The diurnal cycle of the summertime atmospheric hydrologic cycle over the southwestern US

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ABSTRACT

Diurnal variations in the climatological large-scale summertime hydrologic cycle over the southwestern United States are examined using surface and upper-air observations along with regional model output. Rainfall rates are greatest during the daytime, but the hydrologic balance that supports this rainfall changes as the day progresses. During the late morning and early afternoon, the area-averaged rainfall is balanced predominantly by evapotranspiration augmented by low-level moisture convergence; moisture from these two sources is redistributed via eddy diffusion, resulting in an overall moistening of the atmosphere and a divergence of moisture aloft. During the late afternoon, vertical redistribution via eddy diffusion weakens considerably, although precipitation continues at approximately the same rate due to drying aloft which also supports continued large-scale divergence of moisture at these levels. This large-scale divergence aloft persists at all times of day, suggesting that for the domain as a whole, precipitation is dependent upon low-level moisture sources. At finer scales, these balances are modified principally by the presence of moisture convergence/divergence centered on the elevated regions of the domain, suggesting that local balances may be more complex than the area-average balances described here.

1. Introduction

Previous research into the climatology and variability of the North American monsoon system has identified numerous multi-scalar processes responsible for producing the onset and maintenance of increased summertime rainfall over northwestern Mexico and the southwestern US. Among these are: the seasonal evolution of large-scale, upper-level and fine-scale, low-level circulation features (Stensrud et al., 1995; Schmitz and Mullen, 1996; Higgins et al., 1997;
Berbery, 2001); interannual variability in tropical, subtropical, and extra-tropical boundary condition forcing (Higgins et al, 1998; Higgins and Shi, 2001; Kanamitsu and Mo, 2003); the passage of intraseasonal and synoptic disturbances (Carleton, 1986; Anderson et al, 2000b; Mo, 2000; Englehart and Douglas, 2001; Anderson and Roads, 2002; Cavazos et al, 2002); and daily and diurnal variations in the energy, moisture, and momentum fields (Fawcett et al., 2002; Berbery and Fox-Rabinovitz, 2003). Our previous work examined the onset and maintenance of the summer monsoon rains from the standpoint of the hydrologic balances needed to support rainfall both on a climatological and intraseasonal basis (Anderson, 2002; Anderson et al., 2004). However, one of the most important modes of variability within this system is its diurnal evolution (Dai et al., 1999; Berbery, 2001; Trenberth et al., 2003). Here we continue to look at the relationship between precipitation and the other hydrologic tendency terms, focusing on the diurnal variability in these fields over the southwestern US.

2. Datasets

We use a global to regional spectral modeling system developed at the National Centers for Environmental Prediction (NCEP) to produce regional simulations of the summertime atmospheric hydrologic cycle over the southwestern US (Juang and Kanamitsu, 1994; Juang et al., 1997). The modeling system nests the regional spectral model (RSM) within daily forecasts from NCEP's global spectral model (GSM); these GSM forecasts are initialized daily using NCEP's operational analysis data. The modeling system is described in full in Anderson et al. (2004). The RSM domain under consideration (at 25 km resolution with 18 vertical levels) extends from northern California to central Mexico and includes the Sierra Nevada and Rocky Mountain ranges in the United States, the Baja and Sierra Madre mountain ranges in Mexico,
along with the Gulf of California (Figure 1). Five 92-day continuous GSM/RSM simulations of the summertime (July-September) southwestern US atmosphere have been performed for the years 1998-2002; these simulations differ from standard 24-hour weather forecasts in that the coarse-scale GSM and fine-scale RSM short-term forecast fields at 2400 UTC (and not the reinitialized 0000 UTC Reanalysis field) are used as the initial conditions for the next RSM nesting period (Anderson and Roads, 2002). From these simulations we will use the RSM’s explicitly-calculated sigma-level time-integrated budget terms for the water vapor tendency equation (Anderson, 2002):

\[
\frac{\partial q}{\partial t} + \nabla \cdot (qv) + \frac{\partial q}{\partial s} + P - g \frac{\partial E}{\partial s} = F
\]

tendency + (large-scale divergence) + (precipitation - vertical diffusion) = Residual

$q$ - Moisture content (kg)
$v$ - Horizontal velocity vector

$\nabla \cdot$ Two-dimensional divergence operator

$s$ - Vertical (sigma) coordinate (equal to $p/p_s$)

$E$ - Vertical eddy diffusion

$P$ - Precipitation

$F$ - Residual Forcings

Although these terms are output at 6-hour intervals, they are calculated at each model time-step (approximately 90 seconds) before being averaged over the 6-hour period; hence they capture the influence of both the mean and time-varying momentum and moisture fields. Here, vertical eddy diffusion represents the time-rate of change of moisture due to parameterized sub-grid scale vertical motions in the model; the vertical integral of this term is identically equal to evapotranspiration. Residual forcings include horizontal diffusion, semi-implicit model adjustment and boundary forcing. Because of fine-scale variations related to the spectral method, all budget terms are smoothed using a Fourier-based Lanczos smoothing filter of order
1.0 (Duchon, 1979), which is consistent with the smoothing performed on the terrain data within the model itself.

For observations, we use 2-times daily radiosonde profiles, taken from NOAA’s FSL Radiosonde Database (see Acknowledgments for data availability), to provide estimates of large-scale moisture flux divergence values for the region (radiosonde locations shown in Figure 1). Hourly precipitation data from all stations in Arizona, New Mexico, Utah, and Colorado are taken from NCDC’s hourly surface data archive for 1 July - 30 September 1998-2002. We select only those stations in which less than 10% of the days with precipitation are incomplete (because of NCDC archiving protocol, days without precipitation are not recorded and therefore cannot be analyzed for completeness); this yields 78 stations. This data is used to evaluate the diurnal cycle of simulated precipitation from the RSM. We also use the Climate Prediction Center’s (CPC) Unified hourly precipitation data set, which grids quality-controlled data from co-op stations, first-order stations, and hourly observing sites to 2.5x2.0-degree resolution (Higgins et al., 1996; see Acknowledgements for data availability). Finally, we use the NCEP/EMC 4km gridded radar-based precipitation data with bias corrections applied. These estimates are created by the WSR-88D Radar Product Generator on a 131x131 4-km grid centered over each radar site, using gage data to correct biases in the overlying radar estimates (see Acknowledgements for data availability and documentation). For the radar-based dataset, we remove the year 2000 values because of severe missing data. We then compute average values for only those grid-points that have data for all days during the remaining four years. There are gaps in the radar coverage (approximately 75% of the grid-points in the region have consistent data for this time period); in addition, the conversion from radar retrieval to rainfall rates is dependent upon
various underlying assumptions (Carbone et al., 2002). Here we use the data as a qualitative evaluation of the rainfall estimates from the simulations and other observations.

3. Results

The RSM’s ability to simulate variability in the dynamic fields for northwestern Mexico, the Gulf of California and the southwestern US has been evaluated in Anderson et al. (2000a) and Anderson et al. (2000b); in addition, the daily RSM precipitation climatology and variability for the southwestern US has also been diagnosed (Anderson and Roads, 2002; Anderson, 2002; Anderson et al., 2004). This precipitation occurs mostly during the afternoon (18-00UTC; 11:00-17:00LT) and into the evening (00-06UTC; 17:00-23:00LT – Figure 2). This is particularly true over the elevated regions of the Rocky Mountain plateau and the Sierra Madre Occidental. During the late-evening (06-12UTC; 23:00-05:00LT) and morning (12-18UTC; 05:00-11:00LT), the rainfall rate decreases across the domain. The corresponding 6-hour accumulations from the 78 stations indicate that the observed diurnal cycle agrees with that of the simulation, particularly with regard to the dichotomy between daytime rainfall rates (18-00UTC; 00-06UTC) and nighttime rainfall rates (06-12UTC; 12-18UTC). Particular geographic features also show qualitative agreement, including: maximums in precipitation along the Mogollon rim at 18-00UTC; maximums through the elevated regions of Utah at 18-00UTC; maximums in the low-elevation regions of eastern Colorado at 00-06UTC; and equivalent precipitation values in the high elevations of Colorado at both 18-00 and 00-06UTC. There are also some regions where the simulation does not do as well, particularly along the Arizona/Mexico border (here the simulated precipitation amounts are too small, although the diurnal cycling is correct).
The diurnal evolution of the area-average rainfall (Figure 1e) in the model is similar to that in the observational products. All four 6-hour accumulation estimates indicate maximums during 18-00 and 00-06UTC, with minimums during 06-12 and 12-18UTC. In general the CPC estimates appear somewhat smaller than the other three products during the daytime; during the night, the radar estimates tend to be smaller compared with the other three products. Overall, only one station (out of 78) shows higher rainfall for the period 06-18UTC compared with 18-06UTC, while radar and RSM estimates suggest only 3% and 2.3% (respectively) of the region experiences maximums during 06-18UTC, indicating that the area-averaged results are representative of the domain as a whole. Hourly gauge-based area-average estimates peak around 00-01UTC or approximately 1700-1800LT, in agreement with previous results for this region (Dai et al., 1999; Carbone et al., 2002). As such, the 18-00UTC period characterizes the onset and intensification of the diurnal precipitation cycle, while the 00-06UTC period captures the slow decline of this cycle (Carbone et al., 2002). While the 6-hour average values capture the overall time-evolution of the hourly precipitation, they do not capture the full range of the cycle associated with periods of maximum precipitation. Further evaluation of the hydrologic balances for these particular periods will require higher-frequency model data than is available here.

Previous research has suggested that daily rainfall is supported by local evapotranspiration and low-level convergence of moisture, which also results in divergence of moisture aloft (Anderson and Roads, 2001; Anderson et al., 2004). To see how these balances change over the day, the sigma-level diagnostic budget terms for the simulated water vapor tendency equation are area averaged over the southwestern US (see Figure 1 for domain box) and plotted as a function of pressure level (Figure 3); vertically-integrated values are given in Table 1. Because of the heterogeneity in the orography of this region, the grid-point values are first averaged along sigma
levels (which near the surface approximate the height above ground level, while aloft they approach pressure level surfaces); then the sigma-level values are converted to pressure levels by multiplying by the area-averaged surface pressure in order to better compare with the observed data (see Figure 4). Note first that the tendency term itself is non-zero when looking at the diurnal profiles (Figure 3); this differs from the climatological daily profiles in which the tendency term is near zero on seasonal time-scales (Roads and Chen, 2000; Anderson, 2002). Diurnal cycling during periods of high rainfall (18-00UTC; 00-06UTC) shows two distinct types of balances. During early afternoon (18-00UTC), when precipitation is intensifying, the vertical diffusion of moisture shows a large redistribution of moisture from lower levels (negative values) to upper levels (positive values). The vertical integral of this profile shows a large evaporative convergence of moisture into the atmosphere (Table 1). The vertical diffusion term also redistributes low-level moisture supplied by advective convergence (characterized by the positive values below 800mb), leading to a moistening of the atmosphere aloft (represented by positive values of the tendency term), as well as precipitation out of the column and upper-level divergence of water from the column. Vertically integrating the large-scale convergence term indicates weakly convergent fluxes that are about an order of magnitude smaller than the evaporative term (Table 1).

The late-afternoon profiles (00-06UTC) show distinctly different hydrologic balances, despite having approximately the same amount of area-average rainfall (see Table 1). The vertical-diffusion term decreases substantially (Table 1), with moisture convergence confined to the lower levels (below 800mb). At the level at which precipitation condenses, rainfall is balanced by a drying of the atmosphere (represented by the negative tendency term), suggesting rainfall is supported by moisture already in the atmosphere, supplied previously by
evapotranspiration and low-level convergence (average evapotranspiration during the twelve hour period from 18-06UTC is $3.6 \times 10^{-5}$ kg/m$^2$s with a low-level convergence of $1.1 \times 10^{-5}$ kg/m$^2$s; these two sources of moisture are balanced by a precipitation rate of $2.0 \times 10^{-5}$ kg/m$^2$s, overall moistening of the atmospheric column of $2.0 \times 10^{-5}$ kg/m$^2$s and divergence of moisture aloft of $0.7 \times 10^{-5}$ kg/m$^2$s.). The drying aloft also continues to support large-scale divergence of moisture while at lower levels the advective convergence of moisture seen earlier in the day persists, resulting in near-zero vertically-integrated large-scale convergence of moisture (Table 1).

During the non-precipitating periods (06-12UTC; 12-18UTC) there are again two distinct balances. During the nighttime period (06-12UTC), both the vertical diffusion term and the precipitation term decrease substantially, as does the low-level convergence of moisture. Aloft there is still large-scale divergence of moisture, supported entirely by a drying of the column itself. Overall, the largest net vertically-integrated divergence of moisture from the column occurs during this period (Table 1). During the morning period (12UTC-18UTC), the vertical diffusion term, representing evaporative convergence, again becomes an important component of the hydrologic balance (Table 1). In addition, the eddy diffusion of moisture removes moisture from the lower levels and re-distributes it to upper-levels, moistening the atmosphere around 700mb. This re-distribution continues to support divergence of moisture from the column aloft; as with the previous 6-hour period, low-level convergence is minimal, resulting in a continued net, large-scale divergence of moisture (Table 1). As the region transitions from this late-morning, non-precipitating period to the early afternoon, precipitating period (18-00UTC), there is an enhancement in both the vertical diffusion term and the low-level convergence term. The evapotranspiration rate increases by $2.2 \times 10^{-5}$ kg/m$^2$s while the low-level convergence increases
by $0.8 \times 10^{-5} \text{ kg/m}^2\text{s}$, suggesting that enhanced evapotranspiration is contributing more to renewed convergence within the column than are the large-scale dynamic variations.

Hence, on an area-average basis, the daily precipitation is predominantly due to daytime rainfall. This rainfall is the result of moistening of the atmosphere via evaporative processes during the late morning and early afternoon, augmented by low-level convergence of moisture during the early afternoon and continuing into the late afternoon. Note, however, the persistent large-scale moisture divergence aloft throughout the day, indicating large-scale moisture convergence aloft does not contribute to diurnal variations in rainfall (although intraseasonal variability in the large-scale moisture convergence aloft may intermittently bring moisture into the region at these levels - Anderson, 2002).

To see whether the simulated profiles of the moisture budget terms agree with those derived from observations, we calculate large-scale estimates of horizontal moisture divergence using 2-times daily profiles of winds and humidity from radiosondes. The moisture-divergence estimates are derived using an objective line-integral technique developed by Kanamaru and Salvucci (2003), designed to correct for the spurious mass divergence from the observed wind fields that causes errors in the estimated moisture flux divergence. Large-scale moisture divergence estimates are also calculated using simulated, instantaneous 4-times daily profiles (interpolated to the observed station locations) taken from the RSM, both at the standard reporting levels, as well as at higher-vertical resolution (every 50mb through the bottom 500mb).

Overall, estimates from the observations and simulation (Figure 4) show large-scale divergence of moisture above 800mb, both during the day (00UTC) and at night (12UTC), in agreement with the simulated area-average divergence terms shown in Figure 3; the simulated profiles also show upper-level divergence at the other two time periods as well. During the day
(00UTC) the RSM profile based upon standard reporting levels closely matches the observed profile down through 850mb; below this level the interpolation routine for the RSM and observations is different due to differing area-average surface pressures in the two products, which results in the apparent, but spurious, shifts in the profiles (see Anderson et al., 2004). Still, both indicate low-level convergence in agreement with the simulated grid-point moisture divergence profiles during the day (see Figure 3d). The full RSM profile also shows similar structure, except aloft the higher resolution profile captures enhanced moisture divergence that is missed when using the standard reporting levels, suggesting that vertical resolution may be important when calculating overall moisture budget terms (see Table 2).

At night (12UTC), the two RSM profiles closely follow the observed profile down through 800mb (Figure 4). The full RSM profile shows a local minimum at 800mb, slightly above the observed profile at 850mb. Because there is no standard reporting level at 800mb, the standard-reporting RSM profile misses this local minimum and hence does not capture the observed profile as well as the full RSM profile. At lower levels (>800mb), both RSM profiles show net divergence of moisture (approximately 1.9x10^{-5} kg/m²s and 1.2x10^{-5} kg/m²s for the coarse-scale and fine-scale RSM profiles respectively), in agreement with the profiles from the RSM tendency terms; in addition, the observations, integrated from the surface to 850mb also show a divergence of moisture (approximately 2.1x10^{-5} kg/m²s), despite the convergence below 925mb.

All three profiles provide similar estimates of the vertically integrated moisture divergence during this time (Table 2), although these estimates are slightly larger than the nighttime (06-12UTC) grid-point moisture divergence estimates (Table 1). In summary, the simulated grid-point profiles and the observed (and simulated) radiosonde profiles show similar results concerning the large-scale moisture divergence, its vertical structure, and its temporal evolution.
Vertically-integrated moisture tendency maps for 18-00UTC, corresponding to the early-afternoon precipitation period, are presented in Figure 5. These indicate strong boundary effects along the eastern edge of the domain where the RSM is adjusting its momentum, energy, and moisture fields towards the large-scale fields supplied by the GSM, resulting in spurious moisture divergence and drying of the atmosphere (note that the area-averaging domain in Figure 1 avoids averaging over these regions). Away from these boundary regions, rainfall has local maximums over the elevated topography of the Sierra Madres and the Rocky Mountain Plateau, with additional maximums along the Mogollon rim. The evapotranspiration term is large throughout the region. In contrast to the generally homogeneous structure of the evapotranspiration term, the horizontal advection and moisture tendency terms show increased heterogeneity, with large convergence and moistening occurring over the elevated regions, collocated with the areas of maximum precipitation, particularly over the Rocky Mountain plateau. Hence, although evapotranspiration supplies atmospheric moisture throughout the domain during this time, the spatial structure of the resultant rainfall also depends upon augmentation by large-scale advective processes.

During the late afternoon (00-06UTC), there are precipitation maxima over the elevated regions of the domain similar to those at 18-00UTC (Figure 6). However, the evapotranspiration rate throughout the domain has dropped. In addition, there is a shift in the structure of the moisture advection and tendency terms. For advection, the domain is divided into two sub-regions, with the eastern portion still receiving a net vertically-integrated convergence of moisture and the western portion receiving a net divergence of moisture. This dichotomy is mirrored in the moisture tendency term, with a decrease in atmospheric moisture occurring over the western two-thirds of the domain and an increase occurring over the eastern third of the
domain. This pattern suggests that rainfall west of about the Continental Divide is due to a draw down of atmospheric moisture (where the convergence term is negative). East of this region, precipitation appears to be supported by convergent processes, which also moisten the atmosphere during this time, in general agreement with the lagged pressure-induced convergence and precipitation over the high plains (Dai et al., 1999).

**4. Summary and Discussion**

We have investigated diurnal variations in the large-scale summertime hydrologic cycle associated with the northwestern branch of the North American monsoon. Using simulated and observed estimates of precipitation and other diagnostic budget terms related to the moisture tendency equation, we characterized the dynamic and hydrologic processes important for producing summertime rainfall in this region. Although the time-evolution of the moisture tendency balance, and resultant precipitation field, is complex with different processes contributing at different locations and different times, a few generalizations appear to be valid:

a. Daily rainfall rates are dominated by afternoon and evening (18-00UTC and 00-06UTC) precipitation.

b. Early afternoon precipitation (18-00UTC; 1100-1500LT), averaged over the southwestern US, is predominantly balanced by local evapotranspiration and low-level advection. The low-level moisture is redistributed via eddy diffusion processes, resulting in an overall moistening of the atmosphere and net divergence of moisture aloft. On local scales the geographic structure in rainfall is influenced by net, vertically-integrated moisture convergence centered on elevated topography.
c. Late afternoon precipitation (00-06UTC; 1500LT-2100LT) averaged over the southwestern US is associated with drying aloft, with continued moisture divergence at upper-levels and moisture convergence at low-levels. Geographically, the precipitation field can be divided into two regions (with some overlap): west of the Continental Divide, rainfall is principally derived from a net, vertically-averaged decrease in moisture; east of the Continental Divide, vertically-integrated moisture convergence supports both precipitation and a moistening of the atmosphere.

d. At all times of day, the area-average profiles derived from simulations and observations indicate moisture divergence above approximately 800mb. This result suggests that for the domain as a whole, precipitation throughout the day is supported by the local supply of moisture, either through evapotranspiration, low-level convergence, or loss from storage. Large-scale advection aloft, particularly from remote source regions, may help support rainfall, but apparently only at more local spatial scales or more intermittent time-scales.

Overall, these results are derived principally from the diagnosis of model simulations. Although available observations exhibit similar behavior, these results should serve mainly as a set of hypotheses which still need to be verified within the actual system and will likely have to be modified as specific regions are investigated in more detail. In addition, the 6-hour averaging period used here may mask certain important processes/balances associated with the diurnal cycle. For instance, higher temporal resolution data will be needed to further analyze specific features such as the mid-afternoon (1600-1700LT) precipitation maxima found across this region, as well transition processes such as the onset of convection between the 12-18 and 18-00UTC periods.
Acknowledgements. FSL Radiosonde data can be found at: http://raob.fsl.noaa.gov/.

NCEP/EMC Radar data can be found at:
http://www.ofps.ucar.edu/gapp/archive/data_list.html.

CPC Hourly US Precipitation data provided by the NOAA-CIRES Climate Diagnostics Center, Boulder, Colorado, USA, from their Web site at http://www.cdc.noaa.gov/

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REFERENCES


TABLE LEGENDS
Table 1 Vertically-integrated, area-average atmospheric water vapor tendency equation estimates taken from the RSM simulations. Sign convention such that positive values equivalent to atmospheric moisture divergence. See Figure 1 for area-averaging region.

Table 2 Vertically-integrated, area-average atmospheric water vapor divergence estimates using observed radiosonde data and RSM grid-point output interpolated to the radiosonde locations. Sign convention such that positive values equivalent to atmospheric moisture divergence. See Figure 1 for radiosonde locations.

FIGURE LEGENDS

Fig. 1 RSM (dots - 25 km resolution) and GSM (crosses - T62) grid points and RSM orography contours. Orography contour interval is 250 meters; shading interval is 750 meters with maximum shaded elevation of 3000 meters. Location of important geographic and selected upper-air observing stations (O) also shown (NKX - Miramar AFB, San Diego; TUS - Tucson; EPZ - Santa Teresa; MID - Midland; AMA - Amarillo; DDC - Dodge City; LBF - North Platte; SLC - Salt Lake City; DRA - Desert Rock). Box indicates region over which area-average values are calculated - see text. Latitude-longitude lines every 5-degrees.

Fig. 2 Average summertime (July-September) accumulated precipitation for 6-hour intervals, taken from the RSM data. Shading interval is 0.2 mm; minimum shading is 0.2 mm. Average taken over the time-period 1998-2002. Also shown (as circles) are average summertime accumulated precipitation for the same period, taken from NCDC hourly station data. Area of the circle is proportional to precipitation amount. a) 00-06UTC (~1700-2300LT); b) 06-12UTC (~2300-0500LT); c) 12-18UTC (~0500-1100LT); d) 18-00UTC (~1100-1700LT). e) Diurnal cycle of area-average rainfall, plotted over two cycles. Data taken from RSM grid-points (thick, solid line), station observations (thin, solid line), CPC gridded gauge data (triangles), and 4km Radar Reflectivity estimates (circle). Values plotted as total accumulation over 6-hour intervals. Also shown are the hourly station accumulations (points), scaled by 6 and plotted relative to the center of the respective 6-hour interval (i.e. value at 00-06UTC represents hourly accumulation for 03-04UTC).

Fig. 3 Area-averaged, 6-hour mean summertime moisture budget profiles calculated from 4xdaily RSM sigma-level output for the moisture-tendency equation; area-averaging domain found in Figure 1. Profiles calculated for precipitation (solid line), moisture convergence due to eddy diffusion processes (dashed line), moisture convergence due to large-scale advective processes (triangles), and moisture tendency (circles). Units are 10^6 kg (kg^-1 s^-1). Sign convention such that positive values relate to positive moisture tendency (i.e. convergence). 6-hour averaging periods are a) 00-06UTC; b) 06-12UTC; c) 12-18UTC; d) 18-00UTC

Fig. 4 Area-averaged seasonal-mean moisture convergence profiles calculated using wind and humidity data taken from selected 2xdaily (12UTC; 00UTC) radiosonde locations, as well as 4xdaily RSM grid-point output interpolated to the radiosonde locations. Divergence
profiles calculated for observed data (dash-dot line), simulated data interpolated to the standard reporting levels (dashed line), and simulated data interpolated to high resolution pressure levels (every 50mbar below 500mbar; every 100mbar above 500mbar; solid line). Units are $10^{-6}$ kg (kg$^{-1}$ s$^{-1}$). a) 06UTC; b) 12UTC; c) 18UTC; d) 00UTC

Fig. 5 Mean vertically-integrated RSM diagnostic moisture tendency terms for the period 18-00UTC (~1100-1700LT); Sign convention such that positive values relate to positive moisture tendency (i.e. convergence). Shading interval is 20 kg m$^{-2}$ s$^{-1}$; minimum shading is +/-10 kg m$^{-2}$ s$^{-1}$. Positive values are shaded; negative values are dashed. (a) total precipitation (same as Figure 2d but with different scaling); (b) vertical diffusion moisture convergence (equivalent to evapotranspiration); (c) large-scale total moisture convergence; (d) overall moisture tendency.

Fig. 6 Mean vertically-integrated RSM diagnostic moisture tendency terms for the period 00-06UTC (~1700-2300LT); Sign convention such that positive values relate to positive moisture tendency (i.e. convergence). Shading interval is 20 kg m$^{-2}$ s$^{-1}$; minimum shading is +/-10 kg m$^{-2}$ s$^{-1}$. Positive values are shaded; negative values are dashed. (a) total precipitation (same as Figure 2a but with different scaling); (b) vertical diffusion moisture convergence (equivalent to evapotranspiration); (c) large-scale total moisture convergence; (d) overall moisture tendency.
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Fig. 1  RSM (dots - 25 km resolution) and GSM (crosses - T62) grid points and RSM orography contours. Orography contour interval is 250 meters; shading interval is 750 meters with maximum shaded elevation of 3000 meters. Location of important geographic and selected upper-air observing stations (O) also shown (NKX - Miramar AFB, San Diego; TUS - Tucson; EPZ - Santa Teresa; MID - Midland; AMA - Amarillo; DDC - Dodge City; LBF - North Platte; SLC - Salt Lake City; DRA - Desert Rock). Box indicates region over which area-average values are calculated - see text. Latitude-longitude lines every 5-degrees.
Fig. 2 Average summertime (July-September) accumulated precipitation for 6-hour intervals, taken from the RSM data. Shading interval is 0.2 mm; minimum shading is 0.2 mm. Average taken over the time-period 1998-2002. Also shown (as circles) are average summertime accumulated precipitation for the same period, taken from NCDC hourly station data. Area of the circle is proportional to precipitation amount. a) 00-06UTC (~1700-2300LT); b) 06-12UTC (~2300-0500LT); c) 12-18UTC (~0500-1100LT); d) 18-00UTC (~1100-1700LT). e) Diurnal cycle of area-average rainfall, plotted over two cycles. Data taken from RSM grid-points (thick, solid line), station observations (thin, solid line), CPC gridded gauge data (triangles), and 4km Radar Reflectivity estimates (circle). Values plotted as total accumulation over 6-hour intervals. Also shown are the hourly station accumulations (points), scaled by 6 and plotted relative to the center of the respective 6-hour interval (i.e. value at 00-06UTC represents hourly accumulation for 03-04UTC).
Fig. 3 Area-averaged, 6-hour mean summertime moisture budget profiles calculated from 4xdaily RSM sigma-level output for the moisture-tendency equation; area-averaging domain found in Figure 1. Profiles calculated for precipitation (solid line), moisture convergence due to eddy diffusion processes (dashed line), moisture convergence due to large-scale advective processes (triangles), and moisture tendency (circles). Units are \(10^{-6} \text{ kg (kg}^{-1}\text{s}^{-1})\). Sign convention such that positive values relate to positive moisture tendency (i.e. convergence). 6-hour averaging periods are a) 00-06UTC; b) 06-12UTC; c) 12-18UTC; d) 18-00UTC.
Fig. 4 Area-averaged seasonal-mean moisture convergence profiles calculated using wind and humidity data taken from selected 2xdaily (12UTC; 00UTC) radiosonde locations, as well as 4xdaily RSM grid-point output interpolated to the radiosonde locations. Divergence profiles calculated for observed data (dash-dot line), simulated data interpolated to the standard reporting levels (dashed line), and simulated data interpolated to high resolution pressure levels (every 50mbar below 500mbar; every 100mbar above 500mbar; solid line). Units are $10^{-6}$ kg (kg$^{-1}$ s$^{-1}$). a) 06UTC; b) 12UTC; c) 18UTC; d) 00UTC
Fig. 5 Mean vertically-integrated RSM diagnostic moisture tendency terms for the period 18-00UTC (~1100-1700LT); Sign convention such that positive values relate to positive moisture tendency (i.e. convergence). Shading interval is 20 kg m\(^{-2}\) s\(^{-1}\); minimum shading is +/-10 kg m\(^{-2}\) s\(^{-1}\). Positive values are shaded; negative values are dashed. (a) total precipitation (same as Figure 2d but with different scaling); (b) vertical diffusion moisture convergence (equivalent to evaporation); (c) large-scale total moisture convergence; (d) overall moisture tendency.
Fig. 6 Mean vertically-integrated RSM diagnostic moisture tendency terms for the period 00-06UTC (~1700-2300LT); Sign convention such that positive values relate to positive moisture tendency (i.e. convergence). Shading interval is 20 kg m$^{-2}$ s$^{-1}$; minimum shading is +/-10 kg m$^{-2}$ s$^{-1}$. Positive values are shaded; negative values are dashed. (a) total precipitation (same as Figure 2a but with different scaling); (b) vertical diffusion moisture convergence (equivalent to evaporation); (c) large-scale total moisture convergence; (d) overall moisture tendency.