SPURIOUS GRID-SCALE CONVECTION IN THE
NORTH AMERICAN REGIONAL REANALYSIS

by

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ABSTRACT

Spurious grid-scale convection (SGSC) occurs in numerical weather prediction models when the simulated atmosphere becomes convectively unstable and the convective parameterization fails to relieve the instability, resulting in grid-scale ascent, saturation, and precipitation. Case studies illustrate that SGSC in the North American Regional Reanalysis (NARR) results in spurious grid-scale precipitation maxima, grid-scale updrafts, relative humidity/precipitable water maxima, equivalent potential temperature maxima, and absolute vorticity maxima. Some SGSC events also feature anomalous low-level cold pools and sea level pressure maxima. The geographic and temporal distribution of events suggest that SGSC is rare (< 100 cases per year) in the NARR prior to 2003. After precipitation assimilation changes made in 2003, however, cases of SGSC became much more frequent (> 2000 cases per year) due to a processing error in the precipitation assimilation over the oceans. The NARR will be rerun from 2003 to present, which should correct the problem. Implications for hydrometeorological studies are discussed.
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CHAPTER 1

INTRODUCTION

Global and regional reanalyses provide valuable datasets for advancing our understanding of atmospheric processes and phenomena. A reanalysis assimilates many types of archived atmospheric data and combines them with model forecasts (typically 3 or 6-h forecasts) to create long-term, consistent datasets that can be used for meteorological, climatological, and hydrological studies. Due to observational and model analysis errors and uncertainties, however, reanalyses provide only an estimate of the atmospheric state. For reanalysis datasets to be as useful as possible, it is imperative that their strengths and weaknesses be documented since they are the basis for a great deal of meteorological research. In the past 5 years, approximately 25% of the papers published in American Meteorological Society journals have utilized reanalyses.

Because of their widespread use for hydrometeorological investigations, many studies addressing the quality of reanalyses examine biases in water budgets. Betts et al. (1998) found that the European Center for Medium-Range Weather Forecasting (ECMWF) reanalysis (ERA-15, Gibson et al. 1997) contained biases in mixing ratio, evaporation, runoff, and precipitation over the Arkansas-Red River Basin. Evaporation rates were too high in winter, and had a small positive bias on an annual scale. In addition, the average latent heat flux in the surface energy budget was 7% higher than the evapora-
tion in the subsurface water budgets. Runoff was low by a factor of two, and the diurnal cycle had a midday precipitation peak, whereas observations featured a late afternoon peak. Betts and Viterbo (2000) examined the ERA-15 over the Mackenzie River Basin. They found positive precipitation and evaporation biases of 40% and 60%, respectively, and that the snow budget was not closed because the springtime melt and evaporation surpassed the amount of snowpack. There was also a negative bias in the sensible heat flux. Over the Mississippi River Basin, Roads and Betts (2000) compared the National Centers for Environmental Prediction/National Center for Atmospheric Research Global Reanalysis (NCEP/NCAR GR, Kalnay et al. 1996) and the ERA-15 with observations. They discovered that the ERA-15 surface runoff and seasonal surface water variations were too small, and in the NCEP/NCAR GR, seasonal precipitation, runoff, evaporation, and surface water variations were too large. Betts et al. (1996) compared the NCEP/NCAR GR to data from the First International Satellite Land Surface Climatology Project Field Experiment and found that although much of the summer NCEP/NCAR GR precipitation was in good agreement with observations, excessive precipitation occurred for a period in June and early July. Also, the evaporative fraction was too high following precipitation events. Higgins et al. (1996) and Mo and Higgins (1996) analyzed the NCEP/NCAR GR and the National Aeronautics and Space Administration Data Assimilation Office reanalysis (Schubert et al. 1993), and found that both reanalyses overestimate the daily mean precipitation rate over the Southeast United States, and underestimate it over the Great Plains. Further, the interannual variability of precipitation over the Great Plains is too small in the the newer ECMWF reanalysis (ERA-40, Källberg et al. 2004), and too large in the NCEP/NCAR GR (Ruiz-Barradas and Nigam 2005). Lastly, Seneviratne et al. (2004) found
small systematic terrestrial water storage biases over the Mississippi River Basin in the ERA-40.

Some studies focus specifically on precipitation anomalies. Janowiak et al. (1998) compared the NCEP/NCAR GR with Global Precipitation Climatology Project data, discovering that the South Pacific Convergence Zone was too meridionally oriented, the monsoonal precipitation distribution was too asymmetrical, and the rainfall in tropical areas was too intense. Widmann and Bretherton (2000) reviewed the performance of the NCEP/NCAR GR over the Pacific Northwest and found that the reanalysis showed considerable skill when averaged over multiple grid cells, but on the scale of individual grid cells, a dry (wet) bias exists to the west (east) of the Cascades.

Spurious surface pressure, mean sea level pressure (MSLP), and geopotential height analyses are documented in other studies. Bromwich et al. (2000) found that the ERA-15 has suppressed heights over the Southern Ocean. In the NCEP/NCAR GR, Hines et al. (2000) discovered a gradual pressure reduction of 0.20–0.50 hPa per year on a decadal scale south of 45°S that is most pronounced at 65°S. In the summer months of the 1960s, the ERA-40 MSLP has low and sometimes negative correlations with observations in the mid to high latitudes (Bromwich and Fogt 2004). Furthermore, Bromwich and Fogt (2004) identified substantial height differences between the ERA-40 and the NCEP/NCAR GR over the South Pacific during the presatellite era (before the mid-1970s). All of these studies focus on the mid and high latitudes of the Southern Hemisphere. The problems apparently have arisen because the Southern Hemisphere was a very data-sparse region, especially in the presatellite era.
The North American Regional Reanalysis (NARR, Mesinger et al. 2005) is a 32-km/45 layer regional reanalysis based on the Eta model 3D-VAR data assimilation system (EDAS). It provides analyses covering North America from 1979–2004 at 3-h time intervals and is already widely used, with over 1,400 users in the 9 months since its release (NCDC 2005a). It is one of two next-generation, higher resolution reanalyses (the other being the ERA-40), and is expected to be used for the next several years. The purpose of the NARR is to provide a long-term consistent dataset for hydrological and meteorological research, and one of the main goals is to provide improved precipitation analyses. Mesinger et al. (2005) state,

The NARR should help answer questions about the variability of water in weather and climate, in particular as it concerns U.S. precipitation patterns. ...We expect that the NARR should have a good representation of extreme events, such as floods and droughts, and should interface well with hydrological models. ...The assimilation of observed precipitation is by far the most important data addition to the NARR. (Mesinger et al. 2005, p. 2-5)

Only two studies have examined the strengths and weaknesses of the NARR thus far. Mesinger et al. (2005), who describe the NARR in full, mention some of its weaknesses, such as precipitation inaccuracies over Canada due to a lack of rain gauges, and a very slight (~0.5°C) negative temperature bias around 700 hPa. The second study, by Mo et al. (2005), notes that the Gulf of California low-level jet is too strong in the summer.

While developing a climatology of Intermountain cyclones, we discovered spurious grid-scale convection (SGSC) in the NARR. SGSC is associated with local maxima in vertical velocity, precipitable water, relative humidity, equivalent potential temperature ($\theta_e$), and grid-scale precipitation. Additionally, it can be accompanied by anomalously strong absolute vorticity maxima, and in some cases, low-level cold pools and high pressure maxima. SGSC has been documented in the Eta model (e.g., Gallus 1999, Gallus and
Segal 2001, Rogers et al. 2005a, UCAR 2005a,b, Jascourt 2005, Bua 2005), on which the NARR is based, as well as in other modeling systems (e.g., Giorgi 1991, Jascourt 2005). It is typically produced when the convective parameterization cannot relieve developing moist instability rapidly enough, resulting in grid-scale saturation, ascent, and precipitation. Essentially the model is attempting to impose a convective updraft on the scale of the analysis grid.

The purpose of this thesis is to document the existence and characteristics of SGSC and assess its potential impact on hydrometeorological studies that use the NARR. Chapter 2 describes the data and methods used. Chapter 3 presents an overview of SGSC and three examples. Chapter 4 discusses the characteristics of SGSC in the NARR. The thesis concludes with a summary of the findings and their implications for meteorological and hydrological studies involving the NARR.
CHAPTER 2

DATA AND METHODS

Three-hourly gridded NARR analyses were obtained from the National Climatic Data Center’s Model Data Access National Oceanic and Atmospheric Administration Operational Model Archive Distribution System Web Interface (NCDC 2005b). Graphics and diagnostic analyses were generated using the Grid Analysis and Display System (GrADS) following interpolation to an internal grid with 1/3° latitude-longitude grid spacing.

We used an objective SGSC identification technique based in part on the methodology described by UCAR (2005b) to identify SGSC events. The technique searches every grid point at each 3-hourly analysis time for nearly collocated maxima in grid-scale precipitation, vertical velocity, and precipitable water, as well as the presence of convective available potential energy (CAPE), characteristics that typically accompany SGSC in the Eta model. Near collocation is used because the grid-scale precipitation represents a 3-h accumulation, whereas analyses of the other variables are instantaneous and may not be perfectly correlated with 3-h precipitation maxima.

For a selected grid point, the technique queries eight grid points in a surrounding 11x11 grid-point outer box (Fig. 2.1). A grid-scale precipitation maximum exists if the grid-scale precipitation at a selected grid point (1) is the largest within the outer box, (2) is
Figure 2.1. Grid points used to identify SGSC at a given grid point.
> 3 mm, (3) exceeds that at the eight queried grid points by at least 3 mm, and (4) is larger than the convective precipitation\(^1\) at the grid point. A nearly collocated vertical velocity maximum exists if the upward vertical velocity at any grid point within the inner 7x7 grid-point inner box exceeds 50 cm s\(^{-1}\) at 500 hPa, 400 hPa, or 300 hPa and the vertical velocity at the eight grid points is less than 10 cm s\(^{-1}\). A nearly collocated precipitable water maximum exists if the precipitable water at any grid point within the inner box is > 3 mm and exceeds that at the eight queried grid points. If all three maxima are present, and positive CAPE is found at any grid point within the inner box, it is counted as an SGSC event. To ascertain duration, if SGSC was found within 2° lat-lon at the next NARR analysis time, it was considered to be the same event. This represents a large outer bounds for SGSC movement (~74 km h\(^{-1}\)) and is based on inspection of several cases. The threshold values for the algorithm were determined through extensive experimentation and developed to eliminate false positives. The identification technique returns a conservative estimate of the actual number of SGSC events because it does not allow for simultaneous SGSC to exist within an 11x11 grid-point box, and because the NARR analyses are available only at 3-h intervals.

Surface data for SGSC examples were obtained from the National Weather Service, Federal Aviation Administration, and Department of Defense (NWS-FAA-DoD) surface aviation network, and were supplemented by observations from MesoWest, a collection of cooperating mesonets managed by a variety of federal, state, and local agencies,

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1. The NARR produces two types of precipitation: a) “grid-scale precipitation” which represents precipitation that occurs on scales resolvable by the NARR, and is produced by the microphysics parameterization, and b) “convective precipitation” which represents precipitation that occurs on scales too small to be resolved by the NARR, and is produced by the convective parameterization.
as well as private firms (Horel et al. 2002). The data were quality controlled following Splitt and Horel (1998) and by subjective consistency checks done while performing analyses, and were plotted using the General Meteorological Package (GEMPAK). Upper air data were obtained from the University of Wyoming sounding archive (University of Wyoming 2005). Radar reflectivity analyses for the 29 June 2003 example were created from data received and archived at the University of Utah, and for the 6 July 1997 example, obtained from the NCDC Hierarchical Data Storage System Access System (NCDC 2005c), in Next-Generation Radar (NEXRAD) Information Dissemination Service format (Baer 1991). All radar data were plotted using GEMPAK. Satellite imagery was obtained from the National Oceanic and Atmospheric Administration’s Comprehensive Large Array-data Stewardship System (NOAA’s CLASS, NOAA 2005).
CHAPTER 3

EXAMPLES OF SGSC

Background

Since convective instability often occurs on a scale smaller than that resolved by hydrostatic mesoscale models, convective parameterizations are typically used in the models to account for the effects of convection on grid-resolved scales. If, however, a convective parameterization is not used, or fails to remove instability in a timely manner, convective instability may be aliased to the smallest resolvable scale of the model (Molinari and Dudek 1992). This results in SGSC (a.k.a., numerical point storms, grid-point storms, or grid-scale precipitation bombs) that is characterized by anomalous latent heating, low-level convergence, surface pressure falls, and grid-scale precipitation (Koch et al. 1985, Molinari and Dudek 1986, Zhang and Fritsch 1988). Often, SGSC development is preceded by the development of a moist absolutely unstable layer (MAUL; Bryan and Fritsch 2000, UCAR 2005a). Giorgi (1991) provides examples of SGSC in a regional climate version of the NCAR/Pennsylvania State University Mesoscale Model version 4 (MM4, a hydrostatic predecessor to the MM5). Kain and Fritsch (1998) argue that the optimal way to prevent SGSC is to allow convective overturning to occur as both a parameterized and grid-resolved process.
The version of the Eta data assimilation and numerical modeling system used for the NARR employs the Betts-Miller-Janjic (BMJ) convective parameterization (Janjic 1990, Janjic 1994) and the Zhao microphysical parameterization (Zhao and Carr 1997, Zhao et al. 1997), which produces the grid-scale precipitation. Several studies indicate that some Eta configurations produce SGSC. Gallus and Segal (2001) found that SGSC is common in Eta simulations that do not employ a convective parameterization, while Gallus (1999) describes a “gridpoint storm-like” precipitation maximum produced by an Eta simulation that included the BMJ convective parameterization. Rogers et al. (2005a, p. 1) note that the Zhao cloud microphysics parameterization produces “local precipitation maxima associated with grid-scale processes.” UCAR (2005a,b) warns forecasters about “grid-scale precipitation bombs” and “spurious grid-scale convection” in the Eta model (UCAR 2005a,b), and Jascourt (2005) identifies SGSC as a problem in both the Eta and Global Forecast System (GFS, Jascourt 2005) models. Collectively, these studies illustrate that SGSC occurs in a number of Eta model configurations when the convective parameterization is unable to relieve moist instability. The next section presents three examples of SGSC produced in the Eta-based NARR.

29 June 2003: Continental Convection over Mountainous Terrain

Synoptic Overview

At 0300 UTC 29 Jun 2003, a 500-hPa short-wave trough (dashed line in Fig. 3.1a) approaches a cold front that extends from northwest to southeast across Wyoming (Fig. 3.1b). The surface parcel in the 0000 UTC Riverton, WY (RIW, see Fig. 3.1a for location) sounding has 630 J kg$^{-1}$ of CAPE, a dry adiabatic lapse rate up to a lifting condensation level of 655 hPa, and a 16°C surface dewpoint depression (Fig. 3.2). These conditions are
Figure 3.1. Mid-level and surface analyses. (a) NARR 500-hPa geopotential height (black contours every 60 m), absolute vorticity ($\times 10^{-5}$ s$^{-1}$, shaded following scale at right), and 300-hPa vertical velocity (red contours every 10 cm s$^{-1}$) at 0300 UTC 29 Jun 2003. (b) Manual MSLP analysis (every 2 hPa) at 0300 UTC 29 Jun 2003. Surface observations include MSLP (hPa, upper right), potential temperature (K, lower left), and wind (full and half barb denote 5 and 2.5 m s$^{-1}$, respectively).
Figure 3.2. Riverton, WY (RIW) skew $T$-log $p$ diagram [temperature, dewpoint, and wind barbs (full and half barbs denote 5 and 2.5 m s$^{-1}$, respectively)] at 0000 UTC 29 Jun 2003.
favorable for subcloud evaporation and evaporatively driven downflows (Fujita 1959, Srivastava 1987). Convection initiates over northwest Wyoming at 2000 UTC (not shown), and from 0300–0600 UTC moves across central Wyoming (Figs. 3.3a,b). Despite moderate radar reflectivities (approaching 45 dBZ), light storm-total precipitation (< 3 mm) is reported by surface stations (not shown) and estimated by radar (Fig. 3.3c), consistent with substantial subcloud evaporation in the low-levels (Rosenfeld and Mintz 1988).

Analysis of SGSC

The 0300 UTC NARR analysis shows an area of moderate (200–500 J kg\(^{-1}\)) CAPE extending across central Wyoming (Figs. 3.4a,b). The 0300 UTC NARR sounding from point B (see Fig. 3.4b for location), the location of incipient SGSC development, features a dry, well-mixed boundary layer below 700 hPa (Fig. 3.5a). From 700–375 hPa, the atmosphere is conditionally unstable with near constant (6°C) dew-point depressions. In the 3 h ending at 0300 UTC, precipitation over Wyoming is generated by both the convective and grid-scale precipitation schemes, although their relative importance varies geographically. A convective precipitation maximum exists in central Wyoming (point A, Fig. 3.4a), in agreement with radar (Fig. 3.3a), and a grid-scale precipitation maximum is present to the east (point B, Fig. 3.4b).

By 0600 UTC, SGSC develops in eastern Wyoming (point C, Fig. 3.4d) where the convective parameterization remains relatively inactive, producing only 1 mm of precipitation (Fig. 3.4c). Instead, the NARR attempts to produce the convection explicitly, resulting in a > 5-mm grid-scale precipitation maximum and an intense grid-scale updraft (Fig. 3.4d). Although a detailed analysis of the SGSC development was not possible due to the availability of the NARR analyses at 3-h intervals, the ascent over this region at 0300
Figure 3.3. Radar analyses. (a) Radar base-level reflectivity (dBZ, shaded following scale at left) at 0300 UTC 29 Jun 2003. (b) As in (a) except for 0430 UTC 29 Jun 2003. (c) Radar derived storm total precipitation (mm, shaded following scale at top) from 0000–0600 UTC 29 Jun 2003.
Figure 3.4. Precipitation and CAPE analyses. (a) NARR 3-h accumulated convective precipitation (mm, shaded following scale at right), 300-hPa vertical velocity (solid contours every 10 cm s\(^{-1}\)), and CAPE (dotted contours every 200 J kg\(^{-1}\)) at 0300 UTC 29 Jun 2003. (b) As in (a) except grid-scale precipitation. (c) As in (a) except at 0600 UTC 29 Jun 2003. (d) As in (b) except at 0600 UTC 29 Jun 2003.
Figure 3.4 continued.
Figure 3.5. NARR skew $T$-$\log p$ diagram [temperature, dewpoint, and wind barbs (full and half barbs denote 5 and 2.5 m s$^{-1}$, respectively)] (a) at point B of fig. 3.4b at 0300 UTC. (b) As in (a) except at point C in fig. 3.4d at 0600 UTC 29 Jun 2003.
Figure 3.5 continued.
UTC was of sufficient magnitude (> 12 cm s\(^{-1}\), not shown) for the conditionally unstable mid levels to reach saturation\(^1\) soon thereafter. This presumably produced the moist instability that led to the formation of the SGSC by 0600 UTC.

A meridional cross-section illustrates the structure of the SGSC (Fig. 3.6). Vertical velocities exceed 72 cm s\(^{-1}\), and a column of locally high relative humidity (> 90%) extends from 800–500 hPa. A pronounced cold pool, indicated by locally low \(\theta_e\) air and presumably produced by low-level diabatic cooling accompanying the grid-scale precipitation, exists below 800 hPa. The 850-hPa temperatures within the cold pool are roughly 10\(^\circ\)C colder than in the surrounding region (Fig. 3.7a).

Other characteristics are similar to SGSC produced by the operational Eta model (UCAR 2005a,b). In particular, the SGSC is accompanied by local maxima in 500-hPa absolute vorticity and column integrated precipitable water (Fig. 3.7b).

Compared with other SGSC events examined, this cold pool is unusually strong and is accompanied by dramatic MSLP, geopotential height, and temperature extrema. The 1024-hPa MSLP maximum is several hPa higher than the surrounding pressures of 1017–1018 hPa and is anomalously high compared to observed (cf. Figs. 3.8a,b). At 850 hPa, which is close to the mean elevation of the region, a 30-m geopotential height anomaly exists (Fig. 3.7a). A time series shows a 7-hPa spike in surface pressure occurs beneath the developing SGSC between 0300 and 0600 UTC (Fig. 3.9).

This SGSC event provides an example of spurious low-level cold pool development as convective instability above a deep, dry boundary layer is aliased to the smallest

\(^1\) The Eta model produces fractional clouds beginning at 75\% relative humidity over land (Zhao et al. 1997), which could result in MAUL development at < 100\% relative humidity.
Figure 3.6. NARR meridional cross section of relative humidity (%, shaded following scale at bottom), vertical velocity (contours every 10 cm s$^{-1}$, red=up, blue=down), $\theta_{e}$ (black contours every 2K), and wind barbs (full and half barbs denote 5 and 2.5 m s$^{-1}$, respectively) through the SGSC at 0600 UTC 29 Jun 2003.
Figure 3.7. NARR analyses. (a) NARR 850-hPa geopotential height (black contours every 10 m), temperature (white contours and shaded following scale at right), and wind barbs (full and half barbs denote 5 and 2.5 m s$^{-1}$, respectively) at 0600 UTC 29 Jun 2003. (b) NARR precipitable water (contoured every 3 mm) and 500-hPa absolute vorticity (x $10^{-5}$ s$^{-1}$, shaded following scale at right) at 0600 UTC 29 Jun 2003.
Figure 3.8. Surface analyses. (a) NARR MSLP (contoured every 2 hPa) and 850-hPa temperature (°C, shaded following scale at right) at 0600 UTC 29 Jun 2003. (b) Manual MSLP analysis (every 2 hPa) at 0600 UTC 29 Jun 2003. Surface observations include MSLP (hPa, upper right), potential temperature (K, lower left), and wind barbs (full and half barb denote 5 and 2.5 m s\(^{-1}\), respectively).
Figure 3.9. Time series of NARR surface pressure (hPa) at point C in Fig. 3.4d.
resolved scale of the NARR. The strong cold pool likely would not have developed if the instability was removed by the BMJ convective parameterization, which adjusts the temperature and dewpoint to a reference profile only from the model’s convective cloud bottom to top, and does not produce evaporatively cooled downdrafts in the subcloud layer (Betts 1986). Instead, the BMJ convective parameterization can indirectly cool the subcloud boundary layer only through parameterized turbulent mixing, reduction of insolation due to cloud cover, or increasing surface latent heat fluxes (thereby reducing the surface sensible heating) as convectively parameterized precipitation increases soil moisture. The nearby convection in western Kansas, where a well-mixed, dry boundary layer was also present, illustrates this point; the instability was relieved by the BMJ convective parameterization, and grid-scale precipitation and unrealistic cold pools were not observed (e.g., western Kansas, Figs. 3.4b,d and 3.8a).

In contrast, the Zhao grid-scale precipitation scheme can produce evaporative cooling as precipitation falls into the dry subcloud layers. This occurred in the NARR as the instability was relieved by grid-scale convection, resulting in a low-level cold pool (Fig. 3.8a). Although the observed sounding (Fig. 3.2b) suggests evaporative downdrafts were likely in the real world, these downdrafts would have occurred on subgrid scales and there is no evidence of the development of a cold pool on the scale of that produced by the NARR.

Although this event meets our SGSC criteria only at 0600 UTC, it takes ~6 h for the cold pool and mesohigh to decay. In the 3 h ending at 0900 UTC, the SGSC weakens and produces only 2 mm of grid-scale precipitation (point D in Fig. 3.10a). The vertical velocity maximum is also weaker and relative humidities have decreased (Fig. 3.10b). In
Figure 3.10. NARR analyses. (a) NARR 3-h accumulated grid-scale precipitation (mm, shaded following scale at right), 300-hPa vertical velocity (solid contours every 10 cm s\(^{-1}\)), and CAPE (dotted contours every 200 J kg\(^{-1}\)) at 0900 UTC 29 Jun 2003. (b) NARR meridional cross section of relative humidity (%, shaded following scale at bottom), vertical velocity (contours every 10 cm s\(^{-1}\), red=up, blue=down), \(\theta_e\) (black contours every 2K), and wind barbs (full and half barbs denote 5 and 2.5 m s\(^{-1}\), respectively) through the SGSC at 0900 UTC 29 Jun 2003. (c) NARR MSLP (contoured every 2 hPa) and 850-hPa temperature (°C, shaded following scale at right) at 0900 UTC 29 Jun 2003.
the low levels, the cold pool spreads to cover a larger area and becomes less intense (Fig. 3.10c). By 1200 UTC the vertical velocities are weaker still, but the relative humidity maximum is lifted to the mid levels (Fig 3.11a), producing another burst of grid-scale precipitation (point E in Fig. 3.11b). The low-level cold pool spreads and weakens further (Fig. 3.11c) and by 1500 UTC, there is no sign of the SGSC (not shown).

6 July 1997: Continental Convection over the Midwest

Synoptic Environment

At 0000 UTC 6 Jul 1997, a 500-hPa absolute vorticity maximum moves across Wisconsin roughly 450 km ahead of a surface trough (Figs. 3.12a,b). A 0000 UTC sounding from ILX (see Fig. 3.12a for location), roughly 300 km ahead of the surface trough, features a stable layer from 825–700 hPa and is not favorable for deep convection (Fig. 3.13a). Similarly, a stable layer caps shallow convection further to the north at GRB (see Fig. 3.12a for location, Fig. 3.14a). In contrast, the stable layer is higher and weaker at MPX (see Fig. 3.12a for location) where conditionally unstable lapse rates extend from 975 to 650 hPa and the surface-parcel CAPE is 240 J kg$^{-1}$ (Fig. 3.13b). Showers and thunderstorms develop over northwest Wisconsin ~2300 UTC 5 Jul, and by 0300 UTC Jul 6 extend ENE from northeast Iowa to eastern Wisconsin (Fig. 3.15a). The showers move slowly into southeast Wisconsin by 0600 UTC (Fig. 3.15b). Observed and radar estimated precipitation was generally light (< 1.5 mm), but at some stations exceeded 15 mm.

Analysis of SGSC

The 0000 UTC 6 Jul 2003 NARR analyses show a tongue of higher CAPE air extending northeastward over MPX and northern Wisconsin (Figs. 3.16a,b). Analyzed
Figure 3.11. NARR analyses. (a) NARR meridional cross section of relative humidity (%, shaded following scale at bottom), vertical velocity (contours every 10 cm s\(^{-1}\), red=up, blue=down), \( \theta_e \) (black contours every 2K), and wind barbs (full and half barbs denote 5 and 2.5 m s\(^{-1}\), respectively) through the SGSC at 1200 UTC 29 Jun 2003. (b) NARR 3-h accumulated grid-scale precipitation (mm, shaded following scale at right), 300-hPa vertical velocity (solid contours every 10 cm s\(^{-1}\)), and CAPE (dotted contours every 200 J kg\(^{-1}\)) at 1200 UTC 29 Jun 2003. (c) NARR MSLP (contoured every 2 hPa) and 850-hPa temperature (\(^{\circ}\)C, shaded following scale at right) at 1200 UTC 29 Jun 2003.
Figure 3.12. NARR analyses. (a) NARR 500-hPa geopotential height (black contours every 60 m), absolute vorticity (x 10^{-5} s^{-1}, shaded following scale at right), and 300-hPa vertical velocity (red contours every 10 cm s^{-1}) at 0000 UTC 6 Jul 1997. (b) NARR MSLP (contoured every 2 hPa) and 3-h total precipitation (mm, shaded following scale at right) at 0000 UTC 6 Jul 2003.
Figure 3.13. Skew $T$-$\log p$ diagram [temperature, dewpoint, and wind barbs (full and half barbs denote 5 and 2.5 m s$^{-1}$, respectively)] at (a) Lincoln, IL (ILX) at 0000 UTC 6 Jul 1997. (b) As in (a) except at Minneapolis/St. Paul, MN (MPX).
Figure 3.13 continued.
Figure 3.14. Observed and NARR skew $T$-$\log p$ diagrams. Skew $T$-$\log p$ diagram [temperature, dewpoint, and wind barbs (full and half barbs denote 5 and 2.5 m s$^{-1}$, respectively)] at (a) Green Bay, WI (GRB) at 0000 UTC 6 Jul 1997. (b) NARR skew $T$-$\log p$ diagram [temperature, dewpoint, and wind barbs (full and half barbs denote 5 and 2.5 m s$^{-1}$, respectively)] at Green Bay, WI (GRB) at 0000 UTC 6 Jul 1997.
Figure 3.14 continued.
Figure 3.15. Radar reflectivity (dBZ, shaded following scale at right) at (a) 0300 UTC 6 Jul 1997. (b) As in (a) except 0600 UTC 6 Jul 1997.
Figure 3.16. NARR precipitation and CAPE analyses. (a) NARR 3-h accumulated convective precipitation (mm, shaded following scale at right), 300-hPa vertical velocity (solid contours every 10 cm s⁻¹), and CAPE (dotted contours every 200 J kg⁻¹) at 0000 UTC 6 Jul 1997. (b) As in (a) except grid-scale precipitation. (c) As in (a) except for 0300 UTC 6 Jul 1997. (d) As in (b) except 0300 UTC 6 Jul 1997.
Figure 3.16 continued.
CAPE values at MPX are ~1000 J kg\(^{-1}\), substantially higher than observed. The NARR sounding at GRB, the closest upper-air observing site to the area of SGSC development, lacks the stable layer that is evident in the observed sounding (cf. Figs. 3.14a,b). The lack of this stable layer in the NARR analysis results in higher CAPE and a more favorable profile for deep convection than observed across the entire region.

During the 3-h period ending at 0000 UTC, the convective parameterization produces light (< 4.5 mm) precipitation over southern and western Wisconsin (Fig. 3.16a), in general agreement with radar (e.g., Fig. 3.15a). Two weak grid-scale precipitation maxima exist, however, over southeast Wisconsin and along the Indiana–Michigan border where no precipitation is observed (points A and B in Fig. 3.16b). At this time, the grid-scale vertical motion is weak, but intense updrafts form by 0300 UTC (Figs. 3.16c,d). Throughout this period, the precipitation produced at both locations is produced primarily by the grid-scale precipitation scheme (cf. Figs. 3.16c,d). Coincident light convective precipitation suggests that although the BMJ scheme is active, it is unable to remove the moist instability in a timely manner.

Meridional cross-sections through the SGSC at point B illustrate the dramatic changes that occur during SGSC development (Figs. 3.17a-c). At 0000 UTC, a shallow layer of high \(\theta_e\) air (reaching just over 314 K) extends from the surface to ~850 hPa with lower \(\theta_e\) air aloft (Fig 3.17a). The vertical motion is weak (< 4 cm s\(^{-1}\)) in the lower troposphere with weak subsidence aloft. Three hours later, an intense grid-scale updraft of up to 56 cm s\(^{-1}\) extends through the troposphere (Fig. 3.17b). Maxima in relative humidity and \(\theta_e\) accompany the updraft. The SGSC also produces precipitable water and absolute vorticity maxima (Fig. 3.17d). These characteristics are consistent with other SGSC studies.
Figure 3.17. NARR meridional cross section of relative humidity (\%, shaded following scale at bottom), vertical velocity (contours every 10 cm s\(^{-1}\), red=up, blue=down), $\theta_e$ (black contours every 2K), and wind barbs (full and half barbs denote 5 and 2.5 m s\(^{-1}\), respectively) through the SGSC at (a) 0000 UTC 6 Jul 1997, (b) 0300 UTC 6 Jul 1997, and (c) 0600 UTC 6 Jul 1997. (d) NARR Precipitable water (contoured every 3 mm) and 500-hPa absolute vorticity (x 10\(^{-5}\) s\(^{-1}\), shaded following scale at right) at 0300 UTC 6 Jul 1997.
Figure 3.17 continued.
(e.g., UCAR 2005a,b) and arise from the inability to realistically simulate convective processes on the smallest resolved scale of the NARR. The SGSC event weakens rapidly, with no strong ascent and only weak $\theta_e$ and relative humidity maxima apparent by 0600 UTC (Fig. 3.17c)

Unlike the 29 Jun 2003 event, and more consistent with other events we have examined, the low-level temperature and MSLP fields are not strongly affected by these SGSC events. Perturbations were only \( \sim 0.1^\circ \text{C} \) and \( \sim 0.1 \) hPa (not shown), well within the error of observation systems (World Meteorological Organization 1996, NWS 1998) and would not pose a problem for most NARR users.

1 March 2003: Oceanic Convection

Synoptic Overview

This case presents an example of multiple SGSC events occurring simultaneously over the Atlantic Ocean and illustrates a weakness of the search algorithm used in this study. Because of a lack of in situ data, the synoptic overview is based primarily on the NARR analyses.

At 0000 UTC 1 Mar 2003, a low-amplitude, long-wave, 500-hPa trough is exiting the east coast of the United States (Fig. 3.18a). At the surface, a cyclone is centered east of the mid-level trough, with a weak trough extending southwest from its center towards the Bahamas (dashed line in Fig. 3.18b). Further south, a weak easterly wave is located between Hispaniola and the northern tip of Columbia (Fig. 3.18a). Infrared satellite imagery from 2315 UTC 28 Feb and 0245 UTC 1 Mar indicates convective cells at \( \sim 30^\circ \text{N} \) near the trough (Fig. 3.19). Analyzed CAPE values across the tropical and subtropical Atlantic range from 100–1500 J kg\(^{-1}\) (Figs. 3.18c,d). Figure 3.20a presents a NARR sounding from
Figure 3.18. NARR analyses. (a) NARR 500-hPa geopotential height (black contours every 60 m), absolute vorticity (x 10^{-5} \text{ s}^{-1}, shaded following scale at right), and 300-hPa vertical velocity (red contours every 10 cm s^{-1}) at 0000 UTC 1 Mar 2003. (b) NARR MSLP (contoured every 2 hPa) and 3-h total precipitation (mm, shaded following scale at right) at 0000 UTC 1 Mar 2003. (c) NARR 3-h accumulated convective precipitation (mm, shaded following scale at right), 300-hPa vertical velocity (solid contours every 10 cm s^{-1}), and CAPE (dotted contours every 200 J kg^{-1}) at 0000 UTC 1 Mar 2003. (d) As in (c) except grid-scale precipitation.
Figure 3.18 continued.
Figure 3.19. Infrared satellite imagery (cloud top temperatures in °C, shaded following scale at right) at (a) 2315 UTC 28 Feb 2003 and (b) 0245 UTC 1 Mar 2003.
Figure 3.19 continued.
Figure 3.20. NARR skew T-log p diagram [temperature, dewpoint, and wind barbs (full and half barbs denote 5 and 2.5 m s$^{-1}$, respectively)] from (a) event 3 at 0000 UTC 1 Mar 2003. (b) As in (a) except from event 1 at 0300 UTC 1 Mar 2003. (c) As in (b) except from event 2.
Figure 3.20 continued.
Figure 3.20 continued.
the precipitation area labelled 3 in Fig. 3.18b. This sounding is characteristic of much of
the tropical and subtropical Atlantic Ocean at 0000 UTC. Conditionally unstable lapse
rates extend through the greater part of the lower and middle troposphere. Near saturated
conditions at the surface result in limited convective inhibition for surface parcel ascent,
670 J kg\(^{-1}\) of CAPE, and an equilibrium level of 225 hPa. Therefore, a limited amount of
grid scale ascent will result in moist instability unless alleviated by subgrid scale parameter-
erization.

Analysis of SGSC

Four precipitation maxima (labelled 1, 2, 3, and 4 in Fig. 3.18b) are of interest. Precipitation maxima 2, 3, and 4 form in the 3 h prior to 0000 UTC, whereas precipitation maximum 1 has been gradually intensifying since 0300 UTC 28 Feb (not shown). At 0000 UTC, both the convective and grid-scale precipitation schemes are active at all four max-
ima (Figs. 3.18c,d). Despite an active convective parameterization, by 0300 UTC events
2, 3, and 4 have all evolved into SGSC (Figs. 3.21b-d). Cross sections through the three
events feature vertical velocities exceeding 52, 84, and 52 cm s\(^{-1}\), respectively (Figs.
3.21b-d). Event 1 features two vertical velocity maxima, the strongest exceeding 100 cm
s\(^{-1}\) (Fig. 3.21a). This event was not classified as an SGSC event, however, because the
area of large vertical velocities was too broad to meet our criteria, which was designed to
identify smaller scale maxima.

Consistent with the other SGSC, all four events feature relative humidity and mid-
level \(\theta_e\) maxima (Fig. 3.21). Furthermore, in events 1 and 2, areas of > 85\% relative
humidity\(^1\) (Figs. 3.21a,b) and conditionally unstable lapse rates exist from 900–650 hPa
Figure 3.21. NARR meridional cross section of relative humidity (%, shaded following scale at bottom), vertical velocity (contours every 10 cm s$^{-1}$, red=up, blue=down), $\theta_e$ (black contours every 2K), and wind barbs (full and half barbs denote 5 and 2.5 m s$^{-1}$, respectively) through the SGSC in event 1 at (a) 0300 UTC 1 Mar 2003. (b) As in (a) except for event 2. (c) As in (a) except for event 3. (d) As in (a) except for event 4.
Figure 3.21 continued.
(Figs. 3.20b,c), clearly illustrating the presence of moist instability on the grid-scale. As is typical with fully developed SGSC events, the bulk of the precipitation is produced by the grid-scale precipitation scheme (cf. Figs. 3.22a,b), and precipitable water and vorticity maxima are present (not shown).

The MSLP and low-level temperature fields beneath some of these events are affected (Fig. 3.22d). Event 1 has low pressure and warm temperature anomalies, while events 2 and 3 have small cold pools. Event 4 has both a cold pool and a slight high pressure anomaly.

The duration of the events in this case varies widely. Event 1, as discussed previously, was never identified as an SGSC event by the algorithm—however, SGSC was present. This event ended by 0900 UTC 1 Mar 2003, lasting ~33 h in total. Events 3 and 4 are short lived, each persisting for ~6 h. Event 2 commences between 0000 and 0300 UTC 1 Mar 2003, and by 1200 UTC the SGSC develops into three grid-scale updrafts with maximum vertical velocities > 100 cm s\(^{-1}\) (Fig. 3.23a). The SGSC weakens thereafter, and by 2100 UTC maximum vertical velocities are just over 32 cm s\(^{-1}\) (Fig. 3.23b).

**Summary of SGSC Examples**

This section examined three examples of SGSC in the NARR. The first was 29 Jun 2003, which featured high-based convection over a deep, dry boundary layer. The characteristics of the boundary layer in this case led to substantial sub-cloud evaporative cooling, which in turn caused a low-level cold pool, as well as a surface mesohigh. The second example was 6 Jul 1997, which was representative of typical SGSC events, and lasted

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1. The Eta model produces fractional clouds beginning at 85% relative humidity over the oceans (Zhao et al. 1997), which could result in MAUL development at < 100% relative humidity.
Figure 3.22. NARR analyses. (a) NARR 3-h accumulated convective precipitation (mm, shaded following scale at right), 300-hPa vertical velocity (solid contours every 10 cm s\(^{-1}\)), and CAPE (dotted contours every 200 J kg\(^{-1}\)) at 0000 UTC 1 Mar 2003. (b) As in (a) except grid-scale precipitation. (c) NARR MSLP (contoured every 2 hPa), 975-hPa temperature (°C, shaded following scale at right), and wind barbs (full and half barbs denote 5 and 2.5 m s\(^{-1}\), respectively) at 0300 UTC 1 Mar 2003.
Figure 3.23. NARR meridional cross section of relative humidity (%, shaded following scale at bottom), vertical velocity (contours every 10 cm s\(^{-1}\), red=up, blue=down), \(\theta_e\) (black contours every 2K), and wind barbs (full and half barbs denote 5 and 2.5 m s\(^{-1}\), respectively) through the SGSC in event 2 at (a) 1200 UTC 1 Mar 2003 and (b) 2100 UTC 1 Mar 2003.
approximately 6 h, with the low levels not significantly affected. The final example, 1 Mar 2003, illustrated multiple oceanic SGSC events occurring simultaneously in 2003, which we will examine further in the next section.

The SGSC events presented in this section illustrate several common characteristics of SGSC in the NARR. Specifically, NARR SGSC events are characterized by:

- grid-scale precipitation maxima,
- vertical velocity maxima in the middle and/or upper troposphere,
- precipitable water maxima,
- vorticity maxima in the middle and/or upper troposphere,
- relative humidity maxima,
- \( \theta_e \) maxima in the middle and/or upper troposphere,
- and in some cases, low-level cold pools and mesohighs.

Further, SGSC events are typically preceded by the development of a conditionally unstable near saturated layer or MAUL.

This section has focused on what SGSC is, and the NARR fields affected. The next section will address the temporal and geographical distribution of these events.
CHAPTER 4

CHARACTERISTICS OF SGSC IN THE NARR

Geographic and Temporal Distribution

Precipitation assimilation in the NARR uses several data sources over different regions and time periods. Over the continental United States, the unified Climate Prediction Center (CPC) dataset is used from 1979–1998, after which observations from CPC and River Forecast Center datasets are used. Over Mexico and Canada, 24-h rain gauge data are used throughout the NARR. Over the oceans, there is no assimilation of precipitation data north of 42.5°N throughout the NARR analysis period. South of 27.5°N, the CPC Merged Analysis of Precipitation (CMAP, Xie and Arkin 1997, 1998) dataset is used until January 2003, when the NARR switches to the CPC morphing method (CMORPH, Joyce 2004) dataset. In between 27.5° and 42.5°N, there is a linear transition from assimilation of the CMAP or CMORPH dataset to no precipitation assimilation.

The SGSC identification algorithm described in Chapter 2 was run for the years 1981, 1997, and 2003 to determine how common SGSC events are in the NARR. The years 1997 and 2003 are directly before and after the precipitation dataset changes described above. The year 1981 was randomly chosen as a year representative of the beginning of the analysis, to check for consistency between earlier and later years using the same precipitation data.
The geographic distribution and number of SGSC events in 1981 and 1997 are similar, with 95 events in 1981, and 62 events in 1997. In 2003, however, 2235 events are found, two orders of magnitude more than in the previous years. In 1997 and 1981 the events are distributed over the continental United States, Canada, Central America, and the tropical and subtropical Pacific Ocean, with a somewhat higher density over southern Mexico near 20°N (Figs. 4.1a,b). Most of the events (77% in 1981 and 82% in 1997) occur over land.

The results from 2003 are quite different from those in 1981 and 1997 (Fig. 4.1c). There are 179 continental SGSC events distributed over the United States, Mexico and Central America. This is an increase from the previous years, but further investigation is required to determine if this increase is significant. Causes for the lack of events over Canada are unknown. Over the oceans, > 2000 events occur, two orders of magnitude more than in 1997 and 1981. The concentration is greatest south of 30°N, where the CMORPH data was used, and tapers off between 30°N and 40°N, where there was a transition to no precipitation assimilation.

There are also differences in the monthly distribution of SGSC events in 2003. For the entire domain, 1981 and 1997 show a summertime peak in occurrences (Figs. 4.2a,b). The continental cases feature a summertime peak (Figs. 4.3a,b), which correlates well with the observed summertime peak in convection (Dai 2001). The oceanic cases have a summer (1997) or early fall (1981) peak (Figs. 4.4a,b). In marked contrast, the 2003 domain-wide event frequency peaks in late winter (Fig. 4.2c). In addition, continental events feature a bimodal distribution with late spring and early fall peaks (Fig. 4.3c), while over the oceans, the events peak in late winter (Fig. 4.4c).
Figure 4.1. Locations of SGSC events in the NARR in (a) 1997, and (b) 2003. Dashed line denotes NARR domain.
Figure 4.2. Monthly distribution of all SGSC events in (a) 1981, (b) 1997, and (c) 2003.
Figure 4.3. Monthly distribution of continental SGSC events in (a) 1981, (b) 1997, and (c) 2003.
Figure 4.4. Monthly distribution of oceanic SGSC events in (a) 1981, (b) 1997, and (c) 2003.
The diurnal distribution of SGSC events in 1981 and 1997 is bimodal with an abrupt peak at 0900 UTC and gentler peak around 1800–2100 UTC (Figs. 4.5a,b). The results for the continental cases in 1981 and 1997 are very similar to the overall results (Figs. 4.6a,b). The 0900 UTC peak corresponds with the observed maximum in areal extent of mesoscale convective complexes (McAnelly and Cotton 1989), while the 1800–2100 UTC peak agrees with the peak in the genesis of squall lines (Tsakraklides and Evans 2003). Thus, for 1981 and 1997 the frequency of SGSC events over the continents appears to mimic that of observed convective systems. The increased number of events in the hours preceding 0000 and 1200 UTC could be in part because these are the hours furthest from the rawinsonde launch times, the data from which would make a corrective adjustment in the NARR, limiting SGSC. Over the oceans, the number of events is too small to infer meaningful trends by hour during these years (Figs. 4.7a,b). The 2003 overall, continental, and oceanic results all show a tendency for more night time events, with a peak at 1200 UTC (Figs. 4.5c, 4.6c, and 4.7c).

**Duration**

In 1981 and 1997, only 2% of events persist for more than one time interval. The 2003 events tend to be longer lived with 20% of events lasting for > 6 h, 6% for > 9 h, 4% for > 12 h, and a few events persisting for > 15 h. The more persistent events are primarily oceanic, although 8% of the continental events persist for > 6 h. These results suggest that a dramatic change occurred in the NARR oceanic analysis in 2003.
Figure 4.5. Hourly distribution of all SGSC events in (a) 1981, (b) 1997, and (c) 2003.
Figure 4.6. Hourly distribution of continental SGSC events in (a) 1981, (b) 1997, and (c) 2003.
Figure 4.7. Hourly distribution of oceanic SGSC events in (a) 1981, (b) 1997, and (c) 2003.
Characteristics of Affected Fields

As discussed in the case studies, SGSC may be accompanied by spurious MSLP, geopotential height, and temperature extrema. In 1981 and 1997, 15% of events feature MSLP maxima of 1 hPa or greater. This corresponds to a low-level geopotential height anomaly of ~10 m. In 2003, only 1% of events featured MSLP maxima of 1 hPa or greater. This is likely due to the greater percentage of events over the tropical oceans where convection is less apt to generate intense low-level cold pools compared to continental regions.

To give the reader an idea of the typical characteristics of SGSC, the fields used to qualify a grid point as SGSC were averaged for the SGSC events. Vertical velocities averaged 70 cm s\(^{-1}\) in 1981 and 1997, and 68 cm s\(^{-1}\) in 2003. Grid-scale precipitation amounts averaged 11 mm in 1981 and 1997, and 19 mm in 2003. UCAR (2005a) suggests that SGSC typically occurs in high-CAPE environments. This is evidently not the case in the NARR, where average CAPE values for SGSC events are 460 J kg\(^{-1}\), 530 J kg\(^{-1}\), and 306 J kg\(^{-1}\), for 1981, 1997, and 2003, respectively.

Discussion

An automated search for SGSC in 1981, 1997, and 2003, which were selected based on changes to the NARR precipitation assimilation between the latter two years, revealed a dramatic increase in the frequency of SGSC in 2003, namely over the oceans where the change to the CMORPH dataset was made. In 2003, there were 2235 events, compared with only 95 and 65 events in 1981 and 1997, respectively. The geographic and temporal distribution also changed. Specifically, 92% of 2003 events occurred over the
ocean, whereas only 15% did in 1981 and 1997. The annual and diurnal distributions of continental events in 1981 and 1997 were well correlated with those of convective systems over the United States. This was not the case in 2003, which featured a broad 1200 UTC peak.

These results were presented to NCEP in the spring of 2005. Shortly thereafter, NCEP discovered a processing error. The CMORPH dataset, which was used over the oceans starting in January 2003, was read in from south to north, instead of north to south (F. Mesinger and K. Mo 2005, personal communication), resulting in the assimilation of incorrect precipitation amounts and distributions over the subtropical and tropical oceans where the widespread SGSC events existed.

It is likely that the latent heating adjustment in the NARR’s precipitation assimilation scheme, in combination with incorrect precipitation, is the cause of the widespread SGSC over the oceans in 2003. If the observed precipitation ($P_{\text{obs}}$; from the CMORPH dataset) exceeds the Eta 3-h forecasted precipitation ($P_{\text{mod}}$), the NARR precipitation assimilation scheme (Rogers et al. 2005b) adjusts precipitation and latent heating in the NARR in the following manner. If convection is possible, the scheme produces convective precipitation ($P_{\text{conv}}$) to make up the difference ($P_{\text{obs}} - P_{\text{mod}}$), but only up to the maximum amount allowed by the convective parameterization. If after this $P_{\text{mod}} < P_{\text{obs}}$, the NARR grid-scale precipitation ($P_{\text{grd}}$) is adjusted in the following manner. If $P_{\text{grd}} > 0$, the scheme multiplies the grid-scale latent heating profile in the rain producing layers by the ratio $(P_{\text{obs}} - P_{\text{conv}}) / P_{\text{grd}}$ and produces additional $P_{\text{grd}}$ so that $P_{\text{grd}} + P_{\text{conv}} = P_{\text{obs}}$. If, however, $P_{\text{grd}} = 0$, the scheme creates a cloud layer which produces an amount of $P_{\text{grd}}$ such that $P_{\text{grd}} + P_{\text{conv}} = P_{\text{obs}}$, and a corresponding latent heating profile within the cloud layer.
The large amounts of precipitation assimilated into the NARR over the subtropical oceans in 2003 would have induced massive amounts of latent heating within thin cloud layers over the oceans, and is likely what caused these intense updrafts and SGSC. It is anticipated that rerunning the NARR with the correct precipitation distribution will correct this problem (K. Mo 2005, personal communication).
CHAPTER 5

CONCLUSIONS

The analysis described in Chapters 3 and 4 confirms the existence and documents the structure and frequency of SGSC in the NARR. Prior work suggests that SGSC occurs in the Eta model when the convective parameterization cannot relieve moist instability in a timely manner. Although this could not be confirmed with the limited temporal resolution (3 h) of the NARR, the observation of near-saturated conditionally unstable lapse rates or MAULs prior to or during SGSC events strongly suggests this also occurs in the Eta-based NARR, resulting in spurious maxima in grid-scale precipitation, mid and upper-level ascent, mid and upper-level $\Theta_e$, and precipitable water/relative humidity.

The 29 Jun 2003 Wyoming SGSC event occurred over a deep, dry boundary layer. Evaporative cooling accompanying the SGSC produced a low-level cold pool and a 6-hPa mesohigh, which were not present in nearby regions where the BMJ convective parameterization relieved the instability. The 6 Jul 1997 midwestern case provides an example of more typical SGSC in which the low levels are not strongly affected. The 1 Mar 2003 event is representative of oceanic SGSC in 2003, when SGSC is fairly widespread and long-lived.

The years we examined prior to 2003 contain ~100 SGSC events per year, most of them over land, whereas in 2003 there were > 2000 events, most of them over the oceans
(Fig. 4.1). This dramatic change was due to a processing error in the assimilation of the CMORPH dataset, which was used over the oceans starting in 2003. This problem has been corrected, and the NARR is being rerun from 2003-present, which should greatly reduce the number of 2003 SGSC events.

The main purpose of this thesis is to document the existence, structure, and frequency of SGSC for NARR users. SGSC have a dramatic effect on vertical velocity, precipitation, $\theta_e$, moisture, vorticity, and in some cases, temperature, pressure, and geopotential height. NARR users employing the original 2003 and 2004 data are urged to discard them and download the corrected NARR data. With only $\sim$100 cases per year, SGSC will otherwise have little or no effect on long-term hydrometeorological averages (assuming the rerun for 2003–present is successful); however, SGSC could affect studies that examine extreme events, use automated searches to identify phenomena such as cyclones, or concentrate on a single case.
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