The Impact of High-Resolution SALLJEX Data on Global NCEP Analyses

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ABSTRACT

A data assimilation study was performed to assess the impact of observations from the South American Low-Level Jet Experiment (SALLJEX) on analyses in the region east of the Andes Mountains from western Brazil to central Argentina. The Climate Data Assimilation Systems (CDAS)-1 and -2 and the Global Data Assimilation System (GDAS) were run with and without the additional SALLJEX rawinsondes and pilot balloon observations. The experiments for each data assimilation system revealed similar features, with a stronger low-level flow east of the Andes when SALLJEX data were included. GDAS had the strongest low-level jet (LLJ) when compared with observations. In the experiments that used additional rawinsonde and pilot balloon data, the LLJ was displaced westward in comparison to the analyses run without the SALLJEX data. The vertical structure of the meridional wind in the analyses was much closer to observed rawinsonde profiles in the experiments that included SALLJEX data than in the control experiments, and the results show that, although there are more pilot balloon observations than rawinsonde observations in the SALLJEX dataset, most of the improvements in the analyses can be obtained by only including rawinsonde observations. This was especially true for GDAS. The results of this study can serve as a benchmark for similar data impact studies using higher-resolution data assimilation systems.

1. Introduction

In recent years several studies demonstrated the important role that the South American low-level jet (SALLJ) plays in transporting moisture from the Amazon basin to higher latitudes over the continent. Many of these studies have utilized the National Centers for Environmental Prediction (NCEP) reanalysis data (e.g., Nogués-Paegle and Mo 1997; Berbery and Collini 2000; Marengo et al. 2004) and the European Centre for Medium-Range Weather Forecasts (ECMWF) reanalysis data (Salio et al. 2002; Wang and Fu 2004) as the basis for studying climate and climate variability. For data-rich areas, the Climate Data Assimilation Systems, CDAS-1 (Kalnay et al. 1996) and CDAS-2 (Kanamitsu et al. 2002), provide a fairly homogeneous set of analyses spanning more than 50 years, which are ideal for climate studies. However, for data-sparse regions, including many areas in the Southern Hemisphere, uncertainty exists concerning the validity of those analyses. The characteristics (parameterization, resolution, topography, etc.) of the general circulation model (GCM), which serves as a nucleus of the data assimilation system, become increasingly important in determining circulation features as the spatial and temporal resolution of the observations decreases. Anderson and Arritt (2001), using the NCEP–National Center for Atmospheric Research (NCAR) reanalysis data to investigate the low-level jet (LLJ) in the Great Plains, pointed out the risk of using data analyzed at times when the analyses are heavily influenced by the GCM (times when observations are relatively sparse).

The South American Low-level Jet Experiment (SALLJEX) field campaign was carried out in western-

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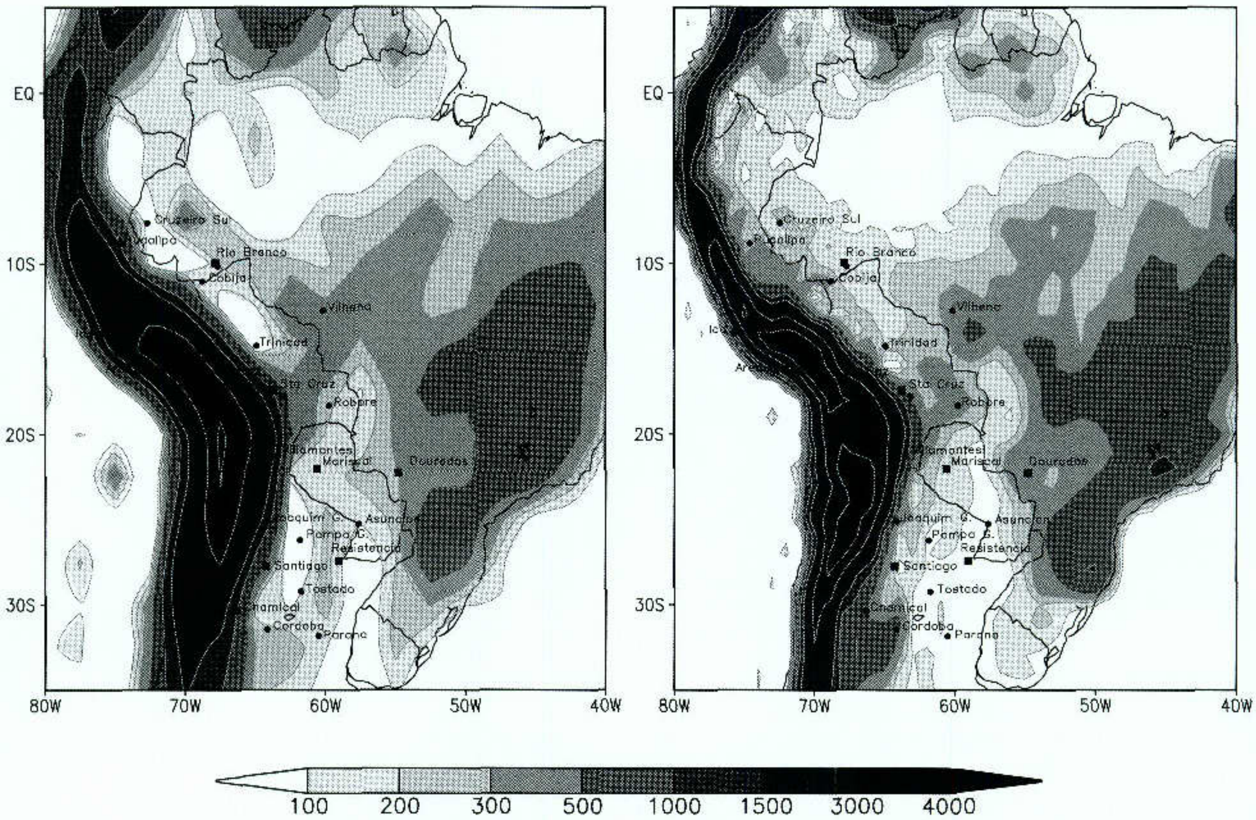

FIG. 1. The SALLJEX upper-air network over South America: SALLJEX rawinsonde (square) and pilot balloons (circle). Topography (m) over South America derived from (left) CDAS and (right) GDAS.

central South America during the period 15 November 2002–14 February 2003 (Vera et al. 2006). The SALLJ program, a component of the Climate Variability and Predictability/Variability of American Monsoon Systems (CLIVAR/VAMOS), is an internationally coordinated effort to contribute to a better understanding of the role of the SALLJ in the moisture and energy exchanges between the Tropics and extratropics and to related aspects of the regional hydrology, climate, and climate variability for the region of the South American monsoon.

During SALLJEX a dense observation network was deployed with 16 new pilot balloon stations and six new rawinsonde stations in Bolivia, Paraguay, central and northern Argentina, western Brazil, and Peru (Fig. 1). Most rawinsonde sites operated twice daily (at 0600 and 1800 UTC, and for Brazilian sites at 0000 and 1200 UTC), except during the Intensive Observing Period (IOP) when some sites operated four times daily. These datasets were not available on the Global Telecommunication System (GTS) and, therefore, they can be used as an independent verification of the sensitivity of assimilation systems [NCEP, ECMWF, and the Data Assimilation Office/National Aeronautics and Space Administration (DAO/NASA)].

The emphasis of this paper is on the impacts of high-resolution field experiment data on the strength, position, and structure of the low-level jet east of the Andes, using the NCEP operational data assimilation systems. Specifically, comparisons are made between analyses produced with and without the SALLJEX data using the CDAS-1, used in the NCEP–NCAR Reanalysis Project (Kalnay et al. 1996); CDAS-2, used in the Reanalysis-2 Project (Kanamitsu et al. 2002); and a reduced-resolution version of the operational NCEP Global Data Assimilation System (GDAS). The present results will serve as a benchmark for similar data impact studies using higher-resolution regional data assimilation systems. The data sources, methodology used to assimilate the data, and a brief description of some aspects of the assimilation systems used are described in section 2. Section 3 describes the impact of SALLJEX data on the analyses derived from the global data assimilation systems. The results are described in section 4, and discussion and conclusions are presented in section 5.

2. Datasets and methods

a. SALLJEX observations

The SALLJEX field campaign took place during 15 November 2002–14 February 2003 over west-central South America east of the Andes Mountains. Enhanced (temporal and spatial) atmospheric soundings were made over Argentina, Bolivia, Brazil, Paraguay, and Peru. These included 22 new upper air observation stations, with 16 pilot balloon (PIBAL) and six rawinsonde (raob) stations (Fig. 1). Most raob stations operated twice daily (0600 and 1800 UTC) while PIBAL stations operated four times daily during the Special Observation Period (SOP) 6 January–14 February 2003. During the Intensive Observation Period most raob sites operated 3–4 times daily and up to 8 PIBAL ascents per day were made at selected sites. These observations were not available on the GTS and were not assimilated into any operational analysis systems in real time. They are used here as an independent verification of the NCEP assimilation systems (CDAS and GDAS). Table 1 shows the soundings that were used by CDAS and GDAS during the period 15 December 2002–14 February 2003.

b. Global data assimilation systems

The basic idea of reanalysis is to use a frozen state-of-the-art analysis/forecast system to perform data assimilation using past data. In this study we compare the analyses, derived from three different data assimilation systems (CDAS-1, CDAS-2, and GDAS), for the period 15 December 2002–14 February 2003.

CDAS-1 is the frozen analysis/forecast system that was used to perform the NCEP–NCAR reanalysis (R-1; Kalnay et al. 1996) for the period from 1948 to present. CDAS-2 is an updated NCEP–NCAR reanalysis (R-2; Kanamitsu et al. 2002), covering 1979 to present, with an improved forecast model and data assimilation system. GDAS is a reduced-resolution version of the operational NCEP global model data assimilation system (version 2005).

The resolutions of the systems are T62L28 for CDAS, approximately 250 km horizontal resolution with 28 levels in the vertical, and T170L42 for GDAS, approximately 100 km horizontal resolution with 42 levels in the vertical.

c. Experiments

To assess the impact that the introduction of the SALLJEX dataset has on the analyses, the following experiments were performed, using CDAS-1, CDAS-2, and GDAS:

1) control runs without the SALLJEX data;
2) runs only including raob data (CDAS-1r, CDAS-2r, and GDASr);
3) runs including all SALLJEX upper-air data, raob and PIBAL (CDAS-1rp, CDAS-2rp, and GDASrp);
4) runs only including PIBAL in GDAS (GDASp).

All of the variables from the SALLJEX raob (meridional and zonal wind, specific humidity, and temperature) and PIBAL (meridional and zonal wind) have been incorporated in the data assimilation systems.

3. Regional impact of SALLJEX

Global reanalysis, which combines general circulation model predictions with observations, is a powerful tool for understanding many climate and weather questions that would otherwise remain elusive because of the limited availability of the data over some regions. However, owing to differences in data assimilation systems (models and assimilation techniques), there is a degree of uncertainty in the reanalyzed fields. An example of this uncertainty is pointed out in Fig. 2, which shows the low-level (850 hPa) vector wind over South America during the period 15 January–14 February 2003. The strength of the low-level flow east of the Andes Mountains varies by up to 40% in the analyses, with CDAS-2 (Fig. 2b) having the strongest jet and GDAS, the operational data assimilation system, having the weakest jet (Fig. 2c). Figures 2d, 2e, and 2f show the impact of including SALLJEX data in CDAS-1, CDAS-2, and GDAS, respectively. The influence of SALLJEX data is concentrated over the region where the raob and PIBAL observations were made (Fig. 1) and the global influence is close to zero outside of the region (not shown). The strength and location of the core of the low-level jet analyzed in the three systems, CDAS-1rp, CDAS-2rp, and GDASrp (Figs. 2d, 2e, and 2f), are in better agreement than in the control runs, CDAS-1, CDAS-2, and GDAS (Figs. 2a, 2b, and 2c).

The results in Figs. 2d, 2e, and 2f show that including the special raob and PIBAL observations does not appreciably affect the large-scale circulation pattern over the South American region. However, there is a discernable effect on the intensity of the northwesterly flow (LLJ) east of the Andes, with stronger winds in all cases where SALLJEX data have been included (right-hand panels in Fig. 2). There are also notable differences in the cross-jet structure between the higher-resolution GDAS analysis and the lower-resolution CDAS analyses. GDASrp (Fig. 2f) shows a narrower jet, with wind speeds greater than 8 m s^{-1}, concentrated

TABLE 1. SALLJEX soundings that were included in the assimilation system (sounding time in h UTC).

	Stations																							
	Mariscal				Santa Cruz				Dourados				Rio Branco				Santiago				Resistencia			
	UTC				UTC				UTC				UTC				UTC				UTC			
Date	00	06	12	18	00	06	12	18	00	06	12	18	00	06	12	18	00	06	12	18	00	06	12	18
December																								
15 2002																		x				x		
16 2002																		x				x		
17 2002		x																x				x		
18 2002		x		x			x											x				x		
19 2002		x		x			x											x				x		
20 2002		x																x				x		
21 2002		x					x											x				x		
22 2002		x					x											x						
23 2002		x																x						
24 2002		x				x												x						
25 2002		x																x				x		
26 2002		x				x												x				x		
27 2002		x				x												x				x		
28 2002		x				x												x				x		
29 2002		x				x																x		
30 2002		x				x												x				x		
31 2002		x																x				x		
January																								
1 2003		x																x				x		
2 2003		x																x				x		
3 2003		x																x				x		
4 2003		x																x				x		
5 2003		x																x				x		
6 2003		x		x														x				x		
7 2003		x		x					x				x				x	x				x		
8 2003				x					x				x					x		x		x		
9 2003				x					x				x					x		x		x		
10 2003		x		x					x				x					x		x		x		x
11 2003		x		x					x				x					x		x		x		x
12 2003		x		x					x			x	x			x						x		x
13 2003				x					x				x					x		x		x		x
14 2003				x									x					x		x		x		x
15 2003		x		x		x		x	x		x	x	x		x	x		x		x		x		x
16 2003		x				x		x		x	x			x	x	x		x		x		x		x
17 2003		x		x		x		x		x	x	x		x	x	x		x		x		x		x
18 2003		x		x		x		x		x	x			x						x		x		x
19 2003		x		x		x		x	x				x					x		x		x		x
20 2003		x		x		x		x	x				x					x		x		x		
21 2003				x		x		x	x		x	x	x		x	x		x	x	x		x		x
22 2003		x		x				x		x	x	x		x	x	x	x	x	x	x	x	x	x	
23 2003		x		x				x		x	x	x		x	x	x	x	x	x	x		x	x	x
24 2003		x					x	x		x	x	x		x	x	x	x	x	x	x	x	x	x	x
25 2003						x		x		x	x			x	x		x	x	x	x	x	x		x
26 2003				x					x				x					x		x		x		x
27 2003		x		x					x				x					x		x		x		x
28 2003		x		x		x		x	x				x					x		x		x		x
29 2003		x				x		x	x				x					x		x		x		x
30 2003		x				x		x	x				x					x		x		x		x
31 2003		x				x		x	x				x					x		x		x		x
February																								
1 2003		x				x		x			x		x		x			x	x	x		x	x	x
2 2003		x				x		x	x		x		x		x		x	x	x	x	x			x

TABLE 1. *(Continued)*

	Stations																							
	Mariscal				Santa Cruz				Dourados				Rio Branco				Santiago				Resistencia			
	UTC				UTC				UTC				UTC				UTC				UTC			
Date	00	06	12	18	00	06	12	18	00	06	12	18	00	06	12	18	00	06	12	18	00	06	12	18
												February *(Continued)*												
3 2003		x				x		x	x				x					x		x		x		
4 2003						x		x	x		x				x			x	x	x		x	x	x
5 2003						x		x					x		x		x	x	x		x	x	x	
6 2003						x		x					x					x	x	x	x	x	x	x
7 2003						x		x					x		x		x	x	x	x	x	x	x	x
8 2003					x	x	x	x					x		x		x	x	x		x	x		x
9 2003					x	x	x	x					x		x			x		x	x	x		x
10 2003					x		x	x					x		x				x	x		x		
11 2003						x		x					x					x		x		x		x
12 2003						x		x	x				x					x		x		x		x
13 2003						x		x	x				x					x		x		x		x
14 2003									x				x					x		x		x		

near the Andes close to Santa Cruz, Bolivia. CDAS-1rp and CDAS-2rp (Figs. 2d and 2e, respectively) also show a stronger jet but farther away from the Andes. These differences in LLJ location are probably related to differences in resolution between CDAS and GDAS and how the Andes Mountains are depicted in the model.

An examination of the vertical structure of the mean meridional wind at 18°S, 62°W (near Santa Cruz) reveals that the maximum impact of including SALLJEX data occurs at low levels at 0600 UTC in GDAS (Fig. 3b). The added effect of including PIBAL with raob data has little impact when compared with raob alone except at 1800 UTC in GDAS (Fig. 3d). Including SALLJEX data noticeably increases the amplitude of the diurnal cycle in the strength of the LLJ, with a maximum strength near 900 hPa between 0600 and 1200 UTC in GDAS and at 850 hPa near 0600 UTC in CDAS-1 and CDAS-2. The mean altitude of the maximum low-level wind increases from 0600 to 1800 UTC in GDAS, a feature not evident in CDAS-1 and CDAS-2. The effects of including SALLJEX data are least at 0000 UTC in GDAS and CDAS-2 and at 1200 UTC in CDAS-1. This is probably related to the lack of raob observations at these times (Table 1), which contributes to increased uncertainty in the analyses.

Figure 4 shows the diurnal cycle of the mean meridional wind at 900 hPa for GDAS and at 850 hPa for CDAS-1 and CDAS-2 averaged for the period 15 January–14 February 2003. The effect of including SALLJEX raob data in GDAS increases the strength of the jet, especially at 0600 UTC (blue line in Fig. 4a). Only slight differences in the strength of the low-level meridional wind result when the PIBAL data are included together with raob data (cf. the blue and green lines in Fig. 4a).

Similar results are found for a point near Mariscal, Paraguay, at 22°S, 60°W (Fig. 5). The greatest effect of including SALLJEX data can be observed at 0600 UTC in all assimilation systems, with the maximum jet intensity occurring between 0600 and 1200 UTC. There is little difference in the wind speeds between the control runs and the runs including SALLJEX data at 0000 and 1200 UTC due to a lack of SALLJEX observations at those times (Table 1).

Case study: Mesoscale convective complex on 22 January 2003

To further illustrate some characteristics of the difference between the analysis and control experiments, we consider the case of an intense mesoscale convective complex (MCC) that developed on 22 January 2003 over northeast Argentina, which produced heavy rainfall amounts as it propagated eastward across Paraguay and southwest Brazil during the nighttime hours (Zipser et al. 2004).

Figure 6 compares the vertical structure of the observed meridional wind (blue dots) at Mariscal (approximately at 22°S, 60°W) with GDAS (black long dash), GDASrp (green), CDAS-2 (red long dash), and CDAS-2rp (dark yellow) for the period of 1800 UTC (22 January), 0000 UTC (23 January), and 0600 UTC (23 January). It is important to note that Mariscal operated as a rawinsonde station at 0600 and 1800 UTC. The GDASrp analyses show stronger low-level flow near 900 hPa in agreement with the observations and a well-defined LLJ at 0600 UTC. The strength of the

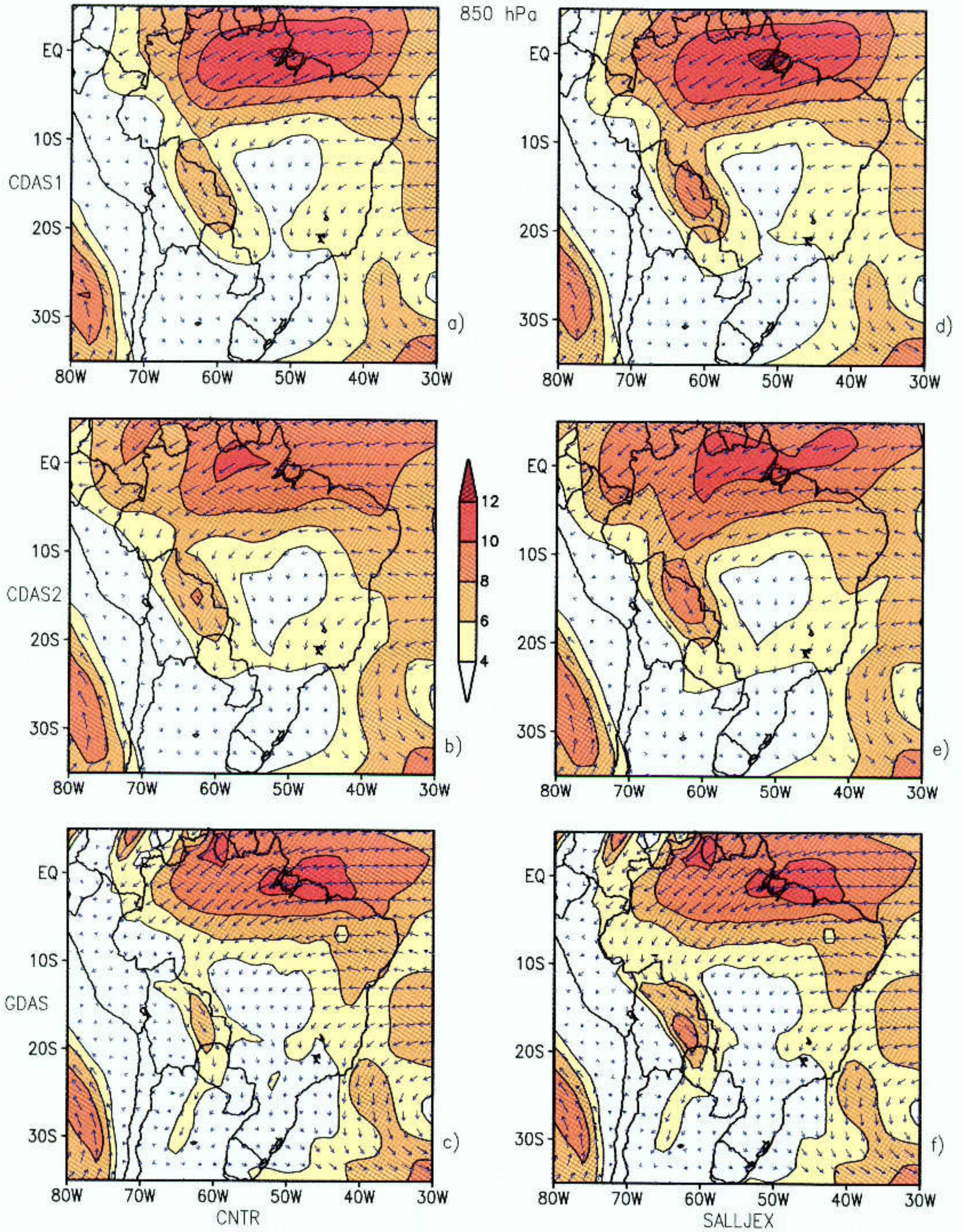

FIG. 2. Mean low-level wind (vector) and wind speed (shaded) at 850 hPa during 15 Jan–14 Feb 2003: (a) CDAS-1, (b) CDAS-2, (c) GDAS, (d) CDAS-1rp, (e) CDAS-2rp, and (f) GDASrp. Values are in m s^{-1}.

low-level flow is much weaker in GDAS, CDAS-2, and CDAS-2rp. The state-of-the-art GDAS seems to be better at assimilating the SALLJEX data, thereby improving the representation of the LLJ in GDASrp. The low-resolution CDAS is not able to take advantage of the additional sounding data to improve the low-level circulation features. Furthermore, the low-resolution CDAS is not able to adequately resolve the topography (Andes Mountains), which also can affect the intensity and position of the LLJ (Anderson and Arritt 2001).

The moisture fluxes in GDASrp are noticeably stronger (on the order of 30 gm kg^{-1} m s^{-1}) than those in the

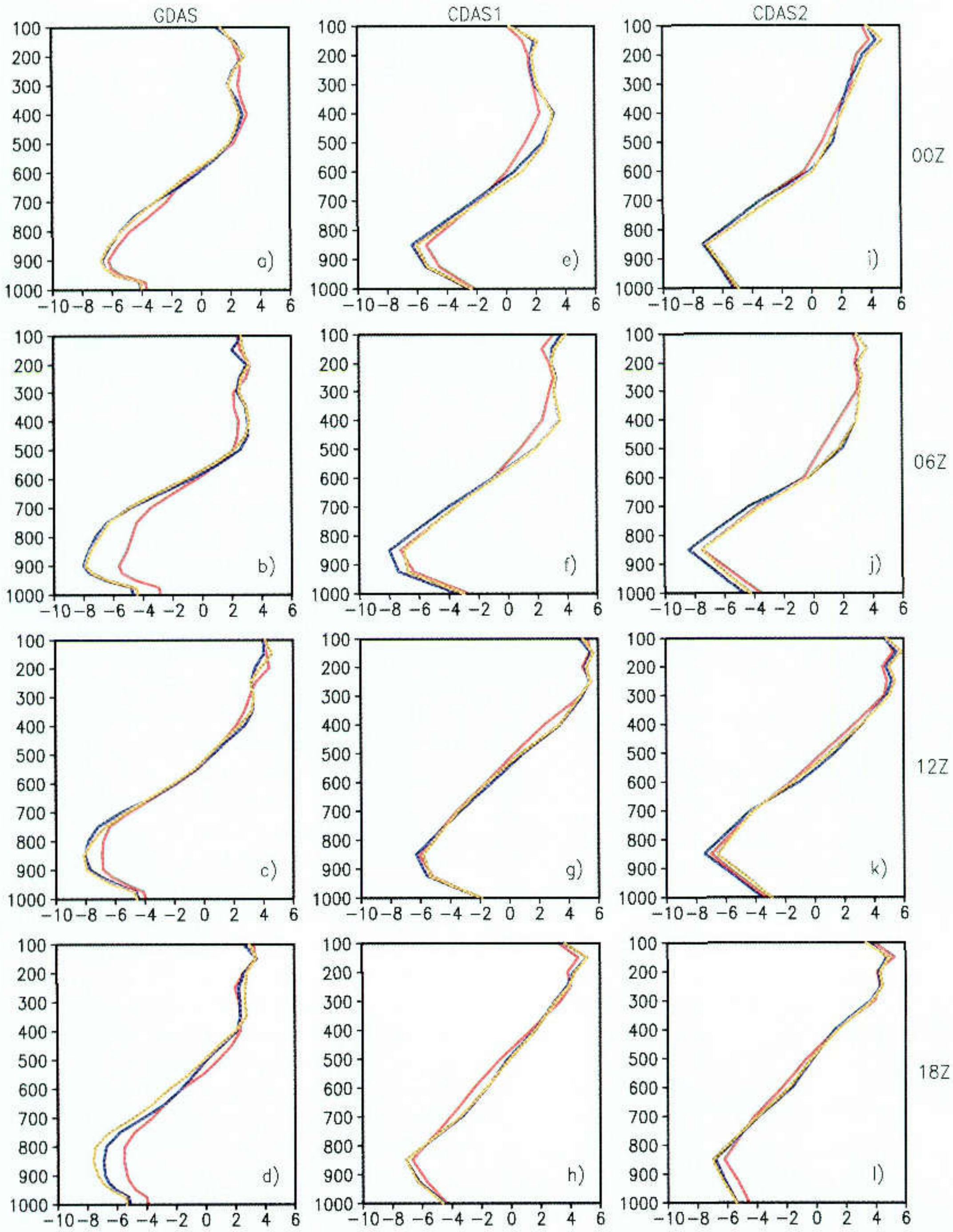

FIG. 3. Mean meridional wind profile composite for control runs (red), including only rawinsonde (blue) and rawinsonde and pilot balloon (yellow) at the grid point nearest Santa Cruz, Bolivia, during 15 Jan–14 Feb 2003. Results from GDAS for (a) 00, (b) 06, (c) 12, and (d), and 18 h UTC; from CDAS-1 for (e) 00, (f) 06, (g) 12, and (h) 18 h UTC; and from CDAS-2 for (i) 00, (j) 06, (k) 12, and (l) 18 h UTC. Units are in m s^{-1}.

control run (GDAS) at all three times (Fig. 7). There is also a slight westward shift in the maximum flux in the GDASrp analyses. This shift is accompanied by stronger upward motion in GDASrp (Fig. 8, cf. left and middle panels), which corresponds well with the pattern of precipitation (Fig. 8, right panel) taken from the Climate Prediction Center (CPC) morphing technique (CMORPH) analyses (Joyce et al. 2004). The CDAS

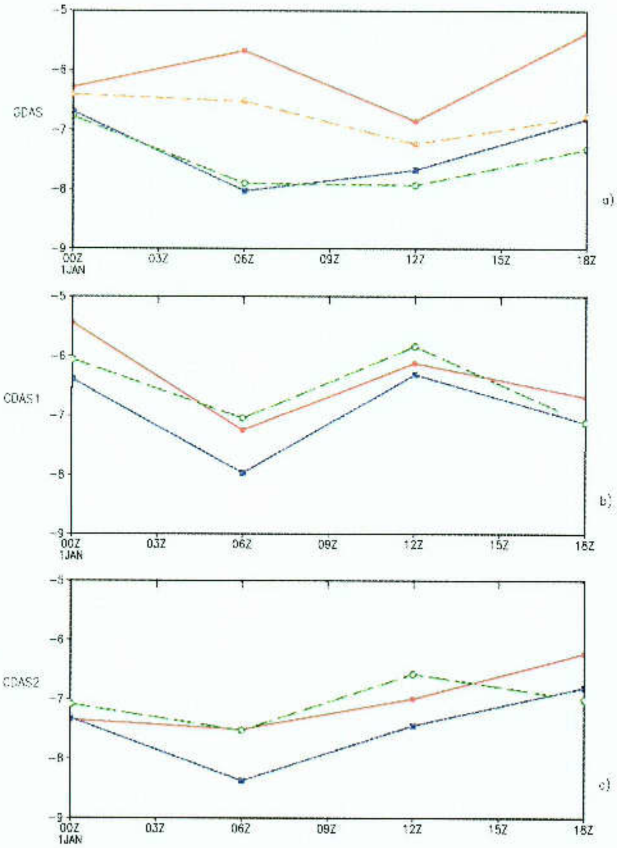

FIG. 4. Mean low-level meridional wind at 18°S, 62°W for (a) GDAS (red), GDASr (blue), GDASp (yellow), and GDASrp (green) at 900 hPa; (b) CDAS-1 (red), CDASr (blue), and CDAS-1rp (green) at 850 hPa; and (c) CDAS-2 (red), CDAS-2r (blue), and CDAS-2rp (green) at 850 hPa. Units are in m s^{-1}.

analyses (with and without SALLJEX data) were not able to capture the circulation features (moisture flux and vertical motion) associated with the intense MCC (figure not shown).

4. Comparison with observations

A comparison between the observed 850-hPa specific humidity at Santa Cruz (see Fig. 1 for station location) with the analyses from GDAS, CDAS-1, and CDAS-2, shows that GDASrp fits well with the raob data (cf. blue triangles with red curve in Fig. 9a), even better than the operational GDAS (green curve in Fig. 9a). Both the operational GDAS and GDASrp capture well the features associated with a strong southerly jet, which occurred during the dry period 23–24 January. In general, the differences between GDAS and GDASrp are less than 2 g kg^{-1}.

The biggest differences between the observations and the analyses occur in CDAS-1 and CDAS-2 (Figs. 9b,c). CDAS-1 shows a much stronger diurnal cycle than that shown in the observations. There is also a positive bias in the specific humidity with values greater than 20 g kg^{-1}, as compared to 15 g kg^{-1} in the observations (Fig. 9b). There is no significant impact on the CDAS-1 analyses when the SALLJEX dataset are included. Similar results are observed with CDAS-2, but the diurnal cycle is not as strong as in CDAS-1 and CDAS-1rp.

Kalnay et al. (1996) classified the gridded fields into four classes in accordance with the relative influence of the observational data and the model on the gridded variable. Specific humidity is considered a class "B" variable, as the model has a very strong influence on its analysis value. Thus, one would expect that the more advanced GDAS with improved physics, higher resolution, and improved data assimilation procedures would better capture specific humidity variations.

Figure 10 shows the 850-hPa meridional wind component for GDAS, GDASrp, CDAS-1, CDAS-1rp, CDAS-2, CDAS-2rp, and the observations. The largest differences occur after the middle of January and extend until the end of the month (Fig. 10a), which is the period having the highest number of raob observations (Table 1). GDASrp agrees very well with the raob data and captures the maximum and minimum (Fig. 10a) associated with the southerly and northerly low-level jet, respectively. In general the control run, GDAS, underestimates the magnitude of the meridional wind.

Both CDAS-1 and CDAS-2 (Figs. 10b and 10c) are unable to capture the extreme values (maximum and minimum) of the 850-hPa meridional wind at the grid point nearest to Santa Cruz. For the CDAS-1rp and CDAS-2rp the differences are small and the meridional winds are generally underestimated. The worst case is associated with the strong, southerly low-level flow during 23–24 January. The observed values are close to 20 m s^{-1}, and for CDAS-1 and CDAS-2 the maximum values are 5 and 3 m s^{-1}, respectively. For CDAS-1rp and CDAS-2rp the values are a little closer to the observed values, 9 and 10 m s^{-1}, respectively.

The specific humidity results for Mariscal in northern Paraguay (Fig. 11) are better than for Santa Cruz (Fig. 9) in all assimilation systems (GDAS, CDAS-1, and CDAS-2: green lines in Figs. 11a, 11b, and 11c, respectively). The results are much better when the SALLJEX data are included and are close to the observed values (red lines in Figs. 11a–c). The better results from CDAS over Mariscal (see Fig. 1 for station location) is probably due to this station being located farther away from the Andes, which reduces the effects of model topography on the low-level flow.

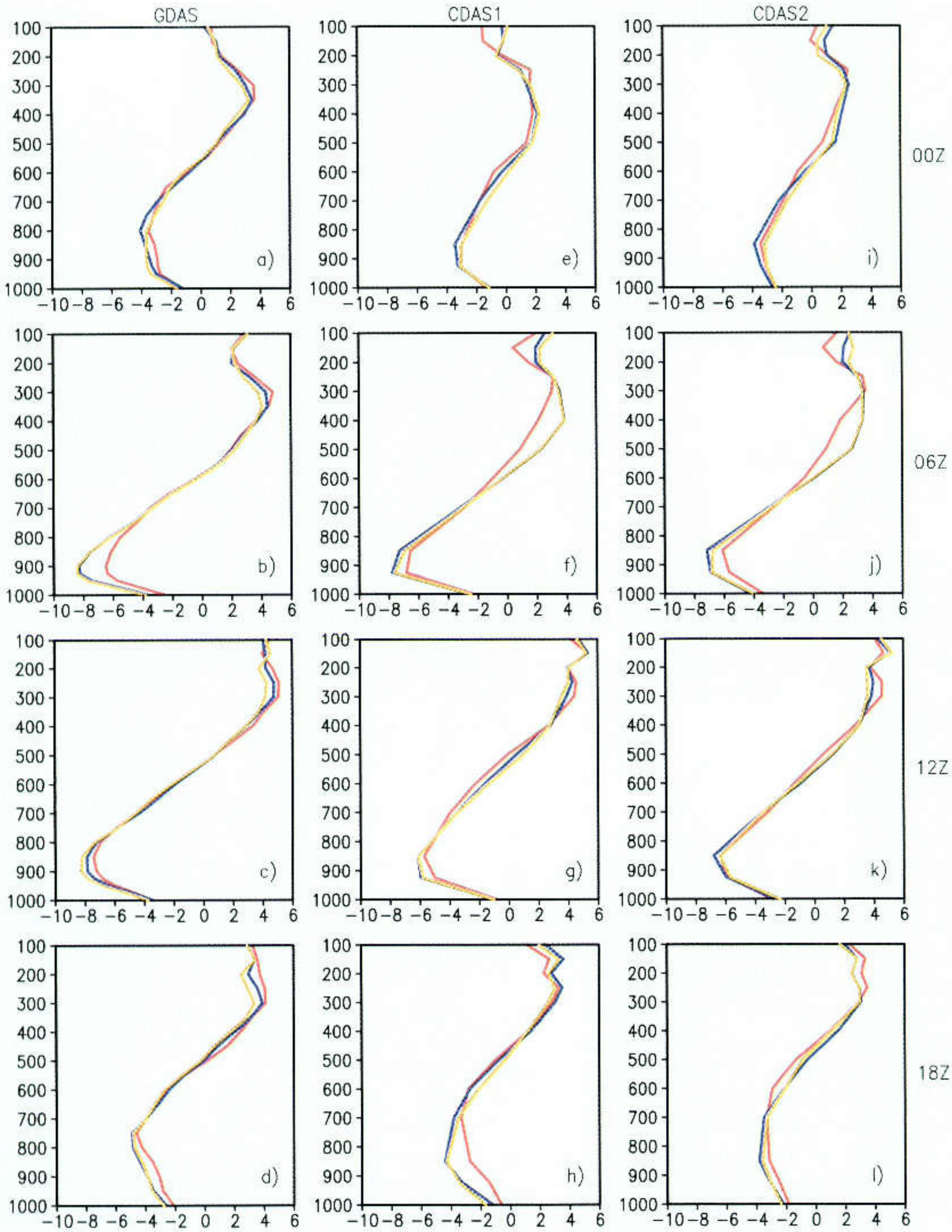

FIG. 5. As in Fig. 3 but for the grid point nearest Mariscal, Paraguay.

The largest differences in specific humidity between CDAS-1 and CDAS-1rp, values close to 5 g kg^{-1}, occurred during the last week of January when the South Atlantic convergence zone (SACZ) was well defined over southeast Brazil and southerly winds and low specific humidity prevailed over Mariscal and Santa Cruz. This relationship between specific humidity and low-level wind are consistent with previous results (Nogués-Paegle and Mo 1997; Herdies et al. 2002).

The meridional wind results for Mariscal (Fig. 12) are similar to those for Santa Cruz (Fig. 10). Again CDAS-1 and CDAS-2 underestimate the extreme

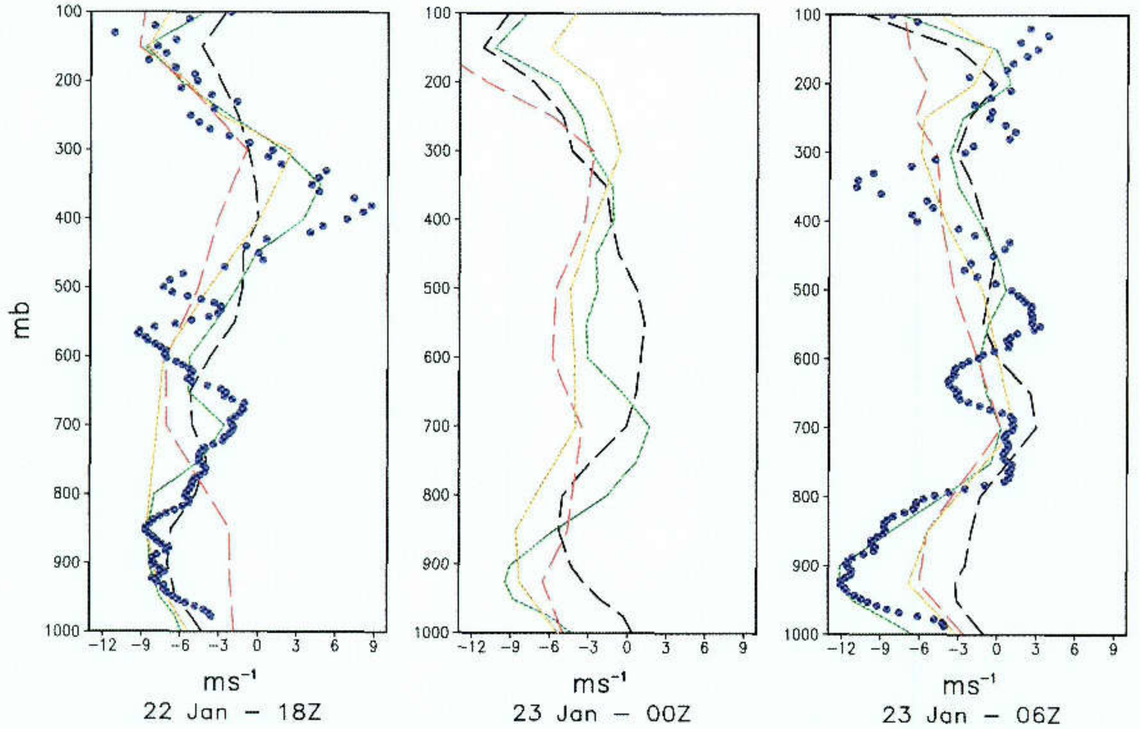

FIG. 6. Vertical profile of meridional wind at Mariscal, with observed data in blue, CDAS-2 (red long dash), CDASrp (dark yellow), GDAS (black long dash), and GDASrp (green) for 1800 UTC 22, 0000 UTC 23, and 0600 UTC 23 Jan. Units are in m s^{-1}.

maximum and minimum 850-hPa wind speeds but they capture well the day-to-day variations. The GDAS results are better and do not show a lot of changes when the SALLJEX data are included (Fig. 12). CDAS-1rp and CDAS-2rp also are in good agreement with the observations (Figs. 12a and 12b, respectively).

With the additional soundings the improvements in the LLJ region are significant and the largest impacts are on the Santa Cruz region (Table 2) where the CDAS and GDAS have the largest uncertainties (RMSE). All simulations show a negative bias (simulation − observation; Table 2) for the zonal wind component, but the biases are significantly reduced with the inclusion of the SALLJEX sounding data. The largest RMSE for the zonal wind is found for CDAS-2 (7.9), followed by GDAS (7.0), and are reduced to 62% (4.9) in CDAS-2r and to 40% in GDASr (2.9).

For the meridional wind component, all simulations show a positive bias (underestimate of the LLJ) for the Santa Cruz region. It is apparent that all the simulations have similar RMSE (near 5.5), but with the additional SALLJEX sounding data improvements in GDASr and GDASrp are more substantial (1.9 and 2.3, respectively), indicating that GDAS is more capable of including the information from the soundings. With the inclusion of PIBAL additional improvements are minor for the u and v wind components.

At Mariscal the differences are smaller than those of Santa Cruz and for all simulations the biases are positive, showing a similar pattern for the meridional wind component as at Santa Cruz. The RMSE is similar for both wind components after the inclusion of SALLJEX sounding data, indicating that all the assimilation systems are able to incorporate information from the special soundings.

Figure 13 compares the observed and SALLJEX assimilated analyses of 850-hPa meridional moisture flux over Santa Cruz and Mariscal. For Mariscal the moisture flux for all assimilation systems is close to the observations (Fig. 13a), with CDAS-1 generally overestimating the moisture flux, but doing much better when the additional sounding data are included (Fig. 13b), with extremes from 150 (g kg^{-1} m s^{-1}) from the south to 120 (g kg^{-1} m s^{-1}) from the north. Santa Cruz shows a stronger transport from the north when compared with values at Mariscal (Figs. 13c and 13d). The strongest transport occurs during the period 20–22 January (Fig. 13d), which resulted in the formation of strong mesoscale convective systems over northern Argentina and Paraguay during 20–22 January (Zipser et al. 2004).

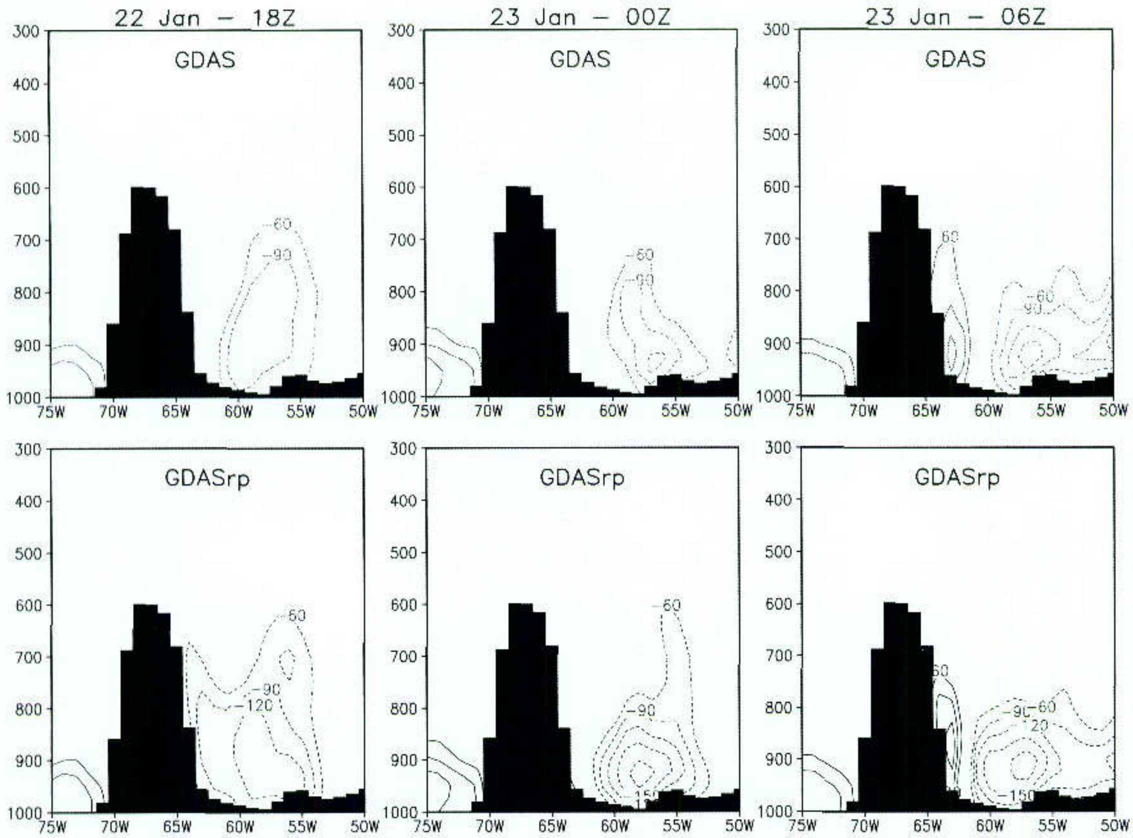

FIG. 7. Cross sections of moisture fluxes (qv) along 22°S (near Mariscal) at 1800 UTC 22, 0000 UTC 23, and 0600 UTC 23 Jan for (top) GDAS and (bottom) GDASrp. Contour interval is 30 g kg^{-1} m s^{-1}.

It is clear that none of the analysis systems were able to capture the strongest transport values without including SALLJEX data (Fig. 13c). During the period of study there is some evidence that the transport over Santa Cruz is more intense than over Mariscal, where GDASrp is in good agreement with the observations (Fig. 13d) and moisture flux is underestimated by CDAS-1rp and CDAS-2rp.

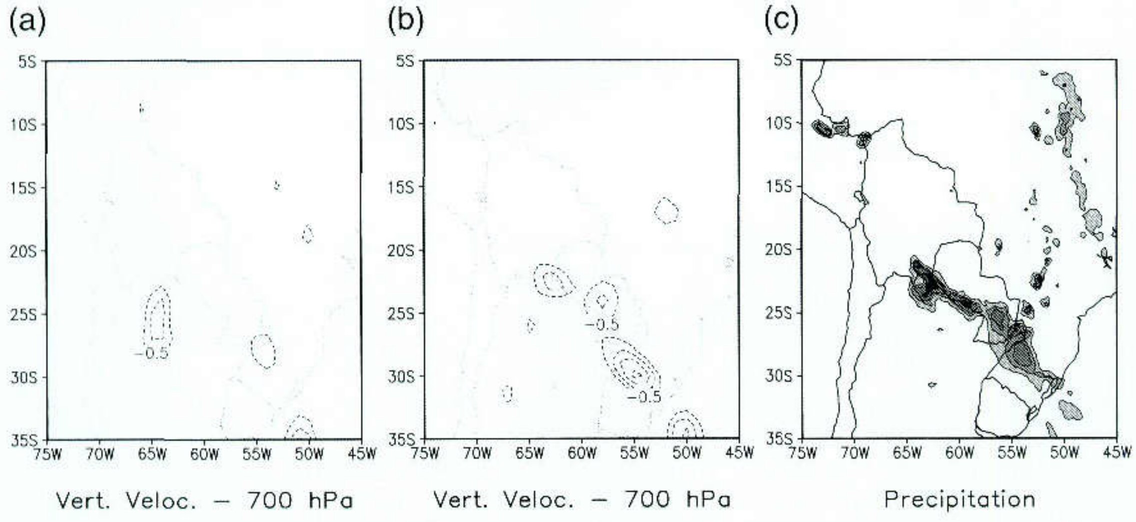

FIG. 8. Vertical velocity at 700 hPa for (a) GDAS, (b) GDASrp, and (c) CMORPH precipitation. Vertical velocity intervals are in 0.5 Pa s^{-1} and precipitation is contoured for irregular intervals of 1, 5, 10, and 20 mm h^{-1} at 0600 UTC 23 Jan 2003.

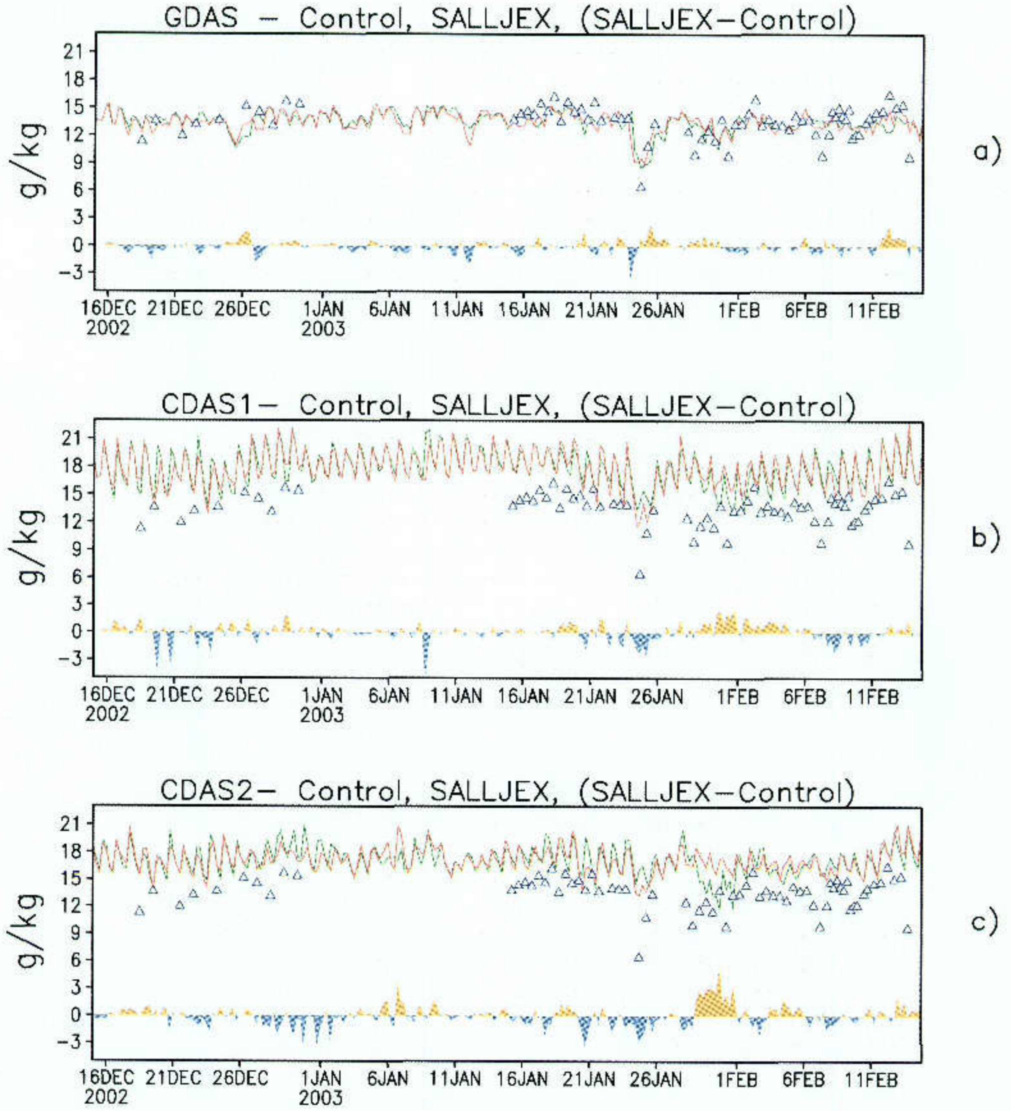

FIG. 9. Time series of 850-hPa specific humidity at the grid point nearest Santa Cruz for 15 Dec 2002–14 Feb 2003 from (a) GDAS (green) and GDASrp (red) and the difference between them. Observational values are indicated by blue triangles. (b) As in (a) except for CDAS-1 and CDAS-1rp. (c) As in (a), except for CDAS-2 and CDAS-2rp. The differences between the analyses with SALLJEX data and the control analyses are plotted at the bottom of each panel. Units are in g kg^{-1}.

The influence from rawinsonde and pilot balloon

Two experiments were conducted to investigate the impact of including SALLJEX rawinsonde and pilot balloon observations separately. GDAS was chosen for these experiments, since the greatest effects of including SALLJEX data are evident for that assimilation system (refer to Fig. 3).

Figure 14 shows the difference between the control analysis (GDAS) and the analysis that assimilated only raob (GDASr) for the synoptic times (0000, 0600, 1200, and 1800 UTC) averaged over 15 January–14 February 2003. The influence from raob is clearly seen in the region east of the Andes, which includes the stations of Santa Cruz and Mariscal (for station locations, see Fig. 1). There is little impact of including the raob data over northern South America, eastern Brazil, or oceanic areas. The most significant effects are at 0600 UTC (Fig. 14c and 14d) near 850 hPa, as shown in the vertical cross sections displayed in the right-hand panels of Fig. 14. The mean sensitivity locally exceeds 3 m s^{-1}, and the strongest influence is at 0600 and 1800 UTC (Figs. 14d and 14h), apparently due to the availability of rawinsonde data at Santa Cruz at those times (Table 1).

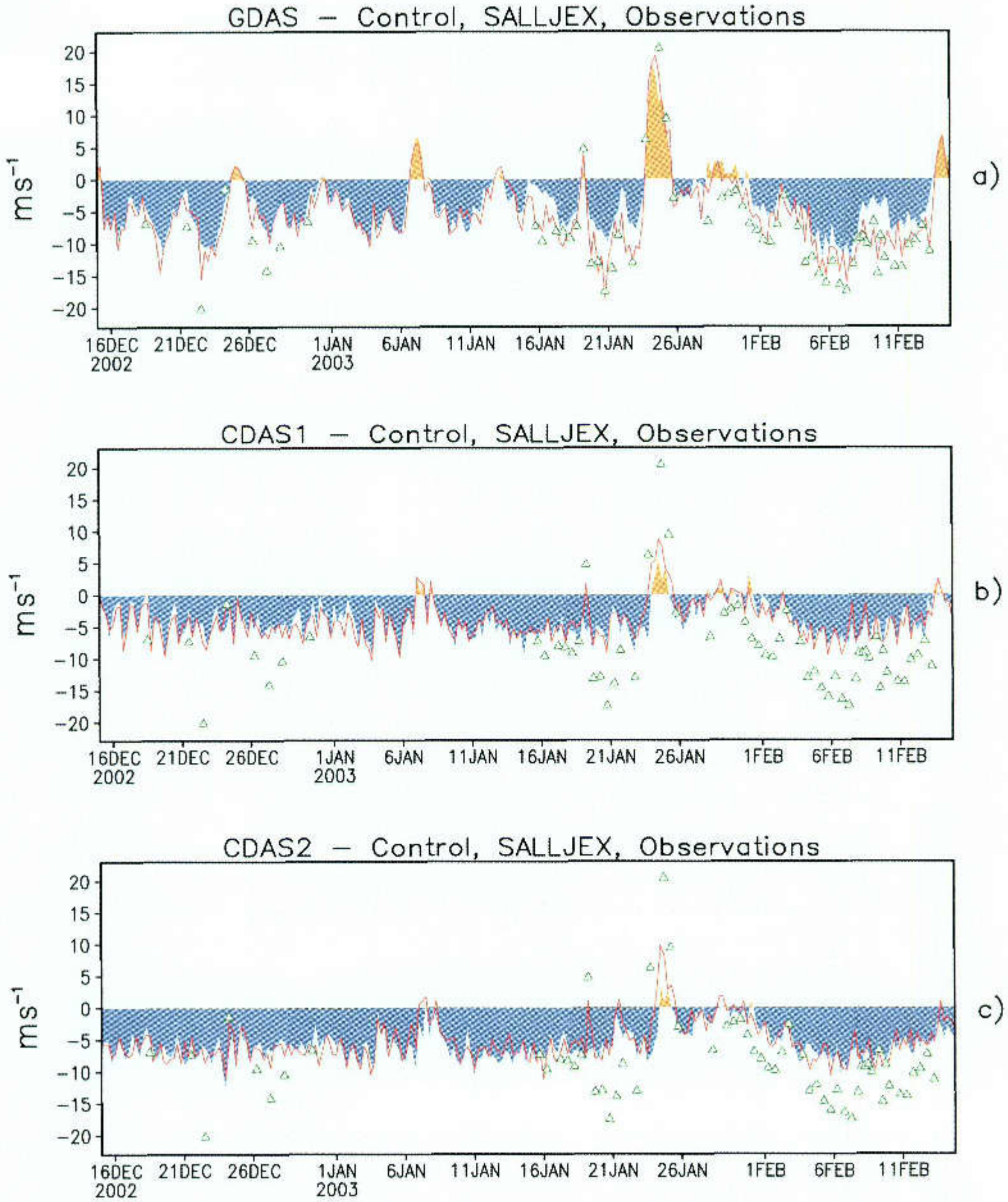

FIG. 10. Time series of 850-hPa meridional wind at the grid point nearest Santa Cruz during 15 Dec 2002–14 Feb 2003 for (a) GDAS (shading) and GDASrp (red line), (b) CDAS-1 (shading) and CDAS-1rp (red line), and (c) CDAS-2 (shading) and CDAS-2rp (red line). The observational values are indicated by green triangles. Units are in m s^{-1}.

Figure 15 displays the results of the assimilation of SALLJEX pilot balloon observations. The strongest effects are again observed around 0600 and 1800 UTC but are somewhat weaker than those related to the rawinsonde observations (Fig. 14).

These results show that, although there are more pilot balloon observations than rawinsonde observations in the SALLJEX dataset, most of the improvements in the analyses can be obtained by only including rawinsonde observations. It is possible that the pilot balloon observations were not as heavily weighted as the rawinsondes by the assimilation systems. The former observations are not easily available at night or above clouds and provide neither thermal nor moisture data that can be crucial to define the humidity transport from the Tropics to extratropics.

5. Conclusions

A data assimilation study was performed to assess the impact of observations from the South American

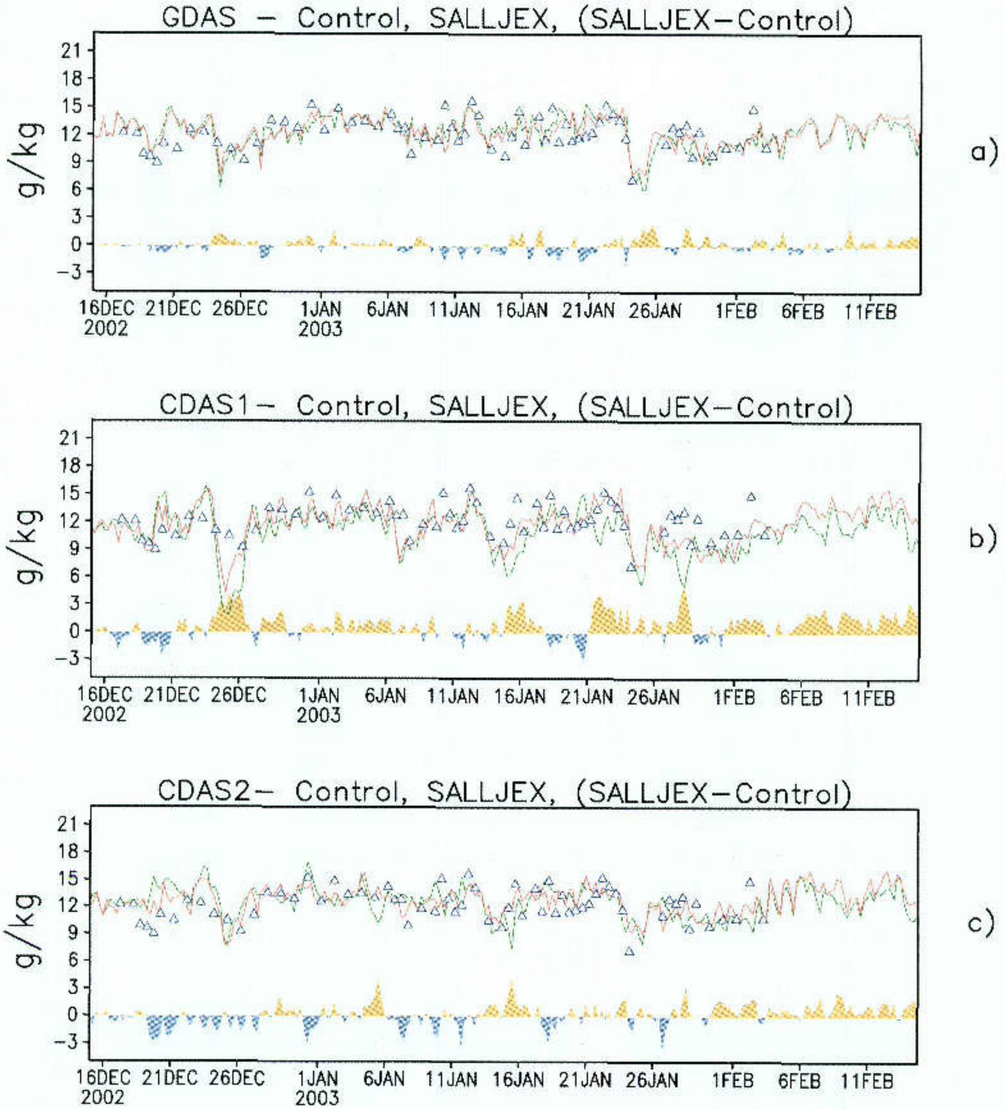

FIG. 11. As in Fig. 9 but for the grid point nearest Mariscal, Paraguay.

Low-Level Jet Experiment (SALLJEX) on analyses in the region east of the Andes Mountains from western Brazil to central Argentina. The data assimilation systems CDAS-1, CDAS-2, and GDAS were run with and without the additional SALLJEX rawinsondes and pilot balloon observations (Fig. 1). This evaluation is crucial to examining the impact of high-resolution field experiment data on the NCEP global analysis and the ability of state-of-the-art data assimilation systems to correctly analyze important climatic features of a major monsoon system.

Most of the effects on the reanalysis that include additional SALLJEX data are regional and concentrated over the SALLJ region, with the largest differences at low levels. All assimilation systems showed improvements in the SALLJ when SALLJEX data were included. The differences between CDAS-1rp and CDAS-2rp are small when compared with the respective control runs. The largest effects for all assimilation systems appear where uncertainties are large, which usually occurs when there is a lack of routine upper-air observations.

The coarse resolutions of CDAS-1 and CDAS-2 (T62 ~250 km) do not adequately resolve the Andes Mountains and, as a result, CDAS systems were unable to exploit the additional sounding data from Santa Cruz to improve the characteristics of the low-level jet and associated moisture transport. CDAS systems displayed only minor analysis improvements when the enhanced SALLJEX sounding data were included, with CDAS-2

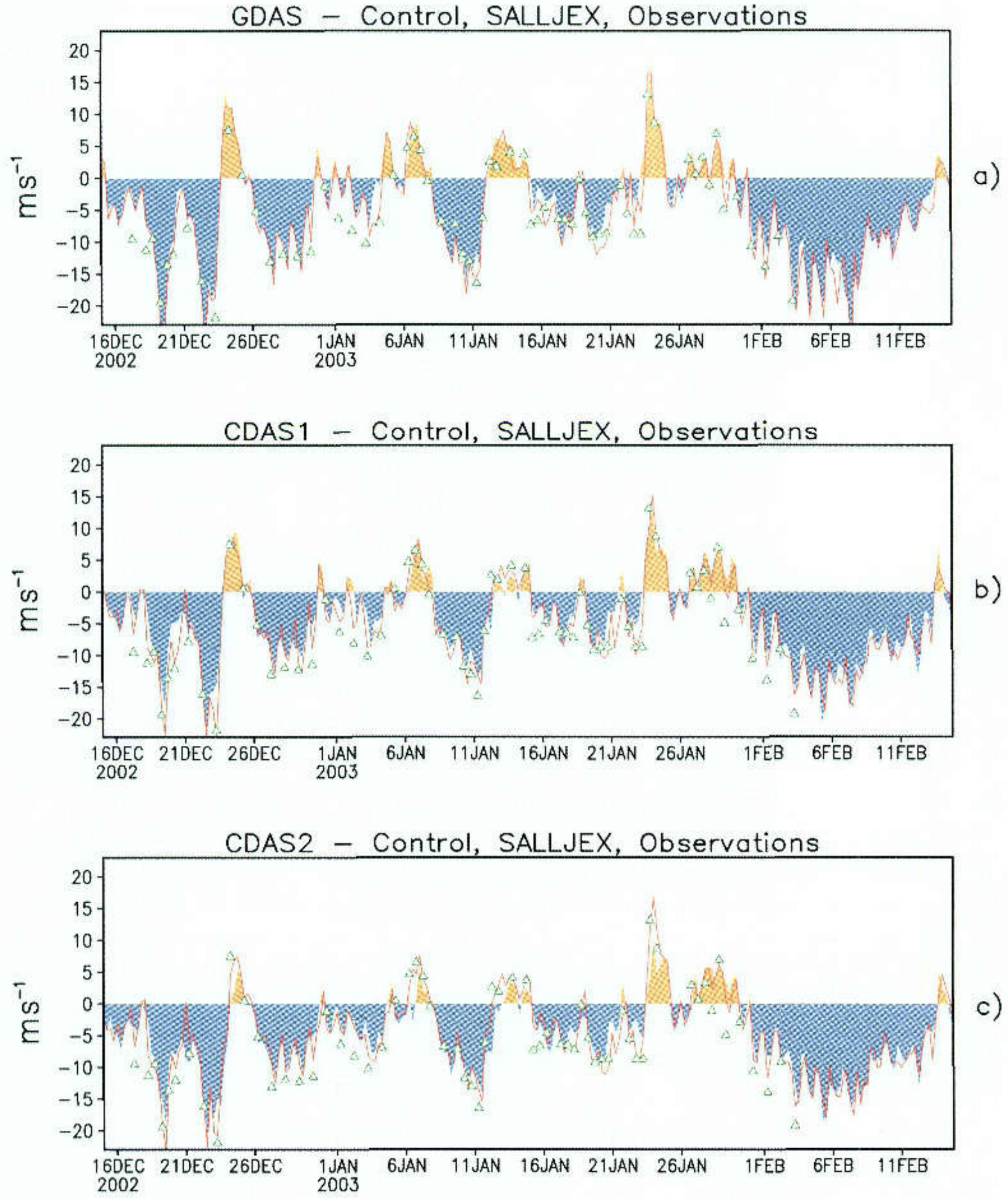

FIG. 12. As in Fig. 10 but for the grid point nearest Mariscal, Paraguay.

TABLE 2. Error statistics of the zonal and meridional wind at 850 hPa from 15 Dec 2002 to 14 Feb 2003 for Santa Cruz and Mariscal.

	Santa Cruz				Mariscal			
Expt	u RMSE	u bias	v RMSE	v bias	u RMSE	u bias	v RMSE	v bias
CDAS-1	6.3	−5.2	5.6	2.1	3.5	1.6	4.3	1.9
CDAS-1r	3.6	−2.7	4.0	1.8	2.3	1.0	2.6	1.0
CDAS-1rp	3.9	−3.0	4.1	2.1	2.4	1.2	2.5	0.9
CDAS-2	7.9	−6.7	5.5	1.8	3.6	0.4	4.6	1.3
CDAS-2r	4.9	−4.0	3.5	1.2	2.3	0.5	2.5	1.0
CDAS-2rp	4.9	−3.9	3.9	1.5	2.4	0.7	2.6	1.2
GDAS	7.0	−5.9	5.4	4.2	3.1	0.5	3.4	1.8
GDASr	2.9	−1.9	1.9	0.9	1.5	0.1	1.5	0.0
GDASrp	3.0	−2.0	2.3	1.0	2.5	0.1	2.3	0.6
GDASp	6.0	−4.6	5.0	3.3	3.1	0.6	3.0	1.0

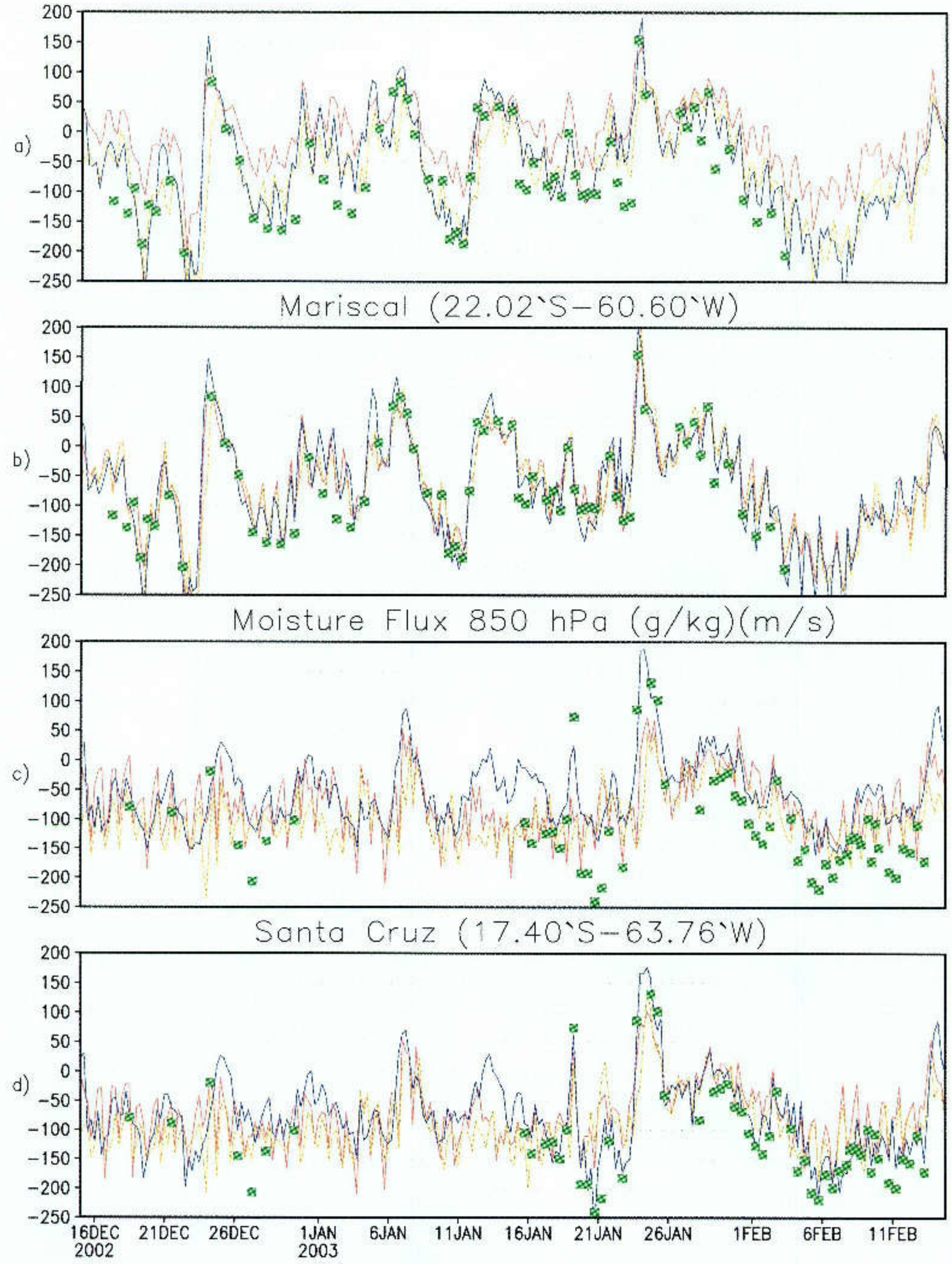

FIG. 13. Time series of the meridional moisture flux at 850 hPa from (a) CDAS-1 (red line), CDAS-2 (yellow line), and GDAS (blue line) for the grid point nearest Mariscal. (b) As in (a) except for CDAS-1rp, CDAS-2rp, and GDASrp. (c) As in (a) except for the grid point nearest Santa Cruz. (d) As in (b) except for the grid point nearest Santa Cruz. Observational values are in green. Units are in m s^{-1}g kg^{-1}.

showing a little improvement over CDAS-1. Also, CDAS systems clearly overestimate the specific humidity in control runs, which was not corrected when SALLJEX data were included.

For all three assimilation systems the inclusion of pilot balloon data does not significantly improve analyses over those produced using only rawinsonde data. In part this may be due to the fact that the pilot balloon ascents use the first guess from the models to locate the correct pressure levels, using the height information provided from pilot balloons. This process can include some error and it is possible that in some cases the pilot

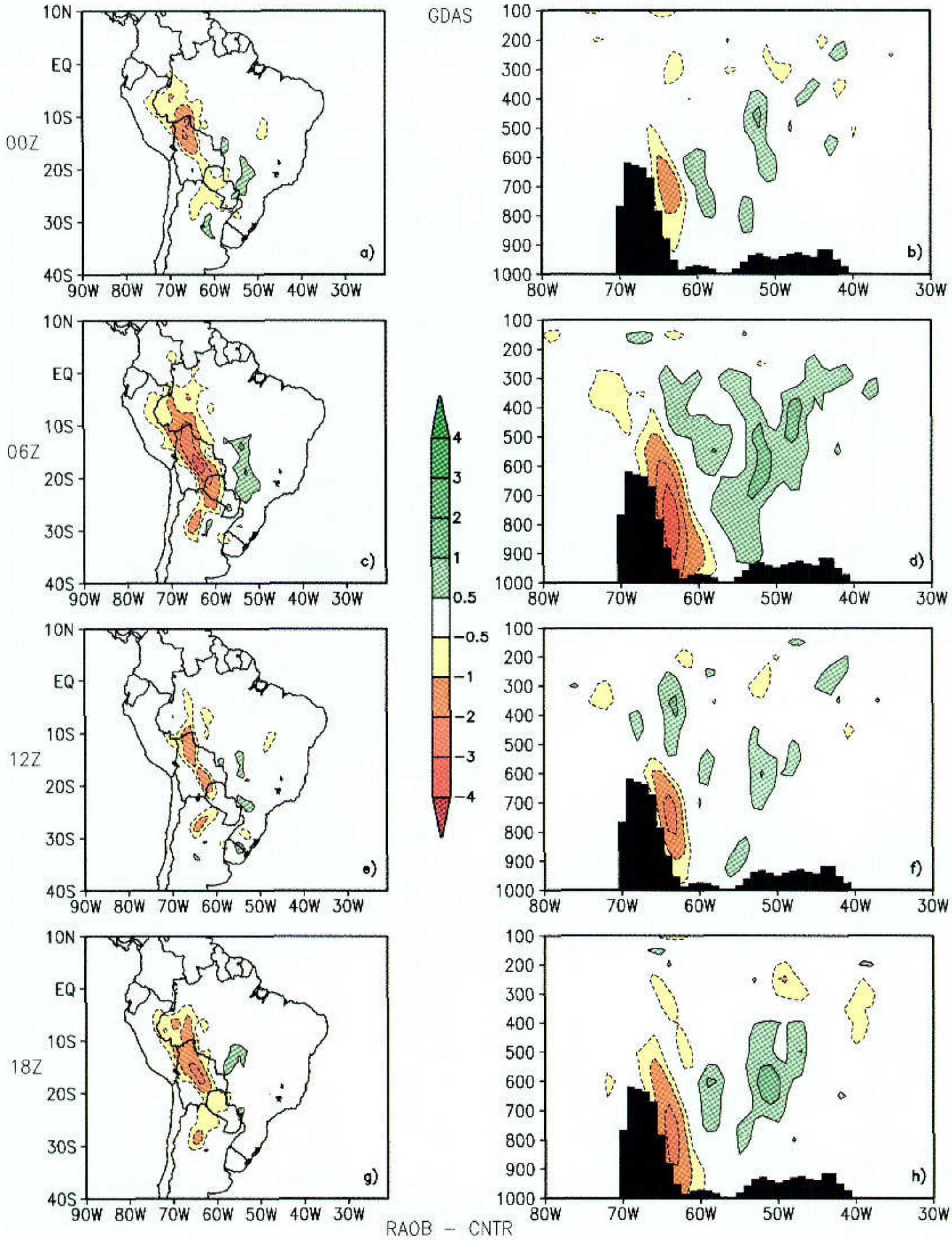

FIG. 14. Mean 850-hPa wind difference between GDAS and GDASr for four synoptic times (left-hand column) and vertical zonal cross sections of meridional wind at 18°S (right-hand column) during 15 Jan–14 Feb 2003. Values are in m s^{-1}.

balloon data were not assimilated because of data rejection criteria.

Some fields, such as winds, temperature, and geopotential height, are generally well defined by observations and, given the statistical interpolation of the observations and first guess, the reanalyzed fields are the best estimate of the evolving state of the atmosphere, which is even better than would be obtained using only observations. For others, such as moisture variables, the model characteristics, which influence the model

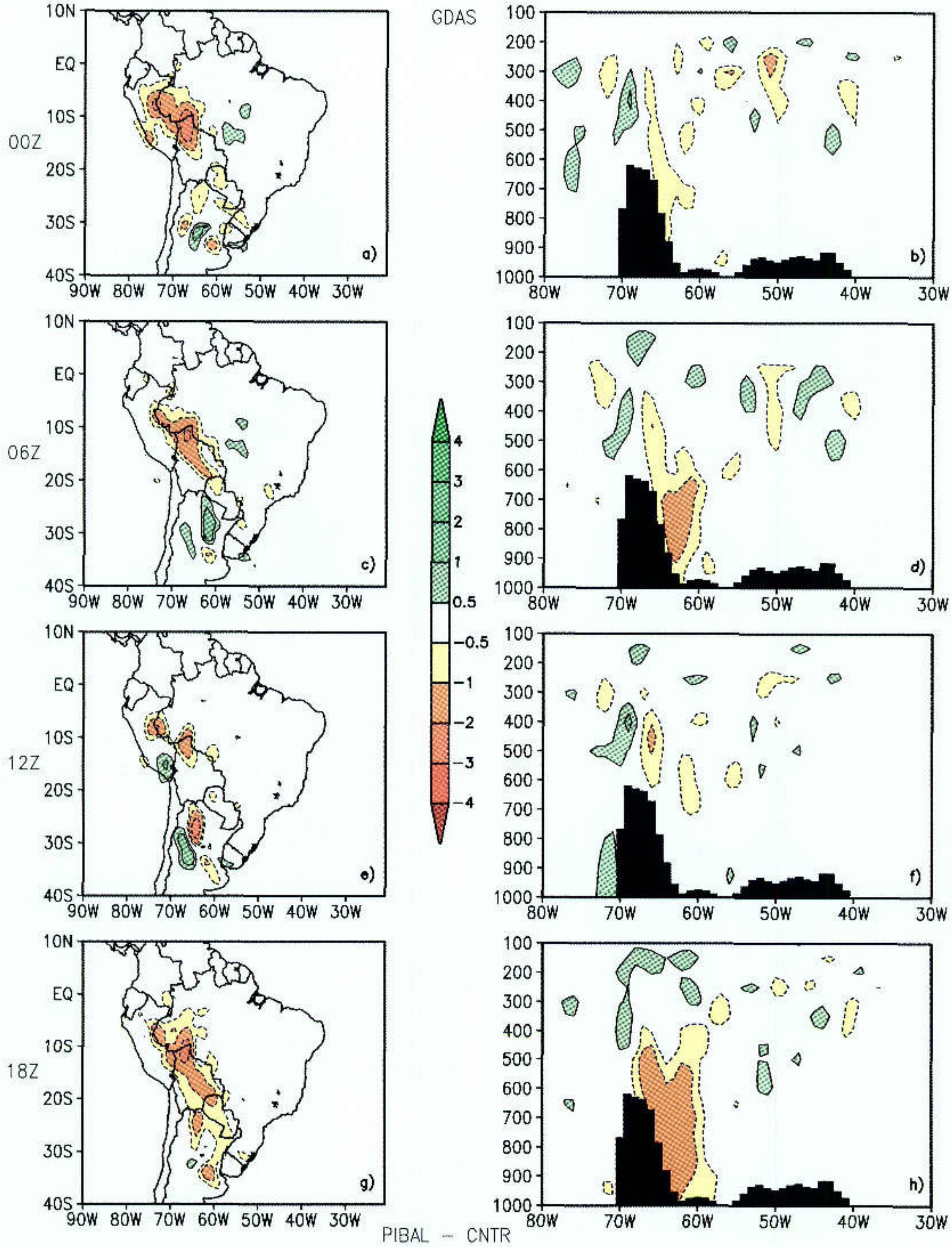

FIG. 15. As in Fig. 14 except for the difference between GDAS and GDASp.

climatology, become more important (Kalnay et al. 1996).

For the global analyses, the GDAS provides the best results because of its higher resolution and state-of-the-art data assimilation system, which is more effective in assimilating satellite data, such as radiances. GDASrp shows a narrow jet concentrated near the Andes with the maximum speed close to Santa Cruz. Silva Dias et al. (2001) found similar results indicating that the higher-resolution model confines the low-level jet to a narrower strip along the Andes. The diurnal cycle in the strength of the LLJ is more evident, with maximum strength at 0600 UTC near 900 hPa in GDAS and 850 hPa in CDAS.

The data impact results for Mariscal in northern Paraguay show considerable improvement in the wind and humidity analyses, especially for CDAS. The better results for CDAS-1 and CDAS-2 at Mariscal are probably due to the greater distance of that site from the Andes, which minimizes the effects of the model topography. The significant reduction of rms errors at Santa Cruz and Mariscal show the ability of the GDAS to assimilate additional sounding data into the analysis.

The results show that, although there are more pilot balloon observations than rawinsonde observations in the SALLJEX dataset, most of the improvements in the analyses can be obtained by only including rawinsonde observations.

The reanalysis dataset produced in this study using the information from SALLJEX has the potential to provide the best possible information to be used for future studies at SALLJ region and can be used for the design of observing systems in the region. This paper points out the importance of regular observations from the region of Santa Cruz to properly depict the position and intensity of the SALLJ.

All of the datasets used in this study are available at the Joint Office for Science Support/University Corporation for Atmospheric Research (JOSS/UCAR) for distribution and use in additional validation/evaluation studies in the future.

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