Influence of the North American Monsoon Experiment (NAME) 2004 Enhanced Soundings on NCEP Operational Analyses

Kingtse C. Mo, Eric Rogers, Wesley Ebisuzaki, and R. Wayne Higgins
NOAA/NWS/NCEP/Climate Prediction Center, Camp Springs, Maryland

J. WoolLEN
NOAA/NWS/NCEP/Environmental Modeling Center, Camp Springs, Maryland

M. L. Carrera
RS Information Systems, McLean, Virginia

(Manuscript received 7 November 2005, in final form 21 April 2006)

ABSTRACT

During the 2004 North American Monsoon Experiment (NAME) field campaign, an extensive set of enhanced atmospheric soundings was gathered over the southwest United States and Mexico. Most of these soundings were assimilated into the NCEP operational global and regional data assimilation systems in real time. This presents a unique opportunity to carry out a series of data assimilation experiments to examine their influence on the NCEP analyses and short-range forecasts. To quantify these impacts, several data-withholding experiments were carried out using the global Climate Data Assimilation System (CDAS), the Regional Climate Data Assimilation System (RCDAS), and the three-dimensional variational data assimilation (3DVAR) Eta Model Data Assimilation System (EDAS) for the NAME 2004 enhanced observation period (EOP).

The impacts of soundings vary between the assimilation systems examined in this study. Overall, the influence of the enhanced soundings is concentrated over the core monsoon area. While differences at upper levels are small, the differences at lower levels are more substantial. The coarse-resolution CDAS does not properly resolve the Gulf of California (GoC), so the assimilation system is not able to exploit the additional soundings to improve characteristics of the Gulf of California low-level jet (GCLLJ) and the associated moisture transport in the GoC region. In contrast, the GCLLJ produced by RCDAS is conspicuously stronger than the observations, though the problem is somewhat alleviated with additional special NAME soundings. For EDAS, soundings improve the intensity and position of the Great Plains low-level jet (GPLLJ). The soundings in general improve the analyses over the areas where the assimilation system has the largest uncertainties and errors. However, the differences in regional analyses owing to the soundings are smaller than the differences between the two regional data assimilation systems.

I. Introduction

During the 2004 North American Monsoon Experiment (NAME) field campaign (1 July–15 September; Higgins et al. 2006), an extensive set of enhanced atmospheric soundings was gathered over the southwest United States, northern Mexico, and the Caribbean. There were 22 stations located over northern Mexico and the southwest United States (Fig. 1), with seven of them (Puerto Penasco, Kino Bay, Empalme, Los Mochis, Loreto, Mazatlan, and La Paz) located along the Gulf of California (GoC). In addition, the Research Vessel (R/V) Altair was stationed at the mouth of the GoC. Most sites operated twice daily, but during the 10 intensive observing periods (IOPs), some sites operated 4–6 times daily. Most of the sounding data entered the Global Telecommunications System (GTS) and were accepted into the National Centers for Environmental Prediction (NCEP) operational global and regional analysis in real time. Table 1 lists the site locations, report frequencies, periods of operation, and number of
reports entering the NCEP operational system during the enhanced observation period (EOP). In addition to soundings, Wang and Xie (2007) analyzed a new multiplatform merged sea surface temperature (SST) dataset based on several satellites and in situ data. Because more input data were included, the new SST data should be more representative than the operational SST analysis (Thiebaux et al. 2003). Recently, a precipitation analysis including the daily gauge network (Higgins et al. 2000), and precipitation from the NAME Event Rain Gauge Network (NERN) (Gochis et al. 2004) were also made available.

The NAME special datasets present a unique opportunity to carry out a series of data impact experiments that highlight the influence of the sounding data, precipitation, and SSTs on the NCEP analyses. In this paper, we present some early results with emphasis on the impact of the NAME special soundings. Work is under way to examine the impact of precipitation assimilation and SSTs in the Gulf of California and address the uncertainties in the analyses.

The impact studies are based on three of NCEP’s data assimilation systems: one global and two regional systems. The global system is the Climate Data Assimilation System (CDAS). During the EOP, data from the operational Global Data Assimilation System (GDAS) forecast system were also archived. The GDAS products serve as a reference because it has higher resolu-

<table>
<thead>
<tr>
<th>Site</th>
<th>Elevation (m)</th>
<th>Lat (°N)</th>
<th>Lon (°W)</th>
<th>Operation dates</th>
<th>EOP frequencies of samples per day</th>
<th>IOP frequencies of samples per day</th>
<th>No. of reports (EOP)</th>
</tr>
</thead>
<tbody>
<tr>
<td>P. Penasco (ISS)*</td>
<td>48</td>
<td>31.18</td>
<td>113.33</td>
<td>8 Jul–13 Aug</td>
<td>2</td>
<td>4</td>
<td>122 9</td>
</tr>
<tr>
<td>Los Mochis (ISS)*</td>
<td>4</td>
<td>25.41</td>
<td>109.05</td>
<td>8 Jul–15 Aug</td>
<td>4</td>
<td>6</td>
<td>200 5</td>
</tr>
<tr>
<td>Loreto (GLASS)*</td>
<td>15</td>
<td>26.01</td>
<td>111.21</td>
<td>10 Jul–15 Aug</td>
<td>4</td>
<td>6</td>
<td>175 46</td>
</tr>
<tr>
<td>Empalme (SMN)*</td>
<td>12</td>
<td>27.95</td>
<td>110.77</td>
<td>1 Jul–31 Aug</td>
<td>2</td>
<td>6</td>
<td>140 2</td>
</tr>
<tr>
<td>Mazatlan (SMN)*</td>
<td>4</td>
<td>23.20</td>
<td>106.42</td>
<td>1 Jul–31 Aug</td>
<td>2</td>
<td>6</td>
<td>137 1</td>
</tr>
<tr>
<td>Chihuahua (SMN)*</td>
<td>1434</td>
<td>28.63</td>
<td>106.08</td>
<td>1 Jul–31 Aug</td>
<td>2</td>
<td>6</td>
<td>157 1</td>
</tr>
<tr>
<td>Torreon (SMN)*</td>
<td>1150</td>
<td>25.53</td>
<td>103.45</td>
<td>17 Jun–30 Sep</td>
<td>2</td>
<td>6</td>
<td>150 1</td>
</tr>
<tr>
<td>Monterey (SMN)*</td>
<td>448</td>
<td>25.87</td>
<td>100.23</td>
<td>1 Jun–22 Aug</td>
<td>2</td>
<td>6</td>
<td>111 1</td>
</tr>
<tr>
<td>Zacatecas/Guaralupe (SMN)*</td>
<td>2265</td>
<td>22.75</td>
<td>102.51</td>
<td>1 Jun–30 Sep</td>
<td>2</td>
<td>6</td>
<td>153 0</td>
</tr>
<tr>
<td>La Paz (SMN)*</td>
<td>19</td>
<td>24.17</td>
<td>110.30</td>
<td>1 Jul–31 Aug</td>
<td>2</td>
<td>6</td>
<td>160 6</td>
</tr>
<tr>
<td>Tucson (NWS)*</td>
<td>788</td>
<td>32.12</td>
<td>110.92</td>
<td>21 Jun–31 Aug</td>
<td>2</td>
<td>4</td>
<td>123 3</td>
</tr>
<tr>
<td>Las Vegas (NWS)</td>
<td>1007</td>
<td>36.62</td>
<td>116.02</td>
<td>21 Jun–31 Aug</td>
<td>2</td>
<td>4</td>
<td>136 1</td>
</tr>
<tr>
<td>San Diego (NWS)</td>
<td>132</td>
<td>32.85</td>
<td>117.12</td>
<td>21 Jun–31 Aug</td>
<td>2</td>
<td>4</td>
<td>130 0</td>
</tr>
<tr>
<td>Flagstaff (NWS)</td>
<td>2179</td>
<td>35.23</td>
<td>111.82</td>
<td>21 Jun–31 Aug</td>
<td>2</td>
<td>4</td>
<td>138 0</td>
</tr>
<tr>
<td>Albuquerque (NWS)</td>
<td>1619</td>
<td>35.05</td>
<td>106.62</td>
<td>21 Jun–31 Aug</td>
<td>2</td>
<td>4</td>
<td>131 0</td>
</tr>
<tr>
<td>El Paso (NWS)</td>
<td>1252</td>
<td>31.87</td>
<td>106.70</td>
<td>21 Jun–31 Aug</td>
<td>2</td>
<td>4</td>
<td>129 0</td>
</tr>
<tr>
<td>Amarillo (NWS)</td>
<td>1094</td>
<td>35.23</td>
<td>101.70</td>
<td>21 Jun–31 Aug</td>
<td>2</td>
<td>4</td>
<td>126 6</td>
</tr>
<tr>
<td>Midland (NWS)</td>
<td>873</td>
<td>31.95</td>
<td>102.18</td>
<td>21 Jun–31 Aug</td>
<td>2</td>
<td>4</td>
<td>132 2</td>
</tr>
<tr>
<td>Del Rio (NWS)</td>
<td>314</td>
<td>29.37</td>
<td>100.92</td>
<td>21 Jun–31 Aug</td>
<td>2</td>
<td>4</td>
<td>132 1</td>
</tr>
<tr>
<td>Yuma (ARMY)</td>
<td>147</td>
<td>32.51</td>
<td>114.00</td>
<td>1 Jun–30 Sep</td>
<td>2</td>
<td>4</td>
<td>239 239</td>
</tr>
<tr>
<td>Phoenix (NWS)*</td>
<td>384</td>
<td>33.45</td>
<td>111.95</td>
<td>8 Jun–24 Sep</td>
<td>2</td>
<td>4</td>
<td>184 5</td>
</tr>
<tr>
<td>Belize City, Belize</td>
<td>5</td>
<td>17.53</td>
<td>88.3</td>
<td>1 Jun–2 Sep</td>
<td>2</td>
<td>—</td>
<td>77 16</td>
</tr>
<tr>
<td>San Jose, Costa Rica</td>
<td>939</td>
<td>9.98</td>
<td>84.22</td>
<td>16 Jun–30 Sep</td>
<td>4</td>
<td>—</td>
<td>171 18</td>
</tr>
<tr>
<td>Res. Vessel Altair (CSU)</td>
<td>5</td>
<td>23.5</td>
<td>108.07</td>
<td>2 Jul–12 Aug</td>
<td>4</td>
<td>6</td>
<td>151 151</td>
</tr>
</tbody>
</table>

* Soundings excluded from the CDASwtmex and RCDASwtmex experiments.
tion and captures the monsoon-related features better than CDAS. The two regional systems are the Regional Climate Data Assimilation System (RCDAS) (Mesinger et al. 2006) and the NCEP operational three-dimensional variational data assimilation (3DVAR)Eta Model Data Assimilation System (EDAS) (Rogers et al. 2001; Ferrier et al. 2003). Brief descriptions of the systems and experiments are provided in section 2. The impact of the soundings on the global CDAS is examined in section 3. The impact on the regional analyses is discussed in section 4. Conclusions are given in section 5.

2. Experiments

The study focuses on the portion of the NAME 2004 EOP from 1 July to 15 August. Because our purpose is to examine the impact of special NAME soundings on the NCEP operational analyses, the NCEP operational systems are considered as the control experiments. During the EOP period, most soundings entered the GTS in real time and were accepted by the operational NCEP systems. The number of missing reports for each station is listed in Table 1. The control experiments (the operational NCEP systems) are labeled as w because all NAME special soundings except Yuma, Arizona, and the R/V Altair (Fig. 1, triangles) were included. Reports from Yuma and the Altair did not reach the GTS in real time and were excluded from all experiments in this paper.

For the data-withholding studies, the model, assimilation systems, and input data for all experiments are identical to the control, with the only distinction being whether or not the NAME special soundings were used. The set of experiments labeled as “wt” excludes all NAME special soundings plotted in Fig. 1. The second set of experiments labeled as “wtmex” excludes only soundings located in the core monsoon region (Fig. 1, dark circles).

a. CDAS

The CDAS has a low horizontal resolution of T62 and 28 levels in the vertical. It is a frozen system identical to that used for the NCEP–Department of Energy (DOE) Reanalysis 2 (R2; Kanamitsu et al. 2002). The CDAS does not assimilate precipitation (P) directly, but it adjusts the soil moisture field according to the Climate Prediction Center Merged Analysis of Precipitation (CMAP) pentad mean precipitation (Xie and Arkin 1997, Xie et al. 2003). This adjustment improves soil moisture and related surface fields (Kanamitsu et al. 2002).

The operational CDAS experiments are labeled CDASw. The total number of reports and the number of missing reports are given in Table 1. Except Loreto, which had 24% of the data missing or not accepted, most NAME special soundings were accepted by CDAS. The first data-withholding experiment CDASwt excludes all stations in Fig. 1. A second experiment, CDASwtmex, only excludes soundings over northern Mexico and two stations (Phoenix and Tucson) over the southwest United States (Fig. 1, dark circles). The purpose of CDASwtmex is to examine the impact of soundings over the core monsoon region on CDAS. To examine the impact on short-range forecasts, we performed forecasts out to 96 h from CDASw and CDASwtmex 0000 and 1200 UTC analyses.

For reference, the GDAS outputs were used for comparison. The GDAS during the 2004 summer had a horizontal resolution of T254 (roughly 50 km). The GDAS did not assimilate precipitation.

b. RCDAS

The RCDAS system is also frozen and is the same system used in the NCEP operational EDAS of 2003 (Rogers et al. 2001; Ferrier et al. 2003). The horizontal resolution is 32 km and there are 45 levels in the vertical. The input data for RCDAS are listed in Mesinger et al. (2006) and Shafran et al. (2004). The RCDAS has the NCEP–Oregon State University–U.S. Air Force–NWS/Hydrologic Research Lab (Noah) land surface model as a subcomponent (Mitchell et al. 2004). The RCDAS assimilates precipitation (P) (Lin et al. 2001). The input P data include the Climate Prediction Center (CPC) operational rain gauge precipitation over the United States and Mexico (Higgins et al. 2000) and the CPC Morphing technique (CMORPH) data (Joyce et al. 2004). The NERN data were not available in real time so they were not included in this study. The CDAS and RCDAS use the same input files, which will be discussed in the next section. The only difference is that the surface temperature data are not used in RCDAS (Shafran et al. 2004).

The operational RCDAS is labeled as RCDASw. The data-withholding experiment RCDASwtmex excludes soundings plotted in Fig. 1 and RCDASwtmex excludes soundings over northern Mexico and the U.S. southwest (Fig. 1, circles).

c. Data inputs

In addition to the precipitation and SSTs, all systems used the Television and Infrared Observation Satellite (TIROS) Operational Vertical Sounder (TOVS) 1b ra-
diance data, rawinsondes, pibals, wind profilers and aircraft reports, and cloud drift winds from the Geostationary satellite. To give a typical example, Fig. 2 shows the input data counts on 13 July 2004, which was the monsoon onset date. The actual data counts varied from day to day, and 0000 UTC usually had more data counts than 1200 UTC. The upper-air data included rawinsonde, pibal, dropwinsonde, and reconnaissance, and had good coverage at 0000 UTC (Fig. 2a). At 1800 UTC, most data came from the NAME special soundings (Fig. 2b). The surface observations from landmasses had very large data counts for both 0000 and 1800 UTC. In the nearby oceans, data included the surface marine ships, buoys, Coastal-Marine Automated Network (C-MAN) platforms, and splash-level drop-sondes (Fig. 2f). The observational data processing procedures are posted online (Keyser 2005).

GDAS and EDAS also used the National Oceanic and Atmospheric Administration-15 (NOAA-15) and NOAA-16 Advanced Microwave Sounding Unit (AMSU-A) 1b radiances and NOAA-15, NOAA-16, and NOAA-17 AMSU-B 1b radiances. In addition, EDAS used Special Sensor Microwave Imager (SSM/I) winds/precipitable water retrievals and the Geostationary Operational Environmental Satellite (GOES) water vapor cloud-top winds.

d. EDAS

The operational EDAS during the summer of 2004 had a horizontal resolution of 12 km and 60 levels in the
vertical. In addition to the horizontal resolution, the major model difference between the two regional systems was that the operational 12-km EDAS uses the Ferrier microphysics scheme (Rogers et al. 2001; Ferrier et al. 2003), while RCDAS uses the Zhao scheme (Zhao et al. 1997), which was used in the operational EDAS prior to November 2001. Unlike RCDAS, EDAS was an operational system. Because the hourly real-time 4-km precipitation radar data (Baldwin and Mitchell 1997) were available only over the United States in real time, there was no precipitation assimilation over Mexico and the adjacent oceans. The SSTs over the Gulf of California were different. The RCDAS used the SSTs from Ripa and Marinone (1989) and EDAS used the operational real-time SST analysis (Thiebaux et al. 2003).

The operational EDAS is the control experiment labeled as EDASw. There is little difference between RCDASwt and RCDASwtmex as indicated later in section 4 so only the EDASwtmex experiment was performed. To examine the impact on short-range forecasts, we performed forecasts out to 84 h initialized from 0000 and 1200 UTC analyses from EDASw and EDASwtmex, respectively.

The comparison between the analyses with and without soundings indicates the impact of these special soundings on the operational analyses. The comparison between the forecasts initialized from analyses with and without soundings indicates the impact of the soundings on the short-range forecasts.

3. CDAS data impact study

The purposes of the CDAS impact study are 1) to examine whether the impact of the NAME special soundings is global or regional and 2) to determine whether the NAME special soundings will improve the depiction of the monsoon circulation. In addition to mean differences averaged over the EOP period (Fig. 3), the daily differences may be quantified by examining the ratio between the mean square difference and the variance of CDASw for any given variable $F$ (Fig. 4). The ratio is defined as

![Fig. 3. (a) Difference of 500-hPa heights between CDASw and CDASwt averaged over the EOP period. Contour interval is 1 m. Positive values are shaded. (b) Same as in (a) but for the 200-hPa zonal wind. Contour interval is 0.5 m s$^{-1}$. (c) Same as in (a) but for the 850-hPa meridional wind. (d) Same as in (a) but for the difference between CDASw and CDASwtmex. (e) Same as in (b) but for 200-hPa meridional wind. (f) Same as in (c) but for the difference between CDASw and CDASwtmex.](http://example.com/fig3.png)
The mean $P$ values for CDASwt (Fig. 6c) and CDASwtmex (not shown) are similar. The mean $P$ from the 6-h forecasts during the assimilation cycle averaged over the EOP period for the CDASw and CDASwt experiments (Figs. 6b and 6c) is lower than the observed $P$ in Arizona due to low resolution. There is an erroneous maximum over the Rockies. None of the CDAS P means capture the maximum over the Great Plains centered in Kansas. Both CDASw and CDASwt indicate a precipitation band extending from the west coast through central Mexico toward New Mexico. CDAS captures the maximum near 18°–21°N, but the magnitudes are 2–4 mm day$^{-1}$ more than the observed and it misses the maximum near 27°N (Fig. 6b). The major differences between CDASw and CDASwt (CDASwtmex) are located over the NAME tier I area with CDASw drier over northern Mexico and wetter near the border between Mexico and the U.S. southwest. The rainfall pattern improves slightly when soundings over northern Mexico and the Southwest are included. All CDAS means show that monsoon rainfall over northern Mexico is likely to occur at 0000 UTC, which is close to the observed maximum in the diurnal cycle (not shown). The differences in 2-m temperature are consistent with the differences in precipitation. Areas with negative $P$ anomalies are warmer (Fig. 6f).

The coarse-resolution CDAS model does not resolve the Gulf of California (GoC) (Schmitz and Mullen 1996). It is interesting to examine whether the assimilation of soundings along the GoC improves the representation of the low-level jet from the Gulf of California (GCLLJ). The vertically integrated moisture fluxes from the operational GDAS (Fig. 7a) clearly show two low-level jets: one from the Gulf of Mexico to the Great Plains (GPLLJ) and the GCLLJ. For the EOP mean, the GPLLJ has a maximum of about 90 kg (m s)$^{-1}$ extending from the Gulf of Mexico northwestward through the border between Texas and Mexico to the Great Plains. The zonal component of the moisture fluxes extends from the Gulf of Mexico to northern Mexico. This zonal branch of moisture fluxes combines with moisture fluxes from the Gulf of California at the northern edge of the gulf. The combined moisture stream is then transported to the southwest United States by the GCLLJ. It is apparent that the major contributions to moisture transport contribute to the Southwest come

$$\text{ratio} = \frac{\sum_{i=1}^{46} (F_{\text{cdasw}} - F_{\text{cdaswt}})^2}{\text{Var}_{\text{cdasw}}},$$

where Var is the daily variance of $F$ averaged over the EOP period for CDASw. Equation (1) can also be applied to CDASwtmex.

The mean differences [CDASw – CDASwt] and [CDASw – CDASwtmex] averaged over the EOP period (1 July–15 August 2004) are similar (Fig. 3). The differences in 500-hPa height and 200-hPa winds are located in the Tropics with larger values over Central America. In comparison with the daily height anomalies, these differences are very small with a ratio of less than 0.5. There is no impact on the upper-level jet streams. Most coherent influences are concentrated in the lower troposphere. For example, the mean differences in the 850-hPa meridional winds are located over the Tropics with the largest differences located over Central America and Mexico. Some larger ratios in the Tropics (Fig. 4) are due to small variations in the winds.

Over North America, all CDAS means show a monsoon anticyclone centered at (26°N, 107°W) over northeastern Mexico similar to GDAS (Fig. 5a). The location and the strength of the 200-hPa zonal wind jetstream (shaded) over North America depicted by all CDAS means are also similar. The CDASw shows a weaker anticyclone in the Gulf of Mexico similar to GDAS, but this feature is absent in the CDASw and CDASwtmex experiments. Overall, the influence of the soundings is primarily local and concentrated over the core monsoon region and Central America.

Because CDAS does not directly assimilate precipitation, we can examine the impact of the soundings on precipitation ($P$). The observed precipitation (Fig. 6a) is from the gridded precipitation analysis of Higgins et al. (2000) at a horizontal resolution of 1°. The mean precipitation ($P$) averaged over the EOP period shows monsoon rainfall along the western slopes of the Sierra Madre Occidental (SMO) and in northern Mexico with maximum daily rates in the range of 6–8 mm day$^{-1}$ near 27°–30° and 18°–21° N. The Great Plains were anomalously wet with heavy rainfall over Oklahoma and Kansas, while northeastern Mexico and southern Texas were anomalously dry in comparison with the climatology from 1948 to 2004 (Higgins et al. 2000).

The coarse-resolution CDAS model does not resolve the Gulf of California (GoC) (Schmitz and Mullen 1996). It is interesting to examine whether the assimilation of soundings along the GoC improves the representation of the low-level jet from the Gulf of California (GCLLJ). The vertically integrated moisture fluxes from the operational GDAS (Fig. 7a) clearly show two low-level jets: one from the Gulf of Mexico to the Great Plains (GPLLJ) and the GCLLJ. For the EOP mean, the GPLLJ has a maximum of about 90 kg (m s)$^{-1}$ extending from the Gulf of Mexico northwestward through the border between Texas and Mexico to the Great Plains. The zonal component of the moisture fluxes extends from the Gulf of Mexico to northern Mexico. This zonal branch of moisture fluxes combines with moisture fluxes from the Gulf of California at the northern edge of the gulf. The combined moisture stream is then transported to the southwest United States by the GCLLJ. It is apparent that the major contributions to moisture transport over the Southwest come
diff**2/var

a) Z500  CDASw–CDASwt

b) Z500  CDASw–CDASwtmex

c) v850  CDASw–CDASwt

d) V850  CDASw–CDASwtmex
from the Gulf of California with small contributions from the North Pacific (Fig. 7a).

All CDAS means show a GPLLJ with a band of maximum meridional transport extending from the Gulf of Mexico to Texas. They all show a broader GPLLJ than GDAS and the center of the jet is located over southern Texas. The maximum of the GPLLJ for CDASw is about 90 kg m$^{-1}$ s$^{-1}$, which is close to that of GDAS. There is little difference in the GPLLJ between CDASw and CDASwtmex, but CDASwt (Fig. 7c) shows a slightly stronger jet with a stronger maximum [110 kg m$^{-1}$ s$^{-1}$] than CDASw and GDAS. The differences may be due to the assimilation of soundings (Del Rio, Midland, El Peso, and Amorillo) over Texas. These soundings were assimilated in CDASw and CDASwtmex, but not in CDASwt. CDASw shows stronger zonal fluxes from the Gulf of Mexico to northern Mexico (Figs. 7c and 7d) owing to the assimilation of soundings over northern Mexico.

The major difference between GDAS and CDAS is in the GCLLJ. All CDAS means show that large moisture transports into southern California and western Arizona come from the eastern North Pacific. Moisture fluxes along the North Pacific coast of California turn northeast at 33°N near Baja California. For CDASw, there is a slight indication of moisture fluxes from the Gulf of California (Fig. 7b). For CDASwt and CDASwtmex, these features are largely absent as indicated by the differences in fluxes. Most fluxes into the Southwest come from the North Pacific. With additional soundings along the Gulf of California, CDASw still does not capture the GCLLJ. Because there is less moisture transported into the Southwest, all CDAS P means show dryness over western Arizona (Fig. 6).

To compare the analyses with the sounding data, the model-generated fields such as temperature, winds, and specific humidity were interpolated to the observational sounding sites from the four nearest grid points. A comparison with the Integrated Sounding System (ISS) sounding from Puerto Penasco (31.18°N, 113.3°W) located at the northern end of the GoC highlights the errors in the meridional moisture transport [qv] from CDAS. Most sounding reports were twice daily when the station was in operation. A vertical cross

Fig. 5. Zonal wind at 200 hPa (shaded) and streamline at 200 hPa averaged over the EOP period for (a) GDAS, (b) CDASw, (c) CDASwt, and (d) CDASwtmex.
section of \([q_v]\) from the soundings at Puerto Penasco (Fig. 8a) shows that the jet is concentrated below 900 hPa with a maximum in the boundary layer around 925 hPa. For the moisture surge days, \([q_v]\) extends above 750 hPa and has magnitudes as large as 100 (g kg\(^{-1}\) m s\(^{-1}\)). There were strong-jet days during the monsoon onset from 7 to 10 July and gulf surge days from 12 to 16 July. These active days were followed by a quiet period from 21 to 29 July. In August, strong jets and related surges occurred during 5–8 August.

For CDASw, there are weak meridional fluxes below 850 hPa but the maximum magnitudes are only about...
20–40 g kg$^{-1}$ m s$^{-1}$. CDASw does not capture the strong jets during monsoon onset or later in the EOP (with the exception of the event on 12–16 July). A careful examination of the station records indicates that the sounding data along the Gulf of California were accepted by CDASw. CDASwt and CDASwtmex do not show meridional fluxes below 850 hPa. Without soundings over the NAME core region, there is no GCLLJ (Figs. 8c and 8d). Thus, if the model does not have sufficient horizontal resolution, it will not be able to take advantage of the additional sounding data to simulate a more realistic GCLLJ.

The situation is different for the GPLLJ, most likely because the GPLLJ has a larger spatial extent and larger magnitudes (Fig. 9). A comparison between twice-daily soundings at Del Rio (29.31°N, 100.92°W) indicates that CDASw is able to capture the active and break jet periods, though there are differences in magnitude. Moreover, the differences between CDASw and CDASwt (CDASwtmex) are small.

Because the differences between CDASwt and CDASwtmex are small, twice-daily forecasts were performed at 0000 and 1200 UTC with initial conditions taken from CDASw and CDASwtmex, respectively. Differences between forecasts initialized from these two different analyses are small and are concentrated over the core monsoon region. The P forecasts have very low skill. The data records are too short to obtain a stable climatology. Therefore, the root-mean-square (RMS) errors between the two sets of forecasts of 850-

Fig. 7. Vertically integrated moisture flux ([$q_u$, [$qv$]) (vectors) averaged over the EOP period from (a) GDAS. The unit vector is 150 kg (m s)$^{-1}$. The vertically integrated moisture flux [$qv$] is contoured and shaded. Contour interval is 30 kg (m s)$^{-1}$. Values greater than 90 (120) kg (m s)$^{-1}$ are shaded light (dark). (b) Same as in (a) but for CDASw. (c) Difference between CDASw and CDASwt. The unit vector is 25 kg (m s)$^{-1}$. The vertically integrated moisture flux [$qv$] difference is contoured and shaded. Contour interval is 10 kg (m s)$^{-1}$. (d) Same as in (c) but for the difference between CDASw and CDASwtmex.
hPa meridional winds and 500-hPa heights (Figs. 10 and 11) are given as examples.

The mean RMS error of the 850-hPa meridional wind forecasts averaged over the Northern Hemisphere (0°–80°N) for the EOP period indicates that the forecasts started from CDASw have a slight advantage (Fig. 10a, open circles) for the first 36 h, but the difference is less than 0.3 m s⁻¹. The RMS error averaged over the area (10°–50°N, 180°–360°) shows similar results with the differences being only slightly larger (about 0.5 m s⁻¹). The advantage shows up in most daily forecasts (Fig. 11c) so it is not due to few cases. After the 60–72-h forecast range, there is no difference in skill between the two sets of forecasts.

The daily RMS error of 500-hPa heights over the Northern Hemisphere does not show differences between forecasts initialized from CDASw and CDASwtmex (Figs. 11a and 11b). This suggests that the soundings have a small impact on the large-scale wave patterns. Over the United States the errors in the 850-hPa meridional wind forecasts are concentrated over the southwest and the Gulf of California, where the analyses have the largest uncertainties (Fig. 10). At 96 h, the forecast errors increase. Forecasts depend less on the initial conditions and the differences initialized from two sets of analyses decrease as the lead time increases.

Overall, the impact of the NAME special soundings on CDAS is small and generally confined to the core North American monsoon region and Central America. There is little change in the long-wave patterns or in the upper-level jetstreams. With the inclusion of the NAME special soundings, the overall monsoon precipitation pattern improves somewhat and there is an indication of fluxes from the Gulf of California, but the magnitudes are very weak. Because of the orographic
dependence of the GCLLJ (Anderson et al. 2001), a low-resolution model is not able to take advantage of the additional soundings to improve the low-level circulation features over the GoC region. CDASw also does not capture important monsoon-related features such as GoC moisture surge events. The advantage to initial short-range forecasts from CDASw occurs within the first 64 h.

4. Impact studies based on the regional analyses

a. Analyses

Over all, the impact of soundings on the large-scale circulation features for both RCDAS and EDAS averaged over the EOP period is small as indicated by the mean differences of selected fields (Fig. 12). The impact on the upper-level winds and heights (not shown) for

Fig. 10. (a) RMS error of 850-hPa meridional wind for the Northern Hemisphere (0°–80°N) averaged for the EOP period for forecasts initialized from CDASw (open circles) and CDASwtxmex (dark circles). (b) Forecast error for 12-h forecasts initialized from CDASw averaged over the EOP period. Contour interval is 0.5 m s⁻¹. Positive values greater than 4 m s⁻¹ are shaded. (c) The 12-h forecast difference between forecasts initialized from CDASw and CDASwtxmex, averaged over the EOP period. Contour interval is 0.5 m s⁻¹. Positive values greater than 4 m s⁻¹ are shaded. (d) Same as in (b) but for 36-h forecasts. (e), (f) Same as in (b), (c), but for 96-h forecasts.
RCDAS is small and concentrated over the core monsoon region and adjacent oceanic areas. The difference in the upper-level fields is in the strength and location of the monsoon anticyclone. RCDASwt and RCDASwtmex are similar. The impact of soundings on EDAS is smaller than it is for RCDAS. The impact is more pronounced in the lower troposphere. The influence of soundings is better demonstrated by examining the vertically integrated moisture fluxes (qfluxes) averaged over the EOP period. Again, the differences between RCDASwt and RCDASwtmex are small so we show only RCDASwt. To compare with RCDAS, the EDAS output was reduced to the RCDAS resolution of 32 km with every other wind vector plotted.

All EDAS and RCDAS means (Fig. 13) show two well-defined low-level jets, but the details differ. The GPLLJs depicted by EDASw and RCDASw (Figs. 13a and 13c) are similar. Both show large [qv] extending from the Gulf of Mexico to the Great Plains with one maximum close to 100–120 kg (m s)$^{-1}$ at (28°N, 100°W) near the border of Texas and northern Mexico and another maximum at (24.5°N, 97°W) along the coast of the Gulf of Mexico. In addition to the meridional transport to the Great Plains, there are zonal moisture fluxes extending from the Gulf of Mexico to northern Mexico. This branch of the zonal transport influences precipitation over northeastern Mexico.

Overall, RCDASw shows slightly weaker zonal and meridional fluxes associated with the GPLLLJ than does EDASw. The soundings have little impact on the GPLLJ analyzed by RCDAS. EDASwtmex shows a stronger jet with a maximum close to 140 kg (m s)$^{-1}$. The soundings weaken the GPLLJ and bring the jet depicted by EDASw closer to the GPLLJ analyzed by RCDASw.

The largest differences are related to the GCLLJ. EDASw shows that most of the moisture fluxes to the Southwest originate from the GoC with small contributions from the North Pacific. The zonal branch of the moisture transport from the Gulf of Mexico combines with the branch from the southern GoC. Moisture is then carried by the GCLLJ to the southwest United States. The pattern is very similar to the operational GDAS (Fig. 7a). EDASw shows a slightly narrower GCLLJ than does EDASwtmex, but the differences are small. All RCDAS means show a stronger GCLLJ than do the EDAS means. Moisture fluxes from the North Pacific along the California coast turn northeastward at 30°–33°N to the southwest. The pattern is similar to CDASw (Fig. 7b). For EDASw and EDASwtmex, the jet core is located over the northern GoC with a maximum near 100 kg (m s)$^{-1}$. Both RCDASw and RCDASwtmex (not shown) show a much stronger GCLLJ with a maximum near 160 kg (m s)$^{-1}$. The jet is broader and extends farther north. The jet maximum is nearly double the strength of the GCLLJ from EDASw or GDAS. This problem is not limited to this year. Mo et al. (2005) examined the climatology of the regional reanalysis from 1979 to 2002 and found that the GCLLJ is too strong and lacks variability. With the assimilation of the NAME special soundings (RCDASw), the GCLLJ reduces to a maximum of 120 kg (m s)$^{-1}$ but it still extends farther northward and is broader and stronger than in EDAS.

Fig. 11. (a) Daily RMS error of 500-hPa heights 24-h forecasts averaged over the Northern Hemisphere (20°–80°N) for forecasts initialized from CDASw (open circles) and from CDASwtmex (dark circles). (b) Same as in (a) but for the 96-h forecasts. (c) Same as in (a) but for 850-hPa meridional winds averaged over (10°–50°N, 180°–360°). (d) Same as in (c) but for the 96-h forecasts.

To compare with the sounding data from Puerto Peñasco, daily mean EDAS and RCDAS outputs were interpolated to the sounding site using the four nearest
grid points (Fig. 14). For EDASw and RCDASw, the vertical profile of \([qv]\) compares well with the sounding data capturing both strong and weak jet periods during the EOP. Without soundings, the \([qv]\) in RCDASwt is consistently stronger with differences larger than 20 g kg\(^{-1}\) m s\(^{-1}\) extending from the boundary layer to above 700 hPa. The vertical profiles for RCDASwt and RCDASwtmex (not shown) are similar because neither have any sounding input along the GoC. The errors are systematic and stronger \([qv]\) occurs during both surge and nonsurge periods.

For a given analysis, anomalies are defined as departures from the mean over the EOP period for that analysis. The meridional moisture transport anomalies for RCDASw and RCDASwt are similar to those of EDASw and the soundings (Fig. 15). All analyses are able to distinguish the \([qv]\) anomalies during strong and weak jet periods and the magnitudes of the anomalies are also similar. The \([qv]\) anomalies at one station do not represent the ability of RCDAS to capture the moisture transport anomalies during strong surge events. Composites of vertically integrated moisture flux anomalies were computed for each analysis. The surge periods chosen were 12–15 July, 5–8 August, and 9–12 August 2004. The composites (Fig. 16) show that all analyses capture the phase reversal between the...
GPLLJ and the GCLLJ documented by Berbery and Fox-Rabinovitz (2003), Mo and Berbery (2004), and many others. Negative anomalies associated with the diminishing GPLLJ from all analyses are similar. Anomalies associated with the GCLLJ are different. The composite from EDASw (Fig. 16a) shows strong moisture transport with large \([q_v]\) anomalies of about 40–60 kg \((m\ s)^{-1}\) extending from the entrance region near the southern end of the GoC to the southwest United States. The RCDASw composite shows large \([q_v]\) extending from the southern GoC only up to about 28\(^\circ\)N (Fig. 16b). Most fluxes to the southwest United States come from northern Mexico. The differences between RCDASw and RCDASwt (RCDASwtnex) indicate that changes of the moisture transport anomalies to the Southwest during surge events are weaker without soundings.

We have shown that additional soundings improve the analyses over the core monsoon region overall and bring the two analyses closer. With soundings along the GoC, systematic errors in RCDAS decrease, but the GCLLJ is still stronger than the EDAS or the GDAS and features associated with a strong GCLLJ during surge events are still not captured.

b. Forecasts

From 12 July to 15 August 2004, 84-h forecasts were made from 0000 and 1200 UTC analyses initialized from EDASw and EDASwtnex, respectively. This was the period in which all soundings along the Gulf of California (Puerto Panasco, Kino Bay, Los Mochis, and Loreto) were in operation. The forecasts were performed using the operational 12-km Eta Model, but the outputs were archived on a 40-km output grid every 3 h. The diurnal cycle of the forecasts based on EDASw (operational forecasts) has also been examined by Janowiak et al. (2007).
To illustrate the diurnal cycle of rainfall depicted by the EDAS forecasts, the P forecasts up to 72 h averaged over all cases initialized from 0000 UTC for two latitude bands are given in Fig. 17. They should be compared to the P from the RCDASw assimilation cycle averaged for the corresponding period. RCDASw assimilates P so it is close to the gridded analysis.

For the latitude band 32°–36°N, the model spins down for the first 3–6 h. After that, the forecasted P magnitudes are comparable with those of RCDASw (Figs. 17a–c). For RCDASw, there is an eastward evolution of P maxima from 110° to 95°W with centers at 110°, 106°, and 101°W, respectively. EDASw captures the center at 106°W with a correct diurnal maximum, but it misses the other centers, while EDASwtmex has a center at 100°W, and the P diurnal maxima come about 3 h earlier than for RCDASw. The diurnal cycle over the southeast depicted by EDASw (EDASwtmex) is too weak.

For the latitude band 26°–31°N (Figs. 17d–f), EDASw and EDASwtmex capture the P center at 106°W and the diurnal maxima, but they do not show the westward evolution of rainfall. They also miss the eastward evolution of rainfall from 90° to 80°W. Overall, the model forecasts have difficulty capturing the diurnal evolution of rainfall maxima.

EDAS quantitative precipitation forecasts were also evaluated using equivalent threat scores and bias scores (Rogers et al. 1996) for the EOP period for selected areas. In Fig. 18, the scores for the 36–60-h forecasts are presented. The conclusions are also true for the 12–36-h forecasts (not shown).

Over the NAME core region (26°–30°N, 106°–112°W) and the northern plains (36°–48°N, 90°–100°W), the inclusion of soundings improves forecasts. The threat scores for forecasts from EDASw are higher and the biases are lower. The forecasts from EDASw are less dry than forecasts from EDASwtmex according to the bias scores. For the southern plains (32°–36°N, 90°–100°W), the differences between forecasts initial-
ized from EDASw and EDASwtmex are small. For the Southwest (32°–36°N, 107°–113°W), EDASw has slightly higher threat scores, but it also has higher dry biases for a P threshold of less than 7 mm day⁻¹. The sample size is too small to test statistical significance, but the forecasts initialized from EDASw have a slight advantage overall.

c. Uncertainties in analyses

Overall, the NAME special soundings have a positive impact on analyses and forecasts, even though the impact is mostly limited to the monsoon region. Next, we compare the impact of the soundings to the uncertainties in the analyses. Because the impact of the soundings is concentrated mostly at lower levels, the differences in the vertically integrated moisture fluxes averaged over the EOP period are used to represent the impact (Fig. 19). To compute the differences, the EDAS output was reduced to 32-km resolution.

Large differences in moisture transport between RCDASw and RCDASwt averaged over the EOP period are located near the GoC (Figs. 19b and 19e). The differences between EDASw and EDASwtmex indicate that the soundings improve the GPLLJ and zonal fluxes from the Gulf of Mexico to northern Mexico (Figs. 19a and 19d) as discussed above. However, the impact of the soundings on a given analysis is smaller than the difference between EDAS and RCDAS (Figs. 19c and 19f). The largest differences between the two regional analyses are located over the southern United States and adjacent oceanic areas. The differences over the interior of the United States are relatively small. In addition to the resolution and physics, one important
difference between the two systems is that EDAS does not assimilate precipitation over the oceans and Mexico. Over the United States both systems assimilate precipitation and there are other data inputs, so the differences are small. Over the oceans, there are not many independent observations available so the differences are larger. The impact of precipitation assimilation will be addressed in the second part of the NAME impact studies.

5. Conclusions

During the NAME 2004 field campaign, special soundings were assimilated by the NCEP global and regional assimilation systems. These soundings present us with a unique opportunity to examine their impact on the circulation and short-range forecasts. To quantify their impact, data-withholding experiments were performed with the global CDAS and the regional RCDAS and EDAS systems. The only difference between the data-withholding experiments and the control is that the soundings in Fig. 1 (Table 1) are not assimilated. We also performed data-withholding experiments by excluding only the soundings over northern Mexico and the U.S. southwest to examine the impact of soundings over the core monsoon region.

The impacts of soundings vary between the assimilation systems examined in this study. Overall, the impacts are regional and concentrated over the core monsoon region. There are very small differences in the upper-level circulation features such as the jet stream and large-scale waves. At lower levels, the differences depend on the assimilation system. The soundings in general improve the analyses over the areas where the...
assimilation system has the largest uncertainties and errors. The soundings also improve short-range forecasts over the monsoon core region.

For CDAS, the horizontal resolution of T62 is too coarse to resolve the GoC. CDAS shows little or no moisture flux from the Gulf of California to the southwest United States. The moisture for the southwest United States comes from the eastern North Pacific. The inclusion of the soundings improves the CDAS analyses and forecasts of the low-level winds in the first 36 h, but the assimilation system is not able to take full advantage of the additional soundings to improve its representation of the GCLLI or moisture transport associated with the monsoon.

Fig. 18. Equivalent threat score for the (a) northern plains (36°–48°N, 90°–100°W), (b) southern plains (32°–36°N, 90°–100°W), (c) U.S. southwest (32°–36°N, 107°–113°W), and (d) NAME core area (26°–30°N, 106°–112°W) from 0000 UTC forecasts initialized from EDASw (solid line) and EDASwtmex (crosses). (e)–(h) Same as in (a)–(d) but for the bias score.
For the regional systems, the inclusion of the soundings brings EDAS and RCDAS closer together. RCDAS is able to capture the GPLLJ but has ongoing difficulties with the GCLLJ. The vertically integrated meridional flux $[qv]$ associated with the GCLLJ is too strong and lacks variability (Mo et al. 2005). With the additional soundings the improvements in the GPLLJ are minor and probably not statistically significant. The largest impacts are on the GCLLJ, where RCDAS has the largest uncertainties. The comparison with EDAS and the soundings at Puerto Penesco indicates that the $[qv]$ associated with the GCLLJs from RCDASwt and RCDASwtmex are twice as strong as that from EDAS. With the NAME soundings, the GCLLJ from RCDASw is closer to that of EDAS and GDAS. Even with soundings, the GCLLJ is still too strong and RCDASw does not capture important features of the moisture transport associated with moisture surge events from the GoC.

EDASwtmex shows a stronger GPLLJ along the coast of the Gulf of Mexico. With soundings, the GPLLJ decreases and is closer to RCDAS, while the impact on the GCLLJ is negligible. This indicates that the impacts of soundings vary from one system to another.

**Fig. 19.** The difference of the vertically integrated meridional moisture flux $[qv]$ between (a) ECDASw and EDASwtmex, (b) RCDASw and RCDASw, and (c) RCDASw and EDASw. Contour interval is 15 kg (m s)$^{-1}$. Negative values less than $-15 (-30)$ kg (m s)$^{-1}$ are shaded light (dark). (d)–(f) Same as in (a)–(c) but for the vertically integrated zonal moisture flux.
other. Overall, soundings will help to correct the analyses and reduce uncertainties over the area near the sounding sites, but they will not eliminate errors entirely.

The small differences observed between RCDASwt and RCDASwtmex indicate that the assimilation of the four Texas rawinsondes in the “wtmex” experiment (El Paso, Amarillo, Midland, and Del Rio) do not have a significant impact, possibly due to the use of other data types described in section 2 by both of the RCDAS experiments. One interesting point is that the differences in analyses due to the soundings are smaller than the differences between the two regional assimilation systems. The largest differences between RCDASw and RCDASwt are entirely concentrated over the Gulf of California where the RCDAS system has deficiencies in the simulation of the GCLLJ. The differences between EDASw and EDASwtmex are related to both the zonal and meridional transport associated with the GPLLJJ. The differences between EDASw and RCDASwt over the continental United States are small because both RCDAS and EDAS assimilate precipitation and there are other observations available. Large differences are located over the core monsoon region and the adjacent oceanic areas, where the input data were sparse. This is also a region in which EDAS does not assimilate precipitation, but RCDAS assimilates precipitation from CMORPH. In addition to precipitation assimilation, the SSTs over the Gulf of California differ. EDASw uses the operational SST analysis (Thiebaux et al. 2003), while RCDAS uses the SSTs from Ripa and Marinone (1989). In a forthcoming paper, we will address the influence of the P assimilation and the SSTs over the Gulf of California on regional analyses.

The impact of the NAME soundings on short-range global CDAS forecasts is small. The impacts on regional short-range forecasts are larger but confined to the monsoon region and the northern plains. The impact of soundings on forecasts decreases with the forecast lead time. Palmer et al. (1998) have pointed out that many methods, such as singular vector, can identify areas in which forecasts are more sensitive to the uncertainties in the initial conditions for a given model. Many studies on adaptive targeting suggest that sites in which forecasts are sensitive to the initial uncertainties are situation dependent (Bishop and Toth 1999). Different synoptic situations may target different regions where additional observations are needed. The targeted areas may not be confined to northern Mexico and the U.S. southwest. It will be interesting to identify the targeted areas for important monsoon-related features, including surges, easterly waves, and interactions between tropical and midlatitude troughs.

Another reason why the impacts on the global forecasts are small is that the monsoon core area is small. The improvements are confined to a small area so there is little change in the long waves. Miguez-Macho and Paegle (2000) found that the initial uncertainties in the long waves have larger impacts on prediction skill than the barotropic or baroclinic instabilities due to local errors. Their findings were based on low-resolution models. It will be interesting to test whether a high-resolution model may lead to different conclusions regarding the local changes of the initial states.

The NAME soundings improve the diurnal cycle and forecast skill over the NAME core region. In general, the model does not capture the eastward or westward progression of the rainfall diurnal cycle. The soundings also improve precipitation forecasts over the northern plains. This may be due to the inverse precipitation relationship between the monsoon and the Great Plains. However, more detailed diagnostics and larger samples are needed to confirm this hypothesis.

Acknowledgments. This work was supported by the grant from the NCPO/CPPA (program GC04-072).

REFERENCES
Janowiak, J. E., V. J. Dagostaro, V. E. Kousky, and R. J. Joyce, 2007: An examination of precipitation in observations and
model forecasts during NAME with emphasis on the diurnal cycle. *J. Climate*, 20, 1688–1700.


