) sequence. In a positive vein, comparison with Fig. 7 shows that the region of ascent ($w \geq 0 \text{ m s}^{-1}$) corresponds well with the inflow area beneath the echo overhang, and that an updraft core ($x, y = 82, -94 \text{ km}$) of $w \geq 8 \text{ m s}^{-1}$ is situated within a zone of streamline confluence near the southern edge of the most intense radar echo. Zero isotachs around the periphery of the observed region indicate that the outer limits of the primary updraft were resolved well by the flight patterns as flown (Fig. 3). Near the storm, however, we note that contours of significant ascent (e.g., $w \geq 3 \text{ m s}^{-1}$) are not closed and open toward the region of heavy precipitation where it is unsafe to fly.

By referring to information in Figs. 3, 4, and 8a, it is evident that Eq. (2) is not only an interpolator but that it also filters the input data to some degree. Two updraft maxima ($w \geq 10 \text{ m s}^{-1}$) appear in the analogue time series in Fig. 4c—one at 1559:20 and the other at 1606:40. These maxima occur along the tracks in Fig. 3b at x, y locations (85, -94 km) and (82, -95 km). Since they are not coincident in storm-relative space, the effect of the range dependent weighting is to spread a damped 8 m s^{-1} updraft over a broader area as illustrated in Fig. 8a.

As stated in Section 1, a primary objective of the aircraft inflow observations was to obtain representative measures of the flux of air and moisture through cloud base for use in comprehensive mass and water budget studies. Contours of water vapor flux per unit area ($10^{-3} \text{ kg m}^{-2} \text{ s}^{-1}$) are given, for the present case, in Fig. 8b. This field is calculated from the product of the interpolated 1-km grid point values of vertical velocity and water vapor mixing ratio.

FIG. 8. Cloud base PPI and grid boundaries as in Fig. 7a with contoured fields of interpolated vertical velocity (a) and associated vertical water vapor flux (b). Updraft isotachs are given at 1 m s^{-1} intervals and water vapor flux per unit area ($10^{-3} \text{ kg m}^{-2} \text{ s}^{-1}$) is contoured in increments of ten. Both fields use an alternating solid, heavy dashed and lightly dashed sequence. Updraft core of $\geq 8 \text{ m s}^{-1}$ at $x, y = 82, -94 \text{ km}$ in (a) corresponds to a maximum in vertical moisture flux of $\geq 40 \times 10^{-3} \text{ kg m}^{-2} \text{ s}^{-1}$ at a similar location in (b).

Although the w and q fields were not in phase nor as well correlated as existing models would predict (e.g., Marwitz, 1972), the vertical moisture flux strongly reflects the vertical velocity distribution in Fig. 8a, largely because mixing ratio gradients were compar-

atively small (varying by no more than 2 to 2.5 g kg^{-1} across the inflow sector).

When integrated over the area of ascent, the water vapor influx computed from Fig. 8b amounts to 3.5 kt s^{-1} . This value compares favorably to previous estimates (e.g., Newton, 1963; Auer and Marwitz, 1968; Foote and Fankhauser, 1973; Fankhauser, 1974 and 1982; Frank and Foote, 1982), but since, as in the case of the vertical velocity, some of the vertical moisture flux is clearly undetected, the representativeness of this and some of the earlier similarly derived estimates is brought into question.

One possible way to evaluate the percentage of unobserved ascent is to take advantage of combined aircraft and multi-Doppler radial velocity measurements. The two observational approaches are complementary in that each provides measurements where the other does not and in most cases there is some region of overlap. The convective situation that has been the basis for discussion to this point did not occur in a location for optimum Doppler radar surveillance. For the examination of the compatibility of the two observing systems we therefore chose data from a well observed case that developed within the CCOPE Doppler radar array. Introduction of data from another case also allows us to demonstrate the general applicability of the aircraft analysis routines and provides a basis for comparison with results already presented.

Storm-relative horizontal airflow comparable to Fig. 7b is given in Fig. 9a for an isolated storm observed on 1 August 1981. As in the case of 23 July 1981, the interpolation is derived from a coordinated two-plane flight pattern, that, in the present example, involves data segments of 13 and 17 minutes advected to an anchor time of 1620 MDT. Although the cloud base airflow in this latter case is less complex, there are features in the inflow to both storms that are quite similar. These include a marked cyclonic curvature to the flow and a zone of confluence that converges toward an updraft core located adjacent to the cloud base radar echo. Since in this present case the strongest updrafts and highest mixing ratios were well correlated spatially, we present only the vertical moisture flux in Fig. 9b for comparison to Fig. 8b. The areal size and the magnitude of the net vertical moisture flux (3.6 kt s^{-1}) also compare closely to the previous case. Again we see that the positive vertical flux is well bounded by a zero isopleth on all sides except in the direction of the heavy precipitation zone. There, as before, flux contours are not closed indicating that a significant portion of vertical moisture transport may have gone undetected.

Streamlines in Fig. 10 represent the stormwide horizontal airflow at cloud base height (2.6 km MSL) created by blending the interpolated aircraft winds with flow derived from multiple-Doppler radial velocity measurements. The shaded area identifies a

FIG. 9. Interpolated storm-relative horizontal wind vectors (a) and corresponding cloud base (2.6 km MSL) radar echo and vertical moisture flux contours (b) as in Fig. 8b for the case of 1 August 1981. Vector scale is 1 km = 5 m s⁻¹. Grid boundaries give x, y position (km) relative to research radar.

sizeable region of data overlap where it is possible to compare observations from the independent measurement systems. Scatter diagrams in Figs. 11a and 11b show the linear correlation between scalar wind components u , v from the aircraft (abscissa) and Doppler (ordinate) analyses. For this correlation we transferred the filtered aircraft components (as in Fig. 4) into the CEDRIC software for direct comparison to the equivalent Doppler estimates at corresponding grid locations. Fairly high correlation coefficients (~ 0.8) and small standard deviation ($\sigma \leq 2-3$ m s⁻¹) demonstrate an encouraging compatibility between the two data sets; this, in spite of the fact that the aircraft data in Fig. 11 are based upon essentially point values while the Doppler velocity components are derived from radial velocity measurements of particle motions within a sizable volume (e.g., $\sim 3 \times 10^7$ m³).

Although compatible results are obtained by combining the aircraft and Doppler derived horizontal flow fields, it is the vertical velocity comparison that

is most critical in evaluating the proportion of vertical flux that is missed in the aircraft mapping. In making such a comparison it is important to recognize that the aircraft vertical motions are direct measurements, while the Doppler estimates are derived quantities based on the integration of vertical profiles of horizontal divergence. Fig. 11c is a scatter diagram produced by plotting cloud base vertical velocity from Doppler integrations as a function of aircraft measurements at the same locations. A linear correlation coefficient of ~ 0.9 and a small amount of scatter indicate that, in general, both systems found the strongest updrafts in the same relative position but departure of the linear regression line from a one-to-one relation identifies a consistent bias between the two sets of data. In cases where direct comparison gives high correlations and small scatter, the aircraft measurements provide a basis for adjusting conditions affecting the Doppler results.

In the example given, the Doppler vertical velocities were computed by upward integration from the surface through the subcloud layer. The indicated tendency for the Doppler derived vertical motion to be underestimated at cloud base can be attributed to uncertain boundary conditions and/or a poorly resolved subcloud divergence profile. The intriguing prospect is to use the flight level divergence as a benchmark for modifying subcloud divergence so that the cloud base vertical velocities in the area of common observation are brought into agreement. Alternately, in regions

FIG. 10. Cloud base radar echo contours at 10 dB increments starting at 0 dBZ for 1630 MDT on 1 August 1981. Superimposed streamlines represent the airflow at the same level (2.6 km MSL) created by blending horizontal velocities from the aircraft interpolations with those derived from multiple-Doppler radar radial velocity measurements. The shaded area identifies the region of overlap observed by both systems.

FIG. 11. Scatter diagrams showing linear correlation between components of air motion (u , v , w) as resolved from the aircraft interpolations (abscissa) and Doppler-derived estimates (ordinate) at common grid points within region of coincident observation (shaded area in Fig. 10). Zero intercept ($C0$) and slope ($C1$) are given at upper right and linear correlation coefficient is at lower right.

of Doppler coverage extending beyond that resolved by aircraft the area of positive upward flux can be evaluated using the revised Doppler estimates based on coefficients derived from the linear regression. The approach is straightforward for air mass flux, but for vertical moisture flux outside the region of aircraft observation, some estimate of water vapor mixing ratio must be made. The most obvious choice is to

apply adiabatic values associated with the mean inflow conditions measured by aircraft.

6. Concluding remarks

The emphasis in developing the objective approach presented here was to obtain estimates of water vapor influx for use in moisture budget studies. Evidence

indicates that the fullest exploitation of the thunderstorm inflow mapping will come through combining kinematic fields observed concurrently by aircraft and by multiple Doppler radars. As well as providing for the creation of spatially continuous meteorological fields from analogue time series, the ACANAL software allows for the transfer of point measurements and data in the form of line segments into three dimensional Cartesian space. A potential application of this type is to position aircraft measurements of hydrometeor size, concentration, and type into the radar domain for direct comparison with related radar reflectivity parameters.

To date, data from 13 individual inflow studies have been subjected to the numerical interpolation routines described here. Observed storm types ranged from isolated thunderstorms of varying size and intensity to squall lines and rather disorganized convective complexes. In general, as the complexity of the convective phenomena increased, the ability to adhere to intended flight plans deteriorated. Several cases, however, exhibited organized continuity for well over an hour, allowing one or both aircraft to observe the temporal evolution of the inflow conditions. Data of this type should prove useful in evaluating results from numerical modeling experiments (Weisman and Klemp, 1982, 1984). In addition to precipitation efficiency studies, one broad objective of future work will be to generalize and/or contrast the inflow characteristics of the diverse sample of convective storms observed in CCOPE.

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