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Analyzing low-level jets in their large-scale environment: Issues involving the combination of operational and research observations during IHOP

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1. Introduction

Two aircraft missions during the International H_20 Project (IHOP; Weckwerth *et al.* 2004) in Oklahoma and Kansas during 2002 were dedicated to multi-scale observations of the Central Plains low-level jet (LLJ). A particular objective during these flights was a determination of the inherent scales of moisture flux within the LLJ. To accomplish this, two research platforms were utilized, each with its own observational characteristics: dropsondes with high vertical resolution released at 50-km intervals, and airborne lidar with resolvable scales of a few km in the horizontal. Given finite aircraft flight speeds, the depiction of the structure of the LLJs of necessity involved a rational juxtaposition of variations in both time and space. The addition of operational observations (profilers and radiosondes) to describe synoptic snapshots of the jets' larger-scale environment further complicates the interpretation of the LLJ structures that emerge from this "witch's brew" of observations.

Given the challenging analytic problem presented by these diverse observations, it is surprising that a coherent picture can in fact be constructed from them. However, in the process of analysis several observational limitations and questions of interpretation do become apparent. These include the extreme shallowness of the upslope (westward) edges of the jets that challenge the vertical resolution of operational analyses and model assimilation, and differences in scale of the longitudinal and lateral structures within the jet. We describe the large scale fields for the two cases, and then attempt to assemble our set of observations into a picture of LLJs that adequately describes both their horizontal and temporal variability. Finally, we discuss issues these results raise for research data analysis and interpretation.

2. The 3 and 9 June LLJ Missions

2.1 Mission Strategy and Flight Pattern

The two IHOP aircraft missions designed to observe mesoscale structures of moisture and winds during LLJ episodes were flown on 3 and 9 June 2002. Each mission consisted of two research aircraft (a Falcon and a Lear Jet), both carrying dropsondes, the Lear having on-board LIDAR instrumentation to measure crosswind components and water-vapor mixing ratio. Dropsondes were deployed at roughly 60 km intervals along rectangular flight patterns designed to encompass the jet core and cut across it orthogonally on two sides. The resulting flight patterns on 3 June and the observed wind structure are shown in Fig. 1.

The set of LLJ observations on 3 June were taken early in the morning, starting about the time of operational radiosonde release. The second set (9 June 2002), were begun almost 2 h later in the day. On-board remote sensors did not operate properly on 3 June and the Lear dropsondes failed to operate properly; nevertheless, dropsonde data from the Falcon reveal the LLJ as a very well formed and sharply peaked maximum at

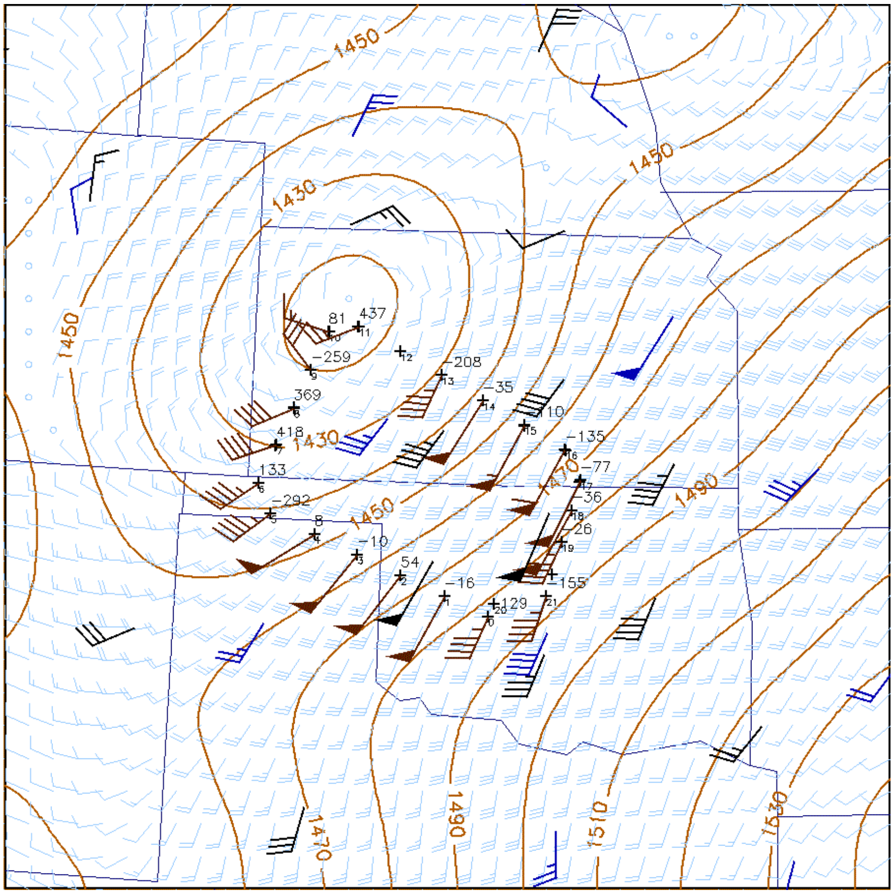

Fig. 1. A depiction of column-maximum wind vectors recorded by aircraft dropsondes (large black vectors), rawinsondes (medium black vectors) and profilers (large blue vectors) against the background of Eta model 850 hPa winds (small blue vectors) and heights (tan contours). The tilted box of dropsonde wind vectors illustrates the flight pattern for this mission. Radiosonde observations and model analysis are at 1200 UTC 3 June 2002.

just below 500 m above ground level (AGL). On 9 June, on-board instruments worked well providing a good data set to be compared with dropsonde data from both aircraft; but the later observation time and somewhat different large-scale weather patterns resulted in a picture of a ragged, dissipating LLJ. Detailed results of this mission are published elsewhere; here we concentrate on the 3 June case and a comparison between both cases.

2.2 Scientific Objectives

The main purpose of IHOP was to characterize the water vapor and fluxes. However, improved characterization of the transport of moisture may also provide important improvements in quantitative precipitation forecasting (QPF). The southerly low-level jet (LLJ) is the major conveyor of low-level moisture from the Gulf of Mexico into the central United States, which increases the potential for deep moist convection and heavy precipitation, especially when organized into mesoscale convective complexes (MCCs; Maddox, 1983) or systems (MCS's). Where the LLJ overruns a low-level boundary such as a warm front, under the right meteorological setting, the low-level lifting of moist air can spawn MCS's (Augustine and Caracena 1994). Higgins *et al.* (1997) estimate that the contribution of the LLJ to low-level moisture transport is almost 50% above average non-LLJ values. The depth, width, and magnitude of moist inflow, and the moisture convergence profile, are all functions both of the water vapor and the wind fields. We need to understand how these factors determine if an MCS will form on a given day, as well as the extent of their influence on MCS intensity, longevity, and total rainfall.

Because only two LLJ missions were flown for this study during IHOP, by chance, no significant convection happened to have resulted near the flight areas. Nevertheless, the datasets furnish a basis for analyzing the detailed structure of two LLJs.

3. Large Scale Analyses

The strongest low-level jet development occurs under large-scale forcing, asociated with the emergence of an upper-level, low pressure trough from the western mountains of North America onto the Great Plains. In this respect, on 3 June, the large-scale 500 mb height and QG-omega patterns were favorable for the development of a strong low-level jet northeastward from the Panhandle of Texas (Fig. 2). Note also the weak couplet of downward motion over the Texas Panhandle and ascent over Kansas in the omega field. Upper air analyses, such as in Figs. 2 and 3, in combination with other forecasting and analysis products, were found very useful in forecasting LLJ development during IHOP.

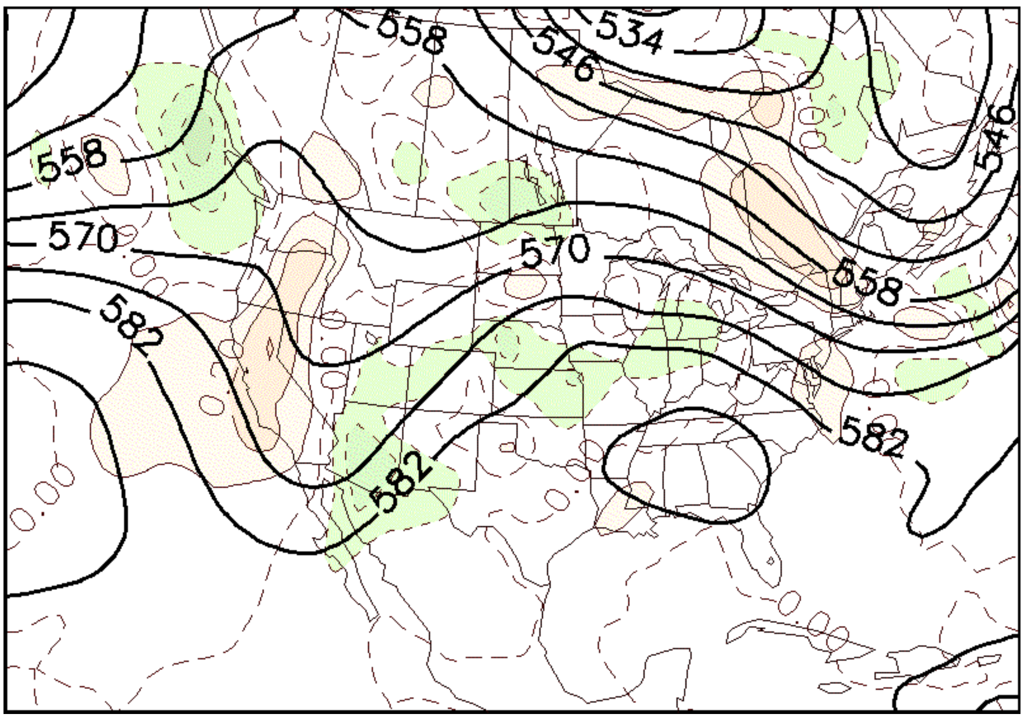

Fig. 2. Analysis of 500 hPa height (dm) and QG vertical motion (Pa/s, shaded) based on initial fields from the 80 km Eta for 1200 UTC 3 June 2002.

Conventional operational model analyses show good agreement in the position of the LLJ compared with research observations from radiosonde, profilers, and dropsondes deployed 1104-1324 UTC from the Falcon (Fig. 1). Note that the dropsondes reveal a lot of small-scale structure in the LLJ maximum that is not captured in the large-scale, operational model and observations. The kinematic data match well along the flow (even in dropsondes taken an hour apart and on opposite sides of the rectangular flight tracks), but have a great deal of cross-stream variation. The indication is that the spacing of dropsondes (about 50 km) is not sufficient to capture details of the cross-stream variation in winds, but would be able to resolve details along streamlines at even coarser densities.

An analysis of lidar data from the Falcon for the 9 June mission (not shown) confirms that it is indeed the case that the dropsonde interval is insufficient to resolve a lot of the cross structure of the LLJ on that day when all instruments were working. The same is likely true for 3 June, although confirming observations are not available.

The pattern of wind observations sampled by dropsondes during the first hour of flight (Fig. 1) indicates that a small-scale LLJ maximum is situated near the NE corner of the flight box and that the jet core is no more than about 150 km across. However, the increased winds have a broader sweep in the initial Eta 850 hPa kinematic field. Profiler winds also reveal strong LLJ winds NNE of the center of the flight box. Note that there is a considerable ageostrophic component of inflow toward the center of the surface low-pressure area. A similar pattern appears in a plot of LLJ maximum winds superposed on an objective analysis of surface altimeter settings (not shown). In typical nocturnal LLJs, the winds at this time of day are becoming super geostrophic.

The vertical structure of the winds and LLJ is shown by the composite hodograph

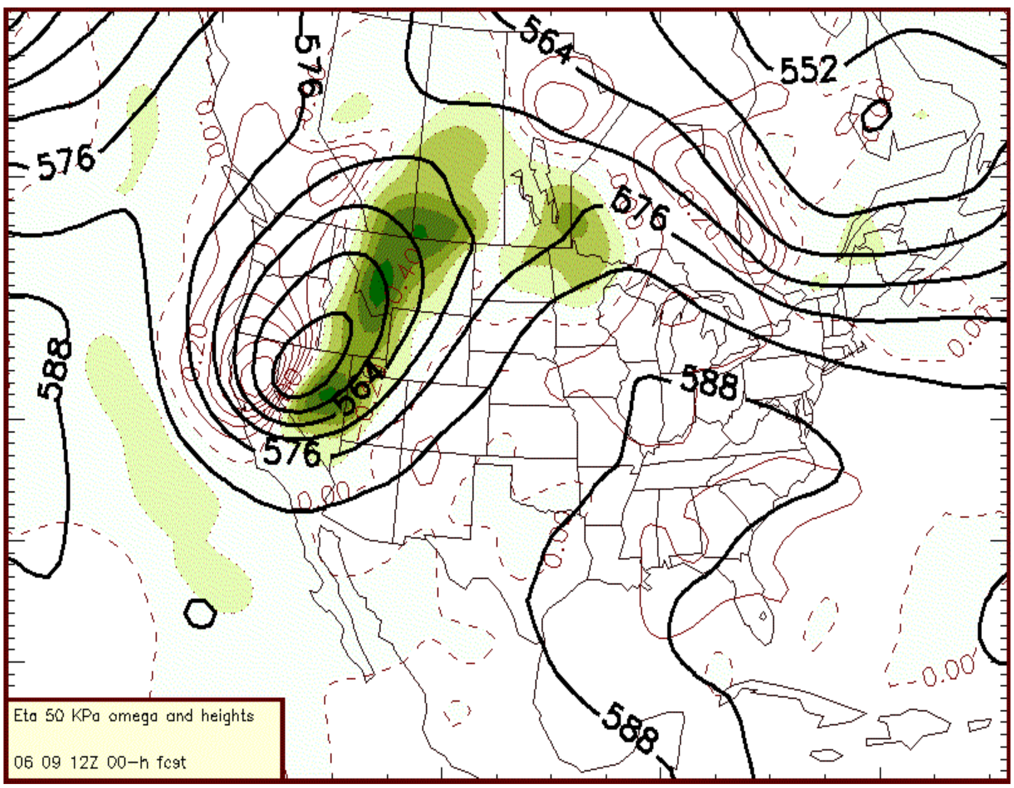

Fig. 3. As in Fig. 2 except for 9 June 2002 IHOP mission.

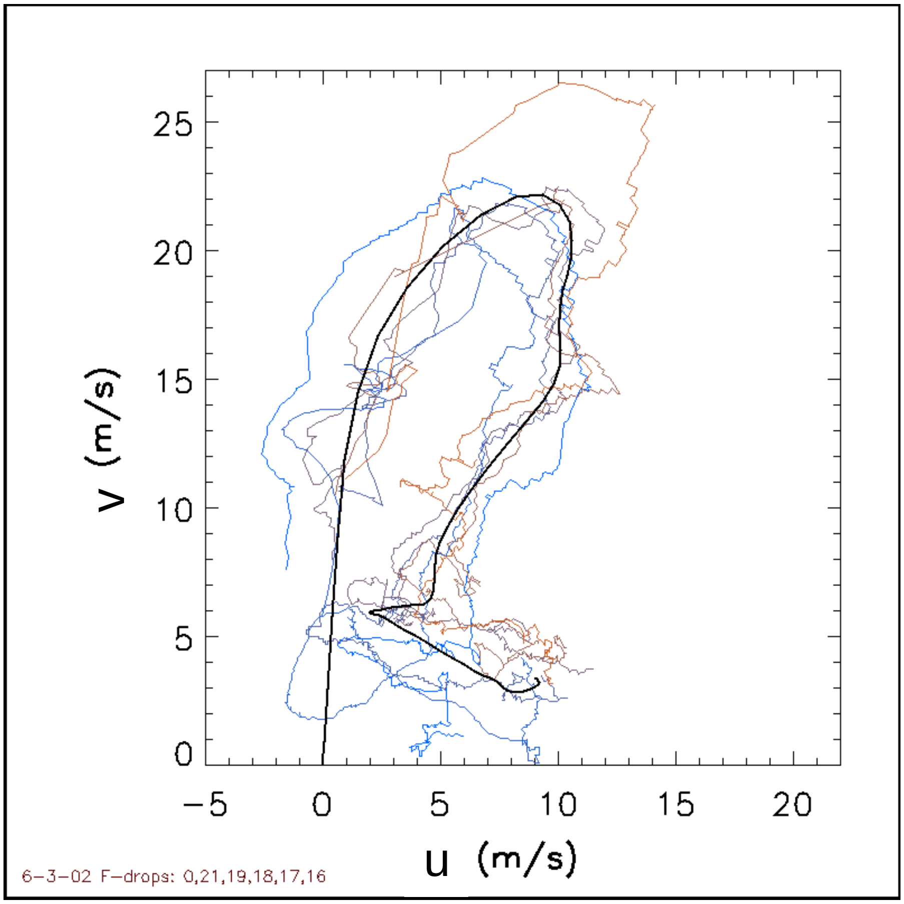

Fig. 4. A hodograph (thick black) composited from several individual dropsondes (light thin plots) released along the LLJ core during the 3 June Mission by the DLR Falcon aircraft. See text for heights of hodograph features.

on Fig. 4 based on Falcon dropsondes released along the LLJ core (see Fig. 1). Most of the composite hodograph corresponds to the flow within 2 km of the surface, and is an Ekman spiral that looks very similar to one computed by Blackadar *et al.* (1965), in which the surface geostrophic wind is coupled with an oppositely directed thermal wind. The plot referred to is depicted also in Brown (1974, p. 43). The maximum wind in the hodograph occurs at just under 500 m, AGL, which is also apparent in a vertical plot of the southerly wind in the core of the LLJ (Fig. 4). Note that the top of the hair pin structure of the hodograph (Fig. 4) ends in a kink at about 1800 m, AGL.

The large-scale, 500 hPa analysis based on Eta initial fields for the 9 June Mission (Fig. 3) is similar to that of 3 June, except that the upper low-pressure area has a tighter gradient and is located farther north. As in the case of 3 June, the low-level jet forms in response to an upper-level trough emerging from the western United States highlands. The jet core on this day was located slightly further west (Fig. 5), and its winds have a slightly more northeasterly direction. In terms of the large-scale setting, the 3 June LLJ is in closer proximity to a synoptic scale low pressure system at mid-levels and near the surface (*e.g.*, the wind turning in the far northwest corner of the aircraft flight pattern on Fig. 1).

data set, which includes LIDAR data. The LLJ on this day is also deeper, more turbulent and more diffuse than on 3 June, either because of the later sampling times or different large-scale conditions. Also, the LLJ on 9 June was observed to have greater atmospheric boundary layer moisture flux. The mix of research data and near-synoptic initial observations make it the most useful of the two missions to study the effects of combining

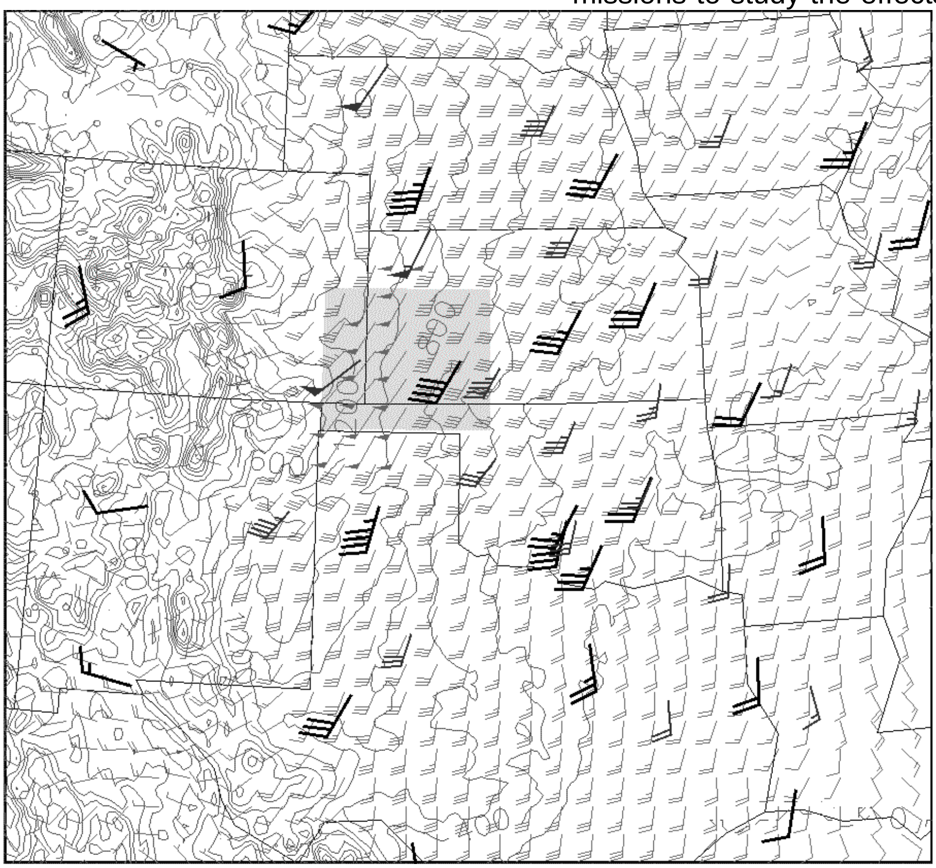

Fig. 5. Observed winds at 820 mb at 1200 UTC 9 June 2002. Largest wind barbs are observations at operational radiosonde observation sites, medium barbs are at profiler sites, and smallest gridded winds are at gridpoints of the WRF wind analysis at 1300 UTC. Terrain contours are displayed in increments of 400 m. The gray-shaded rectangular area denotes the aircraft flight box perimeter around which the two research aircraft flew during the 9 June LLJ mission.

observations from different data platforms (*cf.* Tollerud *et al.* 2005)

The first circuit around the flight track on 9 June began with the first Falcon dropsonde release at 12:44:27 UTC and the Lear release at 12:46:26 UTC. The observations on this day began about an hour and 45 minutes later than on 3 June; but for this day there is a more complete

4. Scale and Limits to Stationarity

A useful research strategy for IHOP and other field experiments is to consider sections of research data observed from aircraft effectively as snapshots of the atmosphere at a given time. For the IHOP missions, for example, an objective was to compute flux values through sections as observed from different platforms with model forecasts at a particular time, and to initialize different model runs with and without these snapshots of dropsonde-derived LLJ observations. The validity of this "stationarity" assumption depends on the scale and magnitude of change in the structure of the LLJ as observed by the dropsonde profiles. A sense of the size of these changes near the core of the LLJ is provided by the series of dropsonde-observed wind hodographs in Fig. 4. Although the general structure of each is remarkably similar, there are significant profile-to-profile variations. However, it is not clear if these changes are temporal or spatial in nature.

To assess the stationarity assumption more directly, we compare two pairs of essentially collocated dropsonde profiles of moisture flux from the 9 June mission separated in time by one and four hours (Figs. 6 and 7). All observations were performed near the LLJ core along the northern side of the shaded flight box in Fig. 5. Clearly, the structure of the LLJ has not changed significantly during the first hour of the mission (Fig. 6). In the four hours between the initial and late morning profiles (Fig. 7), however, the changes are large. The most significant of these changes were the deepening and broadening of the flux layer from its extremely shallow profile early in the morning, and turning of the winds in the layer just above the LLJ.

5. Conclusions

As observed by the operational synoptic network, the two LLJ missions on 3 and 9 June during IHOP shared similar large-scale features. Indeed, experience during IHOP showed that forecasts without extreme resolution were generally successful capturing the location and general horizontal structure of the LLJ. Of

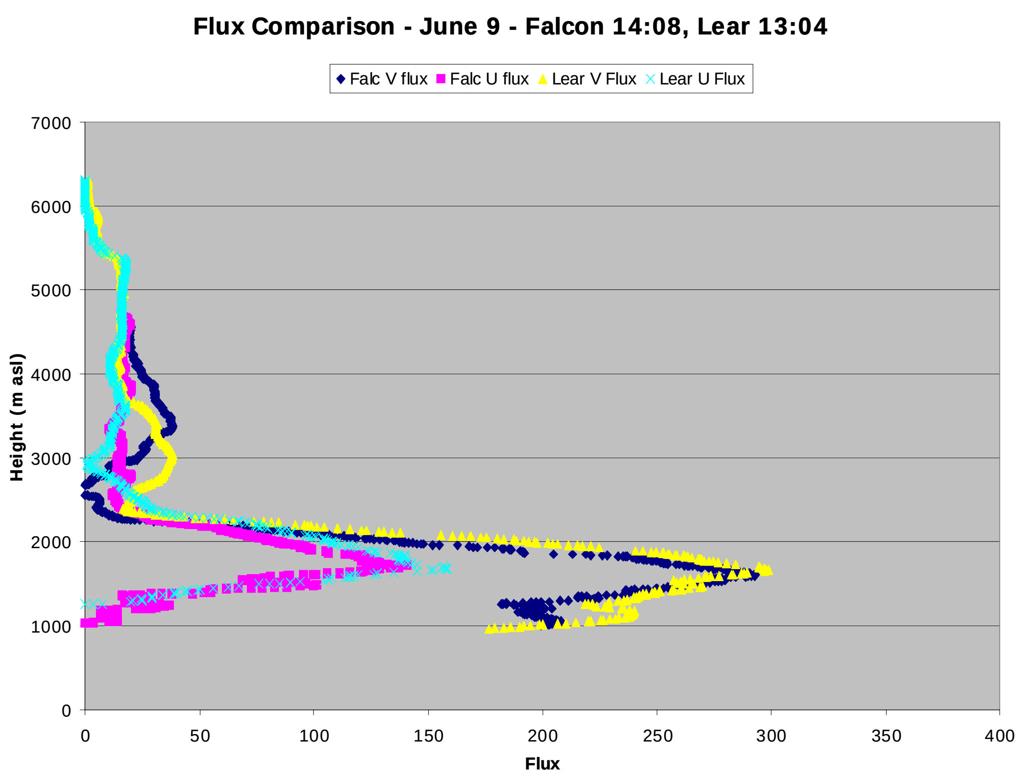

Fig. 6. Dropsonde observations of meridional (v flux) and longitudinal (u flux) horizontal moisture flux (gkg^{-1}ms^{-1}) near the LLJ core along the north side of the 9 June aircraft flight box shown on Fig. 5.

greater difficulty for the model forecasts and analyses were the very shallow and intense LLJ wind and flux peaks observed early in the day and toward the west flank of the jet core by the research aircraft. We hypothesize that greater vertical resolution in model and analyses will be necessary to more closely reflect these LLJ maxima. As for differences in LLJ analyses of moisture flux and winds as provided by operational and research observations, the two were most similar early in the day. As smaller-scale features developed during boundary layer heating, and as the research platform (in this study, dropsonde) observation times departed from the preceding radiosonde observations, the differences between analyses based on the two became large. Similar reservations about the ability of the radiosonde network to adequately represent the LLJ throughout a diurnal cycle are presented in Anderson and Arritt (2001). We conclude that the stationarity assumption can be justified for perhaps one aircraft circuit (1-2 h) but becomes questionable for longer periods.

Acknowledgments

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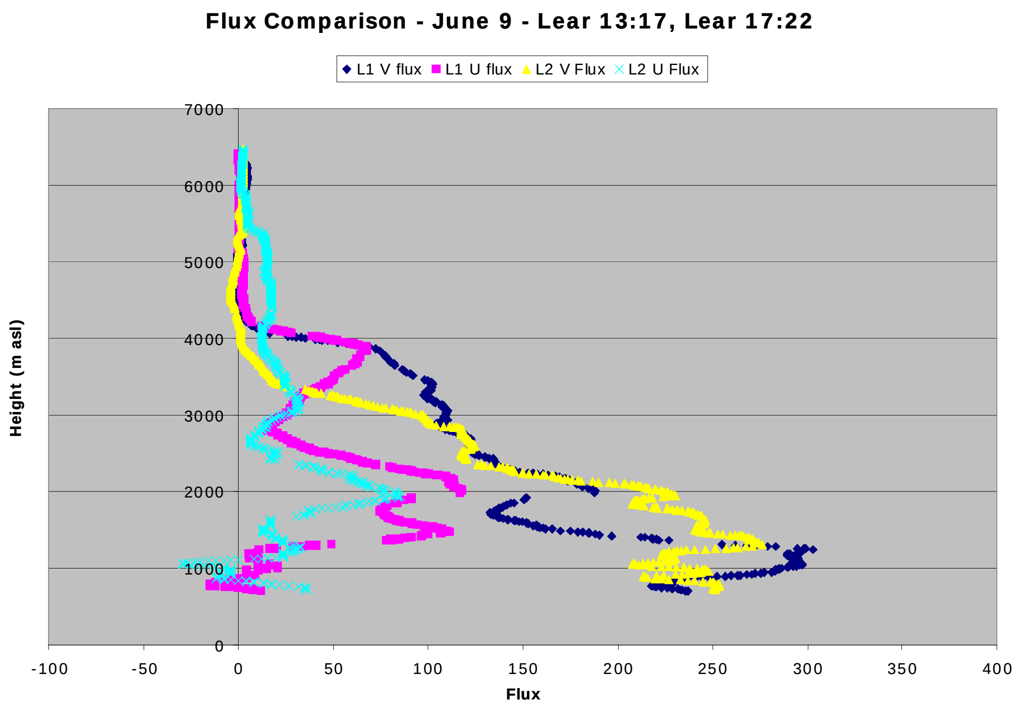

Fig. 7. As in Fig. 6 except for collocated observations during successive circuits by the LEAR aircraft.

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