Test of a Convective Wake Parameterization in the Single-Column Version of CCM3

JOHN J. ROZBICKI, GEORGE S. YOUNG, AND LIYING QIAN
Department of Meteorology, The Pennsylvania State University, University Park, Pennsylvania

(Manuscript received 9 December 1997, in final form 10 June 1998)

ABSTRACT
A convective wake parameterization incorporated into the single-column (SCM) version of the NCAR Community Climate Model CCM3 is tested using observational data from 12 squall line cases to determine whether it can successfully reproduce convectively driven wakes in a global climate model. The key spatial, thermodynamic, and kinematic properties of the modeled versus the observed wakes are examined, as these features determine the effects of the wakes on surface fluxes and the initiation of convection, effects that should be simulated correctly in general circulation models if deep convection and the resulting earth-atmosphere energy exchanges are to be adequately represented. Results from these simulations indicate that, while the SCM-convective wake scheme combination generally produced long-lasting squall/wake systems, the wakes were often too shallow, too warm, and too moist. These differences occurred despite the ability of CCM3’s standard cumulus parameterization to provide the wake scheme with air whose thermodynamic properties were essentially unbiased, although poorly correlated to the case-by-case observations. As a result of these differences, the modeled wakes propagated at speeds that were somewhat lower than those observed. Despite these problems, it is also demonstrated that the wake scheme does act to significantly improve the response of the model’s cumulus downdraft parameterization to case-to-case variations in the presquall environments; that is, it improves upon the correlation between the thermodynamic characteristics of the modeled downdrafts and the thermodynamic changes across the gust fronts of the observed wakes. A test case using an environmental wind and shear effect formulation derived from the mesoscale modeling work of Liu and Moncrieff demonstrated that the differences between previously published descriptions of these effects remain large enough to significantly affect cold pool behavior in the convective wake parameterization.

1. Introduction
Squall lines, a class of mesoscale convective systems, occur in a number of forms and in a variety of convective environments, ranging from the deep convective lines found within tropical cloud clusters to the prefrontal lines accompanying extratropical cyclones in the midlatitudes (e.g., Betts et al. 1976; Houze 1977; Miller and Betts 1977; Zipser 1977; Gamache and Houze 1982, 1985; Johnson and Nicholls 1983; Smull and Houze 1985, 1987a,b; Chalon et al. 1988; Johnson and Hamilton 1988; Wang et al. 1990; Biggerstaff and Houze 1991; Chen and Chou 1993; Garstang et al. 1994; Jorgensen et al. 1997). These systems all generally consist of a leading deep convective line that feeds on the moist, unstable air found in the environment preceding it and produces a brief period of heavy precipitation, followed by a trailing stratiform region of longer-lasting lighter precipitation (Houze 1977; Zipser 1977; Smull and Houze 1985, 1987a,b; Chong et al. 1987; Johnson and Hamilton 1988; Biggerstaff and Houze 1991). The deep convective line is usually characterized by a narrow region (~10–20 km in width) of strong (on the order of tens of m s⁻¹) convective-scale updrafts and downdrafts, while the stratiform region typically contains much weaker (on the order of 0.1 m s⁻¹) mesoscale updrafts and downdrafts that act over a much larger scale (~100 km) (Houze 1977; Zipser 1969, 1977). These systems also typically produce a convective wake (i.e., outflow)—a surface-based pool of relatively colder and (usually) drier air that results from the detachment of convective downdraft air into the boundary layer (Entermacht and Garstang 1976; Houze 1977; Zipser 1977; Gaynor and Mandics 1978; Johnson and Nicholls 1983; Young et al. 1995). The air within these wakes is denser than the surrounding environmental air and therefore spreads as a gravity current (Charba 1974; Goff 1976; Liu and Moncrieff 1996). This cooler, drier wake air acts to increase surface fluxes of heat and moisture (Ulanski et al. 1973; Houze 1977; Johnson and Nicholls 1983; Young et al. 1995) and to suppress further convection in the regions it moves over (Houze 1977; Zipser 1977; Johnson and Nicholls 1983), while its leading edge, the gust front, lifts the unstable environmental air as it propagates outward from its downdraft source.
causing the development of new convective cells just ahead of the existing deep convective line (Goff 1976; Houze 1977; Zipser 1977; Stensrud and Maddox 1988; Rotunno et al. 1988). In this way, squall lines act to both sustain themselves and to stabilize the lower layers of the atmosphere.

Owing to the spatial scales of squall lines, which mostly occur on the mesoscale, these systems and their effects on the atmosphere cannot be explicitly resolved by general circulation models (GCMs) and therefore must be parameterized along with other important subgrid-scale processes occurring in the atmospheric boundary layer and at the earth’s surface. At present, most GCMs parameterize deep convection, but either do not allow for the interaction of deep convection with atmospheric boundary layer and surface processes, or greatly oversimplify these interactions. Such oversimplifications generally consist of either instantly mixing the downdraft air with the environmental air or allowing the downdraft air to instantly recover to the environmental thermodynamic state, rather than feeding the downdraft air into a wake of finite longevity (Qian et al. 1997). As a result, important feedback processes, such as those described in the preceding paragraph, are not accounted for leading to inaccuracies in the respective parameterizations and errors in the overall model solution (Qian et al. 1997). One approach that has been used to circumvent such problems is to directly parameterize convective wakes and their interactions with the surrounding environment and the convection that caused them. This method was most recently adopted by Qian et al. (1997), hereafter referred to as the Qian–Young–Frank or QYF parameterization after its authors, who conducted preliminary tests of a simple convective wake/gust front model that they developed and incorporated into the single-column version of the National Center for Atmospheric Research (NCAR) Community Climate Model CCM3. This scheme generates convective wakes based on the properties of convective downdrafts predicted by the model’s cumulus parameterization scheme, allows for the separation of the boundary layer in each column of a GCM into undisturbed environment and downdraft-fed wake regions, and provides the cumulus parameterization with information concerning the lifting produced by the gust front. The wakes are allowed to behave as expanding gravity currents that are modified and eventually forced to recover through the effects of surface and wake-top-entrainment fluxes. Thus, feedbacks between convection and the boundary layer, between wakes and the earth’s surface, and between wakes and convection are all modeled according to their known dynamics. The single-column (SCM) version of CCM3 was utilized in this effort, as it allowed for the evaluation of this new scheme apart from the nonlinear feedback processes that occur between grid columns in a global integration and would otherwise cloud the results.

As with all GCM parameterizations, subsequent testing of the QYF wake model should involve two steps. First, evaluation of the parameterization’s ability to accurately model the behavior of the parameterized process for the broadest possible range of realistic forcing conditions. This step is generally conducted with a series of carefully selected case studies of relatively short simulated duration. Second, evaluation of the parameterization’s ability to enhance the accuracy of a GCM’s climate simulation. This step is generally conducted using a single-column model version of the GCM and a long observational time series of forcing and response. While this second, long-term verification step is the ultimate test of a parameterization’s utility in GCM applications, the first short-term case study testing step allows for more detailed diagnostic analysis of model behavior. Thus, the case study evaluation is a key step in testing and improving GCM parameterizations. We, therefore, report the results of the case study evaluation of the QYF wake model in this study.

In this study, additional tests of the convective wake parameterization described above were conducted using observational data from 12 squall line cases to determine whether it can successfully reproduce the convectively driven wakes of such systems in a global climate model. The data for these squall line cases—10 individual squall lines and two composite events—were collected from those available in the observational literature. These cases occurred during the following meteorological experiments conducted over the past quarter-century: the Convection Proforme Tropicale Experiment of 1981 (COPT; Sommeria and Testud 1984), the GARP Global Atmospheric Research Programme (GATE; Houze and Betts 1981), the Oklahoma–Kansas Preliminary Regional Experiment for STORM-Central (PRE-STORM) of 1985 (Cunning 1986), the Amazon Boundary Layer Experiment of 1987 (ABLE-2B; Garstang et al. 1990), the Venezuelan International Meteorological and Hydrological Experiment of 1972 (VIMHEX), the Taiwan Area Mesoscale Experiment of 1987 (TAMEX; Webster and Houze 1991), and the Tropical Ocean Global Atmosphere Coupled Ocean–Atmosphere Response Experiment of 1992–93 (TOGA COARE; Webster and Lukas 1992). These experiments were conducted in six geographically and meteorologically diverse regions: sub-Saharan Africa (COPT), the section of the eastern tropical Atlantic near Cape Verde (GATE), the Great Plains of the continental United States (PRE-STORM), equatorial South America (ABLE-2B and VIMHEX), Taiwan and the nearby subtropical western Pacific (TAMEX), and the southwestern equatorial Pacific (EMEX and TOGA COARE). The squall line events used for verification in this study were chosen such that the two most comprehensively studied cases were selected for each of these six regions. In this way, the wake parameterization is tested in a wide variety of convective environments and situations. In each
simulation, the initial atmospheric conditions are provided by an observed presquall sounding taken from the observational literature. The model is then run for a 48-h period and the key spatial, thermodynamic, and kinematic properties of the modeled versus the observed wakes are compared.

The types of data used in this study are described in section 2. Section 3 details the methodology used in collecting and processing the data and also briefly describes the wake parameterization and the modeling procedures. Section 4 presents the relevant environmental, system, and wake characteristics that were derived from the literature, while section 5 discusses the results from the simulations and the sensitivity tests. Finally, section 6 presents a summary of this study and suggests some potential improvements for the QYF wake parameterization.

2. Data

To accomplish the goals of this study, it was first necessary to obtain data representing the conditions of the various presquall environments, the gross characteristics of the squall line systems, and the properties of the convectively induced wakes. These data were obtained or derived from that available in the following sources: Betts et al. (1976), Houze (1977), Miller and Betts (1977), Nitta (1977), Zipser (1977), Gaynor and Mandics (1978), Johnson and Nicholls (1983), Maddox (1983), Roux et al. (1984), Chong et al. (1987), Chalon et al. (1988), Johnson and Hamilton (1988), Roux (1988), Stensrud and Maddox (1988), Johnson et al. (1989), Wang et al. (1990), Alexander (1991), Biggerstaff and Houze (1991), Chen and Chou (1993), Sun et al. (1993), Garstang et al. (1994), Cohen et al. (1995), Trier et al. (1996), J. Halverson and M. Garstang (1996, personal communication), Jorgensen et al. (1997), and M. Nicholls (1997, personal communication). Details of the data acquisition methods for each variable are described in the remainder of this section.

For each of the presquall environments, profiles of temperature, mixing ratio, and the $u$ and $v$ components of the wind were obtained, as was a profile of $\omega$ (vertical velocity in pressure coordinates) thought to represent conditions preceding the squall line. This information was required for initialization and forcing of the GCM. In addition, data consisting of mixed layer (ML) depths and average ML parcel thermodynamic properties were derived from the presquall soundings in each case for the purpose of comparing and contrasting the ambient conditions preceding the various convective systems. The squall line characteristics gathered for each event included the system lifetime, its direction and speed of movement, and the vertical extent of the leading deep convective line. These properties were essential for determining the proper length of the model runs, for converting storm-relative winds to standard Cartesian coordinate winds when needed, and for assessing whether the combination of the convective and wake parameterizations could produce deep convection of depths comparable to nature. Finally, the properties obtained for each wake included its depth, the gust front propagation velocity relative to the ground, measures of the changes in potential temperature and mixing ratio across the gust front, and a measure of the low-level stability within the wake. These characteristics were used to verify the wakes generated by the QYF parameterization.

3. Procedures

a. Collection and treatment of data

1) Presquall environmental characteristics

The presquall sounding data used in this study were primarily taken from figures (e.g., skew $T$–$\log p$ diagrams) or tables provided in the observational literature. Once these data had been obtained, each dataset was processed (if necessary) to ensure that data existed for all variables at all levels. First, any data gaps at the surface and uppermost pressure levels in the datasets were filled. At the surface, such gaps only existed for the $u$ and $v$ wind data in a few of the cases. These were filled by setting the values of $u$ and $v$ to those at the nearest level where such data existed. This method was also used to fill similar gaps in the wind data at the uppermost level. Temperature data existed in all of the datasets at the uppermost level; if mixing ratio data were missing there, it was set equal to zero. At both the surface and uppermost data levels, $\omega$ was set equal to zero. Any remaining gaps at other levels were then filled via linear interpolation. The resulting datasets were subsequently interpolated to the host model levels; any model levels above the uppermost level of the data were assigned the data of that level.

The other data in this study characterizing the presquall environmental conditions, if not explicitly given in the literature, were derived from the sounding data described above. The mixed layer depth ($Z_m$) for a given case was generally determined from the presquall temperature and mixing ratio profiles. The ML-average mixing ratio and potential temperature were then determined based on the sounding data and were used to define the initial characteristics of the average ML parcel. The wet-bulb potential temperature, lifting condensation level (LCL), level of free convection (LFC), equilibrium level (EQL), and lifted index (LI) for this parcel were then determined graphically on a skew $T$–$\log p$ diagram, and the environmental convective available potential energy (CAPE) and convective inhibition (CIN) associated with such a parcel were determined based on this information and the sounding data.

2) Squall line characteristics

If not explicitly given in the observational literature, the squall line characteristics were determined from oth-
er published information in the following ways. The lifetime of a given system was either taken from maps containing squall line isochrones, estimated from satellite data, or deduced from information provided in the text. The movement of a squall line was generally estimated from maps containing squall line isochrones. Lastly, the heights of the deep convective cloud tops in the squall lines were either estimated from infrared satellite data or were inferred from vertical cross sections of Doppler radar-derived wind patterns and/or radar reflectivities.

3) WAKE CHARACTERISTICS

For a given squall line system, the depth of the wake \(Z_k\) was determined from one of two methods. The first, and most often utilized, method involved calculating the depth of the surface-based layer that cooled and dried from the presquall sounding to a sounding taken in the wake region of the squall line system. This layer was assumed to be the layer containing the convective wake. The second method used vertical cross sections (perpendicular to the squall front) of Doppler radar-derived storm-relative wind fields to assess the depth of the wake. In this approach, the wake top was assumed to be at the point where the surface-based layer of rear-to-front flow switched to front-to-rear flow. The changes in potential temperature and mixing ratio across the wake front (gust front), if not explicitly provided in the literature, were determined using one of four methods. The first (and preferred) method was to determine these changes from surface traces of these or related parameters. The second method (which was often used in the absence of surface traces) utilized presquall and wake sounding data to calculate the changes in \(\theta\) and \(q\) across the wake front based on the changes in the surface values of these parameters (or related parameters) from the presquall environment to the wake. The third method utilized surface maps or analyses of temperature and some moisture parameter (usually either dewpoint or mixing ratio) to calculate areal averages of the thermodynamic changes across the gust front. The final method involved the estimation of the changes from low-level aircraft traces of potential temperature and mixing ratio.

The low-level stability within the wake was determined from the sounding data obtained in the wake portion of the squall line system and the previously obtained value of \(Z_k\). The potential temperatures at the surface and the top of the wake were determined; these were then used in the equation

\[
\text{stability} = \frac{\theta_{\text{top}} - \theta_{\text{sfc}}}{Z_k}
\]

(1)

to obtain the low-level stability within the wake. In the event the air in the wake was already recovering and a surface superadiabatic layer existed, the surface potential temperature at the time of maximum stability was estimated using a downward linear extrapolation from the potential temperature value at the top of the surface layer. The wake stability was then calculated using this estimated surface potential temperature value.

Finally, the gust front speed, if not explicitly given, was either 1) estimated from surface maps and/or time series of surface observations at various stations that the squall line system passed over or 2) arbitrarily assumed to be the same as the system motion if that data was available. It should be noted here that when the former method was used, the obtained speed matched that of the squall line systems in every case; thus the observed gust front speeds obtained in this study are not separately shown in the observed characteristics as they can be seen by examining the speeds of the squall line systems.

b. Modeling

1) BRIEF DESCRIPTION OF THE QYF WAKE PARAMETERIZATION

The QYF parameterization was originally documented by Qian et al. (1997). As the current study expands upon the preliminary tests conducted in that paper, only a brief description of the QYF parameterization is presented here; the reader is referred to that paper for a more complete discussion. The QYF scheme uses convective downdrafts generated by a cumulus parameterization [in this study, the standard Zhang–McFarlane (1995) scheme of CCM3] to generate a convective wake that is rectangular in shape, uniform in depth (except at the gust front head), and well mixed in the vertical. The thermodynamic properties of this wake, which are a function of the temperature and moisture characteristics of the downdrafts, are assumed to be constant in the along-squall direction and vary linearly from the front to the rear of the wake, with the coldest and driest air found at the leading edge. The wake propagation is governed by gravity current theory (Simpson 1969; Charba 1974; Goff 1976). Because gust fronts have an ongoing mass flux from the convective downdrafts, the gravity current propagation speed is modified to include the effects of convective cell drift, that is, the cloud-layer average wind (Lucero 1983; Qian et al. 1997).

In the atmosphere, the propagation of a gust front into undisturbed environmental air can initiate new convection. The information needed to model this process (updraft diameter, updraft velocity, and maximum vertical extent of gust frontal lifting) is made available to cumulus parameterizations by the QYF wake parameterization. The Zhang–McFarlane (1995) cumulus parameterization used in CCM3 does not, however, use a triggering-dependent closure and so makes no use of this wake/convection coupling information.

The maximum areal extent of the wake is limited to 90% of the cross-sectional area of a grid column (40 000 km^2); if it grows larger than this, it is mixed with the environmental air. As observed by Houze (1977), Zipser
(1977), Johnson and Nicholls (1983), and Young et al. (1995), the wake recovers from the rear due to a combination of surface fluxes and entrainment fluxes at the wake top. The surface sensible and latent heat fluxes in the wake are calculated using bulk aerodynamic theory with the transfer coefficients fixed at $1.5 \times 10^{-3}$ as in the work of Qian et al. The moisture availability at the surface is fixed at 1.0; this is done because seven of the cases in this study were oceanic in nature and the other six produced rainfall that would most likely have raised moisture availabilities to approximately this level. The surface wind speed used in these calculations varies linearly from the gust front speed at the wake front to the wake rear-propagation speed, as suggested by Simpson and Britter (1980) and Young et al. (1995). Wake-top-entrainment fluxes are calculated via mixed layer modeling theory (Deardorff 1972, 1974; Betts 1973; Tennekes 1973) using an entrainment velocity derived from the assumption that the wake-top buoyancy flux is $-0.2$ times the surface buoyancy flux. If the mean wake temperature warms to within 0.5 K of the environmental temperature (a small arbitrary threshold), it is eliminated and mixed with the environment.

2) Effect of shear

While a complete similarity theory for the effects of environmental values of wind, shear, and stability on gravity current behavior has yet to be developed, the available results suffice for testing the sensitivity of the QYF wake model to the influence of environmental shear. Because of their relative completeness, the two-dimensional nonhydrostatic gravity current model results of Liu and Moncrieff (1996, hereafter LM) provide the basis for the formulation used in the sensitivity tests reported in section 5b. Liu and Moncrieff present their results in graphical form from which the relationships listed below were derived. Because their simulations all used a fixed set of downdraft thermodynamic characteristics, caution should be exercised before applying these relationships to cases with dissimilar thermodynamics. As discussed in section 6, development of generally applicable forms of these relationships cannot be undertaken until the cloud-resolving modeling community has published the results of a much larger set of case studies spanning the full dimensionality of the parameter space including downdraft thermodynamics, environmental wind speed, environmental shear, and environmental stability.

The environmental shear correction to the gravity current propagation speed formula of QYF depends on whether the gravity current face in question is propagating up- or downshear. The downshear propagation results portrayed in Fig. 14 of LM can be modeled as

$$C_s = C_g(1 + 0.029S),$$

where $C_s$ is the basic gravity current speed, $C_g$ is the shear-corrected gravity current speed, and $S$ is the magnitude of the shear in m/s km$^{-1}$. Similarly, the upshear propagation results from this figure can be modeled as

$$C_s = C_g(1 - 0.035S).$$

The environmental wind speed effect on the gravity current propagation speed is shown in Fig. 7 of LM and can be modeled as

$$C_{sw} = 1.2C_g + 0.75U_0,$$

where $U_0$ is the environmental wind speed (positive if the gravity current is going downwind) and $C_{sw}$ is the gravity current propagation speed corrected for both environmental shear and environmental wind speed. For the sensitivity tests, this formula replaces the older version used by QYF.

Liu and Moncrieff (1996) also provide graphical results to which formulations for the effects of environmental shear and environmental wind on gravity current head height $h$ can be fit. Figure 5 of LM shows that different formulas are needed for the upwind and downwind propagation directions:

$$h_w = h(1 - 0.30\frac{U_0}{C_{sw}})$$

models the results of LM for downwind propagating gravity currents, where $h_w$ is the head height corrected for environmental wind, and

$$h_u = h(1 - 0.56\frac{U_0}{C_{sw}})$$

models their results for upwind propagating gravity currents. The environmental shear correction to the gravity current head height as shown in Fig. 13 of LM and can be modeled as

$$h_{sw} = h_u(0.0085S^{2.2})$$

for downshear propagating gravity currents, where $h_{sw}$ is the gravity current head height corrected for both environmental shear and environmental wind speed. For upshear propagating gravity currents,

$$h_{sw} = 0.9h_u.$$
3) MODELING PROCEDURES

Once the presquall sounding data had been obtained, processed, and interpolated to the model levels, it was then input to the model as the initial atmospheric conditions for the grid column in which the squall line was observed. The model time was set to the time and date of the actual presquall sounding. The model provided the necessary boundary datasets for the specified squall location (e.g., surface properties); these consisted of monthly average climatological data from European Centre for Medium-Range Weather Forecasts analyses or model-generated results (Hack et al. 1997). If the grid box was located over the oceans, a sea surface temperature (SST) was provided by the model for the grid box; if the grid column was located over land, the surface conditions were supplied by CCM3’s Land Surface Model (LSM). During some of the preliminary runs on the continental squall line cases, it was noticed that the LSM initialized the land surface temperatures anywhere from 10 to 15 K too cold and kept them too cold throughout the model run. This error required correction as it had an undesirable effect on the modeled surface fluxes and thus the recovery of the modeled wakes. To correct this problem, all of the reported simulations run over land surfaces utilized a 24-h dynamic initialization period to allow the LSM to spin up correctly. To accomplish this, the model was started 24 h prior to the time of the initial sounding with the initial sounding data and was forced to run for a 24-h period with the convective parameterizations turned off. At every time step (every 20 min) during this period, the sounding data was reset to the initial sounding. Over a full diurnal cycle, these procedures allowed the atmospheric model to nudge the surface temperature data of the LSM toward that of the lowest level of the presquall sounding. This procedure produced much more realistic surface temperatures by the end of the 24-h initialization period, at which point the convective parameterizations were turned on and the model was allowed to run normally. Over the oceans, no dynamic initialization period was necessary as the SSTs provided by the model were found to be rather accurate. The model was allowed to run normally for a 48-h period in all cases, as the lifetimes of the squall line systems used in this study were all less than this.

Large-scale forcing through the 48-h period in a given model run was provided by the \( \omega \) profile input with the initial sounding data. For some of the squall line cases, large-scale vertical velocity data neither existed in the literature nor were otherwise available; in these instances, physically reasonable vertical velocity profiles were used to force the model. These events included the COPT, PRE-STORM, ABLE-2B, VIMHEX, and TAMEX systems. For the COPT cases, an average of the \( \omega \) profiles from the two GATE cases was used; this was thought to be reasonable as squall lines that form in sub-Saharan Africa in effect become Cape Verde–area squall lines once they move off the West African coast. The South American events (ABLE-2B and VIMHEX) were assigned the \( \omega \) profile of the EMEX case rather than the composite GATE profile or the TOGA COARE profile; this was done because 1) it has been noted by Frank and McBride (1989) that the large-scale environment of GATE appeared to be moderately atypical of mean conditions in the Tropics and 2) the maximum upward vertical velocity in the EMEX case was located at a level (~700 mb) much more typical of the genesis stage of tropical squall lines than that in the TOGA case (400 mb) (Frank and McBride 1989). The simulations of the TAMEX cases and one of the PRE-STORM cases used a profile modeled after that given in Maddox (1983) for the composite preconvective environment of 12 mesoscale convective complexes that occurred over the continental United States; this profile was chosen as it was generally associated with the presence of a weak shortwave at the 500-mb level, a feature present in the PRE-STORM case and one of the TAMEX cases. The remaining PRE-STORM case, which was associated with a dryline but no 500-mb shortwave, was assigned a profile containing no vertical motion as this system appeared to have no significant large-scale atmospheric forcing associated with it.

The sensitivity of the QYF wake model to the effects of environmental wind shear and to the differences between various published forms of the wind speed correction formulas was tested using the alternative formulation described in section 3b(2) above. Results for the TOGA squall line will be presented for three versions of this model: the basic QYF model that assumes shear effects to be negligible, another shearless version wherein only the wind speed correction formulas have been altered to match the results of Liu and Moncrieff (1996), and a final version where both the wind speed correction and shear correction formulas follow their results. The TOGA COARE 22–23 February 1993 squall line (case 12 in Tables 1, 2, 3, and 4) was selected for these sensitivity tests because its environmental conditions in the Tropics and 2) the maximum upward vertical velocity in the EMEX case was located at a level (~700 mb) much more typical of the genesis stage of tropical squall lines than that in the TOGA case (400 mb) (Frank and McBride 1989). The simulations of the TAMEX cases and one of the PRE-STORM cases used a profile modeled after that given in Maddox (1983) for the composite preconvective environment of 12 mesoscale convective complexes that occurred over the continental United States; this profile was chosen as it was generally associated with the presence of a weak shortwave at the 500-mb level, a feature present in the PRE-STORM case and one of the TAMEX cases. The remaining PRE-STORM case, which was associated with a dryline but no 500-mb shortwave, was assigned a profile containing no vertical motion as this system appeared to have no significant large-scale atmospheric forcing associated with it.

The sensitivity of the QYF wake model to the effects of environmental wind shear and to the differences between various published forms of the wind speed correction formulas was tested using the alternative formulation described in section 3b(2) above. Results for the TOGA squall line will be presented for three versions of this model: the basic QYF model that assumes shear effects to be negligible, another shearless version wherein only the wind speed correction formulas have been altered to match the results of Liu and Moncrieff (1996), and a final version where both the wind speed correction and shear correction formulas follow their results. The TOGA COARE 22–23 February 1993 squall line (case 12 in Tables 1, 2, 3, and 4) was selected for these sensitivity tests because its environmental conditions in the Tropics and 2) the maximum upward vertical velocity in the EMEX case was located at a level (~700 mb) much more typical of the genesis stage of tropical squall lines than that in the TOGA case (400 mb) (Frank and McBride 1989). The simulations of the TAMEX cases and one of the PRE-STORM cases used a profile modeled after that given in Maddox (1983) for the composite preconvective environment of 12 mesoscale convective complexes that occurred over the continental United States; this profile was chosen as it was generally associated with the presence of a weak shortwave at the 500-mb level, a feature present in the PRE-STORM case and one of the TAMEX cases. The remaining PRE-STORM case, which was associated with a dryline but no 500-mb shortwave, was assigned a profile containing no vertical motion as this system appeared to have no significant large-scale atmospheric forcing associated with it.

4. Observed characteristics

To demonstrate the large amount of variation in the observed characteristics of the presquall environments, the squall lines themselves, and their attendant wakes, we present the relevant observations below. Table 1 shows the observed thermodynamic characteristics of a mixed layer parcel (obtained by averaging that segment of the sounding within the mixed layer) in the presquall environment for each of the squall line cases used in this study. The squall line systems used in this study
Table 1. Table of characteristics for the presquall environments of the squall lines used in this study. The data from the 12 Sep 1974 GATE case is split into two parts to reflect the north–south variability in the environmental conditions preceding the squall line as documented by Gamache and Houze (1982, 1985) and Johnson and Nicholls (1983).

<table>
<thead>
<tr>
<th>Expt</th>
<th>COPT</th>
<th>COPT</th>
<th>GATE</th>
<th>GATE</th>
<th>PRE-STORM</th>
<th>PRE-STORM</th>
<th>ABLE-2B</th>
<th>VIMHEX-72</th>
<th>TAMEX</th>
<th>TAMEX</th>
<th>EMEX</th>
<th>EMEX</th>
<th>TOGA COARE</th>
</tr>
</thead>
<tbody>
<tr>
<td>Month</td>
<td>Jun</td>
<td>Jun</td>
<td>Sep</td>
<td>Sep</td>
<td>Jun</td>
<td>Jun</td>
<td>Apr</td>
<td>July</td>
<td>May</td>
<td>May</td>
<td>Feb</td>
<td>Feb</td>
<td>Feb</td>
</tr>
<tr>
<td>Day(s)</td>
<td>23–24</td>
<td>22</td>
<td>12 (N)</td>
<td>12 (S)</td>
<td>4–5</td>
<td>10–11</td>
<td>23–24</td>
<td>25–26</td>
<td>17</td>
<td>16</td>
<td>30</td>
<td>30</td>
<td>1–2</td>
</tr>
</tbody>
</table>

Presquall thermodynamics (mixed layer parcel)

<table>
<thead>
<tr>
<th>Sounding time (UTC)</th>
<th>2202(^b)</th>
<th>0348</th>
<th>0910</th>
<th>1215</th>
<th>1200</th>
<th>0134</th>
<th>0000</th>
<th>1500</th>
<th>2131(^a)</th>
<th>1200</th>
<th>0900(^c)</th>
<th>0000</th>
<th>2100</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sounding time (LST)</td>
<td>2202(^b)</td>
<td>0348</td>
<td>0710</td>
<td>1015</td>
<td>1000</td>
<td>1934</td>
<td>1800</td>
<td>1100</td>
<td>1731(^a)</td>
<td>2000</td>
<td>1700(^c)</td>
<td>0900</td>
<td>0800</td>
</tr>
<tr>
<td>ZL (m)</td>
<td>1100</td>
<td>1570</td>
<td>771</td>
<td>580</td>
<td>327</td>
<td>1499</td>
<td>1824</td>
<td>505</td>
<td>1156</td>
<td>n/a</td>
<td>n/a</td>
<td>367</td>
<td>500</td>
</tr>
<tr>
<td>q (g kg(^{-1}))</td>
<td>16.8</td>
<td>15.7</td>
<td>18.0</td>
<td>15.1</td>
<td>16.9</td>
<td>13.3</td>
<td>11.0</td>
<td>18.7</td>
<td>14.8</td>
<td>17.2</td>
<td>16.3</td>
<td>18.1</td>
<td>19.0</td>
</tr>
<tr>
<td>theta (K)</td>
<td>306.0</td>
<td>302.7</td>
<td>299.1</td>
<td>298.2</td>
<td>297.0</td>
<td>307.4</td>
<td>313.5</td>
<td>299.6</td>
<td>303.3</td>
<td>298.7</td>
<td>300.4</td>
<td>299.7</td>
<td>300.2</td>
</tr>
<tr>
<td>theta(w ((^\circ)C))</td>
<td>24.8</td>
<td>23.3</td>
<td>23.9</td>
<td>21.6</td>
<td>22.6</td>
<td>22.8</td>
<td>22.9</td>
<td>24.3</td>
<td>23.0</td>
<td>23.3</td>
<td>23.1</td>
<td>24.1</td>
<td>24.7</td>
</tr>
<tr>
<td>LCL (mb)</td>
<td>860</td>
<td>880</td>
<td>960</td>
<td>932</td>
<td>975</td>
<td>797</td>
<td>705</td>
<td>962</td>
<td>862</td>
<td>960</td>
<td>922</td>
<td>955</td>
<td>960</td>
</tr>
<tr>
<td>LFC (mb)</td>
<td>800</td>
<td>855</td>
<td>960</td>
<td>881</td>
<td>961</td>
<td>655</td>
<td>556</td>
<td>958</td>
<td>805</td>
<td>875</td>
<td>825</td>
<td>913</td>
<td>945</td>
</tr>
<tr>
<td>EQL (mb)</td>
<td>124</td>
<td>164</td>
<td>165</td>
<td>294</td>
<td>290</td>
<td>175</td>
<td>231</td>
<td>144</td>
<td>183</td>
<td>177</td>
<td>400</td>
<td>182</td>
<td>106</td>
</tr>
<tr>
<td>CAPE (J kg(^{-1}))</td>
<td>2819</td>
<td>1284</td>
<td>2619</td>
<td>547</td>
<td>893</td>
<td>1370</td>
<td>1227</td>
<td>1544</td>
<td>1002</td>
<td>1358</td>
<td>288</td>
<td>1294</td>
<td>1904</td>
</tr>
<tr>
<td>CIN (J kg(^{-1}))</td>
<td>-10</td>
<td>-14</td>
<td>-5</td>
<td>-42</td>
<td>-14</td>
<td>-79</td>
<td>-331</td>
<td>-18</td>
<td>-69</td>
<td>-56</td>
<td>-74</td>
<td>-43</td>
<td>-16</td>
</tr>
<tr>
<td>LI ((^\circ)C)</td>
<td>-6.7</td>
<td>-3.7</td>
<td>-4.1</td>
<td>-0.4</td>
<td>-2.3</td>
<td>-5.2</td>
<td>-3.2</td>
<td>-1.7</td>
<td>-8.0</td>
<td>-9.0</td>
<td>-2.5</td>
<td>-3.9</td>
<td></td>
</tr>
</tbody>
</table>

\(^{a}\) A composite date–time associated with a composite case.

\(^{b}\) The sounding used in this case was a composite of a 2032 UTC and a 2332 UTC sounding.

\(^{c}\) No mixed layer was apparent in these cases; data given are for a parcel representing the average conditions in the lowest 50 mb.
Table 2. Table of characteristics of the squall lines used in this study.

<table>
<thead>
<tr>
<th>Case</th>
<th>Month</th>
<th>Year</th>
<th>Day(s)</th>
<th>System characteristics</th>
<th>Lifetime (h)</th>
<th>System motion from (dir)</th>
<th>Speed (m s(^{-1}))</th>
<th>Height of cloud tops (km) convective line Cb's</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Jun</td>
<td>1981</td>
<td>23-24</td>
<td>30.0 ± 14.0</td>
<td>13.5 ± 10.0</td>
<td>10.0 ± 6.0</td>
<td>90 ± 37 ± 10.0</td>
<td>116.4 ± 12.0</td>
</tr>
<tr>
<td>2</td>
<td>Jun</td>
<td>1981</td>
<td>22</td>
<td>36.0 ± 23.0</td>
<td>15.0 ± 12.5</td>
<td>12.5 ± 6.0</td>
<td>63 ± 30 ± 40</td>
<td>10.0 ± 12.0</td>
</tr>
<tr>
<td>3</td>
<td>Sep</td>
<td>1974</td>
<td>4-5</td>
<td>23.0 ± 12.0</td>
<td>15.0 ± 10.0</td>
<td>12.5 ± 6.0</td>
<td>30 ± 18 ± 20</td>
<td>15.0 ± 15.0</td>
</tr>
<tr>
<td>4</td>
<td>Sep</td>
<td>1974</td>
<td>23-24</td>
<td>22.5 ± 11.5</td>
<td>15.0 ± 10.0</td>
<td>12.5 ± 6.0</td>
<td>30 ± 18 ± 20</td>
<td>15.0 ± 15.0</td>
</tr>
<tr>
<td>5</td>
<td>May</td>
<td>1987</td>
<td>1-2</td>
<td>19.0 ± 10.0</td>
<td>15.0 ± 10.0</td>
<td>12.5 ± 6.0</td>
<td>30 ± 18 ± 20</td>
<td>15.0 ± 15.0</td>
</tr>
<tr>
<td>6</td>
<td>May</td>
<td>1987</td>
<td>16</td>
<td>6.0 ± 3.0</td>
<td>15.0 ± 10.0</td>
<td>12.5 ± 6.0</td>
<td>30 ± 18 ± 20</td>
<td>15.0 ± 15.0</td>
</tr>
<tr>
<td>7</td>
<td>May</td>
<td>1987</td>
<td>17</td>
<td>3.0 ± 1.0</td>
<td>15.0 ± 10.0</td>
<td>12.5 ± 6.0</td>
<td>30 ± 18 ± 20</td>
<td>15.0 ± 15.0</td>
</tr>
<tr>
<td>8</td>
<td>May</td>
<td>1987</td>
<td>1987</td>
<td>17.0 ± 15.0</td>
<td>15.0 ± 10.0</td>
<td>12.5 ± 6.0</td>
<td>30 ± 18 ± 20</td>
<td>15.0 ± 15.0</td>
</tr>
<tr>
<td>9</td>
<td>May</td>
<td>1987</td>
<td>1987</td>
<td>17.0 ± 15.0</td>
<td>15.0 ± 10.0</td>
<td>12.5 ± 6.0</td>
<td>30 ± 18 ± 20</td>
<td>15.0 ± 15.0</td>
</tr>
<tr>
<td>10</td>
<td>May</td>
<td>1987</td>
<td>1987</td>
<td>17.0 ± 15.0</td>
<td>15.0 ± 10.0</td>
<td>12.5 ± 6.0</td>
<td>30 ± 18 ± 20</td>
<td>15.0 ± 15.0</td>
</tr>
<tr>
<td>11</td>
<td>May</td>
<td>1987</td>
<td>1987</td>
<td>17.0 ± 15.0</td>
<td>15.0 ± 10.0</td>
<td>12.5 ± 6.0</td>
<td>30 ± 18 ± 20</td>
<td>15.0 ± 15.0</td>
</tr>
<tr>
<td>12</td>
<td>Feb</td>
<td>1993</td>
<td>1-2</td>
<td>12.0 ± 5.0</td>
<td>15.0 ± 10.0</td>
<td>12.5 ± 6.0</td>
<td>30 ± 18 ± 20</td>
<td>15.0 ± 15.0</td>
</tr>
</tbody>
</table>

*Case 1 is a composite case; thus date is a composite and data shown are for a composite system.

*The squall line motion was highly variable in this case; data shown are for the mature stage of the system when in motion was quasi-steady state.

*Data are not available; could not be determined from available information.
Table 3. Table of characteristics of the observed convective wakes attending the squall line systems used in this study; the data for the 12 Sep 1974 GATE case are split into two parts to reflect the observed north–south variations in the wake described by Johnson and Nicholls (1983).

<table>
<thead>
<tr>
<th>Case</th>
<th>Expt</th>
<th>Month</th>
<th>Day(s)</th>
<th>Year</th>
<th>Pre-storm</th>
<th>VIMHEX-72</th>
<th>TAMEX</th>
<th>EMEX</th>
<th>TOGA COARE</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>COPT</td>
<td>Jun</td>
<td>23–24</td>
<td>1981</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Feb 22</td>
</tr>
<tr>
<td></td>
<td>COPT</td>
<td>Jun</td>
<td>22</td>
<td>1981</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Feb Feb</td>
</tr>
<tr>
<td>1</td>
<td>GATE</td>
<td>Sep</td>
<td>12 (N)</td>
<td>1974</td>
<td>10–24</td>
<td>17</td>
<td>16</td>
<td>17</td>
<td>1–2</td>
</tr>
<tr>
<td>2</td>
<td>GATE</td>
<td>Sep</td>
<td>12 (S)</td>
<td>1974</td>
<td>23–24</td>
<td>25–26</td>
<td>17</td>
<td>17</td>
<td>22–23</td>
</tr>
<tr>
<td>8</td>
<td>GATE</td>
<td>Feb</td>
<td>22–23</td>
<td>1993</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>9</td>
<td>GATE</td>
<td>Feb</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>10</td>
<td>PRE-</td>
<td>Jun</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>11</td>
<td>STORM</td>
<td>Jun</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>12</td>
<td>STORM</td>
<td>Jun</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Outflow characteristics

- **Depth in wake—** $Z_k (m)$: 900/2700$^a$, 2000/3000$^b$, n/a$^c$, 333
- **Change in theta at leading edge (K)**: $-6.0$, $-4.0$, $-1.9$, $-1.2$, $-3.3$, $-2.2$, $-2.0$, $-2.0$, $-0.3$, $-2.4$, n/a$^a$, n/a$^b$, $-1.7$
- **Stability in wake (K km$^{-1}$)**: 2.5, n/a$^a$, n/a$^b$, 11.4, 6.7, 6.7
- **Wake sounding time (UTC)**: 0238, 0849, 0240, 0440, 1515, 1500, 0624, 0440, 1515, 1500, 0624, 0440, 1515, 1500, 0624, 0440, 1515, 1500, 0624, 0440
- **Wake sounding time (ST)**: 0238, 0849, 0240, 0440, 1515, 1500, 0624, 0440, 1515, 1500, 0624, 0440
- **Time since onset of event (hh:mm)**: 2:53, 4:19, 2:24, 1:40, 3:24, 3:10, 1:30, 2:10, 5:00, 1:50, 0:27$^b$
- **Distance behind leading edge (km)**: 140, 300, 117, 60, 220, 55, 74, n/a$^d$, 297, n/a$^a$, 100, 20

---

$^a$ The case is a composite case; thus date is a composite and data shown are for a composite system.
$^b$ Data were either not available or were not readily determinable from available information.
$^c$ Initial wake depth due to convective-scale downdrafts.
$^d$ Subsequent wake depth after the combination of convective-scale and mesoscale downdrafts.
$^e$ Average values from a number of observations; the number of observations used varies from case to case.
$^f$ In most cases, these data were calculated using a time-space conversion; distance is along the axis of squall line movement.
$^g$ Time difference is that between the time of a presquall sounding composite and the time of a postsquall sounding composite; the actual start time of the event is unknown.
$^h$ Low-level sounding data were taken by aircraft 20 km behind the leading convective line at an unknown time; a space–time conversion was done to get an approximate time differential corresponding to the amount of time it would take for the squall line leading edge to move 20 km beyond a given point.
Table 4. Table of characteristics of the convective wakes modeled in this study. As the northern and southern portions of the observed wake associated with the 12 Sep 1974 GATE squall line exhibited different characteristics (Johnson and Nicholls 1983), these were each simulated separately.

<table>
<thead>
<tr>
<th>Case</th>
<th>1</th>
<th>2</th>
<th>3a</th>
<th>3b</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
<th>9</th>
<th>10</th>
<th>11</th>
<th>12</th>
</tr>
</thead>
<tbody>
<tr>
<td>Expt</td>
<td>COPT</td>
<td>COPT</td>
<td>GATE</td>
<td>GATE</td>
<td>PRE-</td>
<td>STORM</td>
<td>PRE-</td>
<td>STORM</td>
<td>ABLE-2B</td>
<td>VIMHEX-</td>
<td>TAMEX</td>
<td>TAMEX</td>
<td>EMEX</td>
</tr>
<tr>
<td>Day(s)</td>
<td>23±24</td>
<td>22</td>
<td>12 (N)</td>
<td>12 (S)</td>
<td>4±5</td>
<td>10±11</td>
<td>23±24</td>
<td>25±26</td>
<td>17*</td>
<td>16</td>
<td>17*</td>
<td>1±2</td>
<td>22±23</td>
</tr>
<tr>
<td>Modeled characteristics</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$Z_k$ (m)</td>
<td>259</td>
<td>197</td>
<td>315</td>
<td>234</td>
<td>303</td>
<td>132</td>
<td>152</td>
<td>360</td>
<td>225</td>
<td>227</td>
<td>239</td>
<td>279</td>
<td>229</td>
</tr>
<tr>
<td>change in $\theta$ at front (K)</td>
<td>-2.1</td>
<td>-0.9</td>
<td>-1.9</td>
<td>-2.9</td>
<td>-1.4</td>
<td>-3.8</td>
<td>-6.7</td>
<td>-1.2</td>
<td>-3.5</td>
<td>-2.7</td>
<td>-2.9</td>
<td>-2.1</td>
<td>-2.1</td>
</tr>
<tr>
<td>change in q at front (g kg$^{-1}$)</td>
<td>-3.3</td>
<td>-1.9</td>
<td>-2.0</td>
<td>-0.8</td>
<td>-2.6</td>
<td>-2.1</td>
<td>0.9</td>
<td>-2.9</td>
<td>-1.5</td>
<td>-1.0</td>
<td>-0.2</td>
<td>-1.2</td>
<td>-0.8</td>
</tr>
<tr>
<td>gust front speed (m s$^{-1}$)</td>
<td>13.4</td>
<td>11.5</td>
<td>23.0</td>
<td>24.4</td>
<td>9.4</td>
<td>6.7</td>
<td>9.3</td>
<td>5.2</td>
<td>7.9</td>
<td>13.9</td>
<td>13.5</td>
<td>15.9</td>
<td>10.7</td>
</tr>
<tr>
<td>cloud-top height (km)</td>
<td>12.5</td>
<td>8.9</td>
<td>12.7</td>
<td>10.8</td>
<td>9.0</td>
<td>10.6</td>
<td>8.7</td>
<td>12.8</td>
<td>10.7</td>
<td>10.8</td>
<td>9.0</td>
<td>12.8</td>
<td>12.8</td>
</tr>
</tbody>
</table>

* The case is a composite case; thus date is a composite and data shown are for a composite system.

5. Modeling results

a. QVF results

To assess the effectiveness of the QVF scheme in replicating observed squall line-induced wakes in the single-column version of CCM3, the features of the observed wakes in Table 3 are now compared to the characteristics of the wakes produced in the model simulations. Results from each of the model runs are presented in Table 4, which contains simulated wake depths, changes in potential temperature and mixing ratio across the leading edges of the wakes, gust front speeds, and convective cloud-top heights.

The changes in potential temperature across the leading edges of the modeled wakes were also greatly underestimated, with drops in $\theta_u$ at least 2 K smaller than those observed in most cases. To provide some insight as to why this bias occurred, we present the results of some statistical analyses of the relationships between the observed virtual potential temperature ($\theta_v$) drops at the leading edges of the wakes, the modeled $\theta_v$ drops at the observed virtual potential temperature (in $\theta_v$) across the gust fronts, and the modeled $\theta_v$ differences between the environmental air and the downdraft air detraining at the top of the wakes. Three independent analyses were made, each examining the statistical relationship between two of the three parameters given above.

The changes in potential temperature across the leading edges of the modeled wakes were also greatly underestimated, with drops in $\theta_u$ at least 2 K smaller than those observed in most cases. To provide some insight as to why this bias occurred, we present the results of some statistical analyses of the relationships between the observed virtual potential temperature ($\theta_v$) drops at the leading edges of the wakes, the modeled $\theta_v$ drops at the observed virtual potential temperature (in $\theta_v$) across the gust fronts, and the modeled $\theta_v$ differences between the environmental air and the downdraft air detraining at the top of the wakes. Three independent analyses were made, each examining the statistical relationship between two of the three parameters given above.

The changes in potential temperature across the leading edges of the modeled wakes were also greatly underestimated, with drops in $\theta_u$ at least 2 K smaller than those observed in most cases. To provide some insight as to why this bias occurred, we present the results of some statistical analyses of the relationships between the observed virtual potential temperature ($\theta_v$) drops at the leading edges of the wakes, the modeled $\theta_v$ drops at the observed virtual potential temperature (in $\theta_v$) across the gust fronts, and the modeled $\theta_v$ differences between the environmental air and the downdraft air detraining at the top of the wakes. Three independent analyses were made, each examining the statistical relationship between two of the three parameters given above.
the gust fronts. This result implies that the cumulus parameterization provides the wake scheme with air of reasonably unbiased thermodynamic properties. Lastly, the third analysis, which related the modeled differences in \( \theta_c \) between air in the presquall environments and the downdrafts, and the modeled drops in \( \theta_c \) at the gust fronts, revealed that the latter were, on average, 1.5 K smaller than the former (a \(-33\% \) bias). This result, in conjunction with that of the second analysis given above, suggests that the QYF scheme warms the wake air too quickly, most likely through the overestimation of surface and wake-top-entrainment fluxes. Given the magnitudes of these biases, it is probably fair to say that the wake parameterization accounts for the largest portion of the bias in the modeled drops in \( \theta_c \) (and thus \( \theta \)) at the gust fronts.

However, these statistical biases are not sufficient in and of themselves to permit a useful assessment of the accuracy of the QYF scheme at portraying the drops in \( \theta \) at the gust fronts of the convective wakes simulated in this study. To complete the picture, one must also examine the correlations between the parameters discussed in the preceding paragraph. The first analysis, despite the model bias toward smaller values of \( \Delta \theta_c \) at the gust fronts, revealed that the observed and modeled drops in \( \theta_c \) across the gust fronts were at least moderately correlated with a correlation coefficient (\( r \)) of 0.54. Thus, the QYF scheme exhibited at least some skill in simulating the case-to-case variations in the observed \( \theta_c \) (and thus \( \theta \)) drops at the gust fronts. In contrast, the second analysis showed that the observed drops in \( \theta_c \) at the gust fronts and the modeled differences in \( \theta_c \) between air in the presquall environments and the downdrafts were poorly correlated with \( r = 0.18 \). This result suggests that, although the cumulus parameterization supplies the QYF scheme with downdraft air of relatively unbiased \( \theta_c \), it has very little skill in replicating the influence of the case-to-case variations in the presquall environments on the downdrafts and, thus, the wakes. Finally, the last analysis, which related the modeled differences in \( \theta_c \) between air in the presquall environments and the downdrafts and the modeled drops in \( \theta_c \) at the gust fronts, demonstrated that these two parameters were rather strongly correlated with an \( r \) of 0.87. In light of the moderate correlation between the observed and modeled drops in \( \theta_c \) at the gust fronts and the poor correlation between the observed drops in \( \theta_c \) at the gust fronts and the modeled differences in \( \theta_c \) between air in the presquall environments and the downdrafts, this result suggests that, although the QYF scheme may cause a warm bias in wake temperatures, it improves the correlation between the \( \theta_c \) characteristics of the downdraft air and the observed \( \theta_c \) drops at the gust fronts; that is, it acts to improve upon the response of the cumulus parameterization to the case-to-case variations in the presquall environments.

The bias toward weaker potential temperature differences across the gust fronts would contribute to the slightly lower-than-observed gust front speeds obtained for most of the simulated convective outflows, because the gust front speed in the QYF scheme is governed by gravity current theory and is thus proportional to the square root of the virtual potential temperature difference across it. In contrast, the previously mentioned assumption that the wake propagates in the mean cloud-layer wind direction could lead to overestimations in the gust front propagation speeds. These competing factors apparently result in a lack of skill (\( r = -0.06 \)) in the modeled gust front propagation speeds. As mentioned in section 3, the Zhang–McFarlane cumulus parameterization does not take into account the low-level forcing provided by gust fronts and other boundary layer triggering mechanisms. Thus, the anomalously low (bias = 25%) and relatively unskilled (\( r = 0.44 \)) deep convective cloud-top heights obtained in the simulations may indicate that this scheme is biased toward lower cloud-top heights when simulating squall line events.

As was the case with the modeled changes in potential temperature across the gust fronts, the modeled changes in mixing ratio across these same features were typically smaller than the observed changes, averaging 0.9 g kg\(^{-1}\) less than the observed values. This error represents a \(-36\% \) bias from the observed values, a number strikingly similar to the \(-38\% \) bias of the modeled \( \theta_c \) drops from the observed \( \theta_c \) drops at the gust fronts. The correlation coefficient between the observed and modeled values of the change in \( q \) at the gust fronts was 0.57, indicating that the QYF scheme had a moderate amount of skill in replicating the case-to-case variation of the observed changes in \( q \) across the gust fronts. This value is again very close to that obtained for the correlation of the modeled \( \theta_c \) drops to the observed \( \theta_c \) drops at the gust fronts (\( r = 0.54 \)). These results suggest that, as was the case with the potential temperatures, the smaller-than-observed mixing ratio changes across the gust fronts may well be due to overestimations of the surface and wake-top-entrainment fluxes, as such errors would lead to a more rapid recovery (i.e., moistening) of the wake. In addition to this factor, the weaker mixing ratio changes across the gust fronts may also result in part from the lack of a mesoscale downdraft parameterization, as mesoscale downdrafts typically are responsible for the entrainment of drier air into wakes (Zipser 1969, 1977) and may be the cause of the secondary minimum in \( q \) that is commonly observed toward the rear of these features (Zipser 1977; Fitzjarrald and Garstang 1981; Johnson and Nicholls 1983). It should be noted here that the QYF scheme is currently unable to resolve such a secondary minimum in \( q \), as it is currently assumed that both potential temperatures and mixing ratios increase linearly across the wakes from front to rear.
b. QYF wind and shear formulation sensitivity

As discussed in section 3b(3), two additional simulations were conducted to assess the sensitivity of the QYF wake model to details of the wind and shear effect formulations. The initial sensitivity test on the QYF wake model altered only the equations related to the effect of environmental wind on gust front propagation speed, head height, and gust front updraft speed. Because of the time-integrated effect of the resulting change in propagation speed, wake depth also changed. That change acts through the QYF formulation to change the head height as well. Thus, the formulation used for the effect of environmental wind speed affects head height both directly and indirectly via its effect on propagation speed. The observed propagation speed for the TOGA COARE test case was 12.0 m s\(^{-1}\) while the basic QYF formulation yielded 10.7 m s\(^{-1}\) and the revised LM-based formulation yielded 10.0 m s\(^{-1}\). The effect of the LM-based wind speed effect formulation led to more rapid wake propagation speed formulation caused virtually no difference in wake behavior of approximately the same magnitude as those caused by altering the wind effect formulation alone. The addition of the shear effect to the propagation speed formulation caused virtually no difference until the wake depth began to decrease rapidly after 12 h of simulation. Thereafter, it resulted in a much steadier propagation speed of 10.0 m s\(^{-1}\), whereas the LM-based results without the shear effect formulation varied slowly between 9 and 11 m s\(^{-1}\). Again, the indirect effect on the wake depth was more substantial than the direct effect on the gust front propagation speed. While the shear effect on wake depth was minor during the first 12 h of the simulation, it doubled the wake depth in the last 24 h thereby bringing the wake depth into better agreement with the observations (Table 3) in the latter half of the simulation. Head height varied proportionally with wake depth, suggesting that, as with wind speed, the direct affect of shear on head height was not as great as the indirect affect via its alteration of propagation speed and thus wake depth.

6. Summary and conclusions

A convective wake parameterization (the QYF scheme) developed and incorporated into the single-column version of the NCAR Community Climate Model CCM3 by Qian et al. (1997) was tested using observational data from 12 squall line cases to determine whether it could successfully replicate convectively driven wakes and their effects in a GCM. The squall line cases, all of which were chosen from those well documented in the observational literature, were selected from six geographically and meteorologically diverse regions so that the parameterization could be tested in a wide array of convective environments. In each simulation, the initial atmospheric conditions were provided by an observed presquall sounding. The model was then run for a 48-h period, and the key characteristics of the modeled versus the observed wakes were compared. Results showed that the modeled wakes were biased too shallow, too warm, and too moist, despite the fact that the cumulus parameterization used in this study provided the wake scheme with air of approximately unbiased temperature and humidity. As a result, the wakes propagated at speeds that were somewhat lower than those observed. However, it was also demonstrated that the wake scheme acted to significantly improve the response of the cumulus parameterization to case-to-case variations in the presquall environments; that is, it improved upon the correlation between the thermodynamic characteristics of the modeled downdrafts and the observed thermodynamic changes across the leading edges of the wakes.

The observed biases toward shallower, warmer, and moister wakes in the model simulations likely resulted...
from a combination of factors. The shallow wake depths probably resulted from the scheme’s assumption that convective wakes consist of a mixed layer capped by a sharp inversion. This simplified stability profile differs from nature, in which convective outflows typically exhibit at least some degree of stability and the capping inversion is often of considerable depth. The excess warmth and moisture in the wakes was most likely caused by overestimations in the surface and wake-top-entrainment fluxes. The existence of such errors is not too surprising considering the relatively simple flux formulations implemented in the original QYF wake parameterization. The lack of a mesoscale downdraft parameterization also probably contributed to the higher-than-observed values of mixing ratio found in the modeled wakes, as such downdrafts are often responsible for the entrainment of drier air into convective outflows from aloft. The warmer-than-observed wakes probably contributed to the somewhat lower-than-observed gust front speeds, although in some cases, this effect may have been somewhat obscured, if not entirely counteracted, by an opposing effect resulting from the QYF scheme’s assumption that the squall line’s downdraft mass flux source propagates in the cloud-layer mean wind direction. Such an assumption differs from nature, in which squall line systems (and their attendant outflows) are typically observed to be oriented perpendicular to the low-level wind shear and therefore are only affected by the component of the cloud-layer wind that is perpendicular to them. Thus, the assumption used in the wake scheme can lead to overestimations in the gust propagation speed in cases where the mean cloud-layer wind is not oriented normal to the squall line.

Because, however, the main goal of the QYF parameterization was to successfully resolve the effects of squall line–induced convective wakes in a GCM, these problems do not make the scheme unserviceable, as they do not preclude it from replicating the gust fronts and generating wake-induced increases in surface fluxes over appropriate timescales in the simulations. In addition, the wake scheme’s ability to significantly improve upon the response of the cumulus downdraft parameterization to case-to-case variations in the presquall environments further suggests that the modeling approach tested here has considerable merit. In conjunction with these successes, the problems discussed above do not therefore represent the failure of the QYF approach; rather, they indicate that there is room for significant improvement in some aspects of the implementation.

Therefore, we offer the following suggestions for improving the current scheme. First, to ameliorate the bias in gust front speeds, squall line orientations should be incorporated via a parameterization such as that of Alexander and Young (1992) so that the squall line speed is calculated using only the component of the mean cloud-layer wind that is perpendicular to the squall line. In addition to improving the modeled gust front speeds, this change would advance the ability of the scheme to correctly estimate the upward vertical velocities produced at the gust fronts.

Second, the effects of wind shear and stability of the preconvective environment should be accounted for in the model equations for wake depth and gravity current propagation speed. This improvement would make the QYF wake parameterization more responsive to the full range of environmental forcing conditions under which mesoscale convective systems occur. While prior modeling studies and the sensitivity tests reported above demonstrate the potential importance of the shear effects, the formulation used in our sensitivity tests was based on the as yet incomplete data available in the literature. Thus, we recommend redevelopment of these relationships when nonhydrostatic modeling or laboratory results become available that fully document the behavior of gravity currents under the interacting influences of varying gravity current thermodynamics, environmental wind, environmental shear, and environmental stability. It is expected from the Buckingham Pi theory of fluid dynamics that the final relationships will depend on nondimensional ratios of these quantities. These relationships may prove to be more complex than those used in this work as four nondimensional groups would be involved.

Third, a mesoscale downdraft parameterization should be developed and incorporated into the scheme so that drier air can be entrained into wakes at their tops, as is commonly observed in nature. Such an implementation, while a major undertaking, should alleviate to some degree the problem of overly moist wakes shown in this study. Finally, more sophisticated methods should be used for the calculation of the surface and wake-top-entrainment fluxes so as to reduce the rate bias in wake recovery processes. This modification would improve the scheme’s skill at modeling the thermodynamic changes across the gust fronts and therefore would further enhance its ability to improve upon the response of the cumulus parameterization to case-to-case variations in the presquall environmental conditions.

Acknowledgments. The authors would like to extend heartfelt thanks to Dr. Melville Nicholls, Dr. Jeffrey Halverson, Dr. Michael Garstang, Dr. William Frank, and Mr. Houjun Wang for providing sounding data used in this study. They would also like to express their sincere gratitude to Stanley Trier for generously providing a copy of the paper by Jorgensen et al. (1997) prior to its date of publication. Dr. Michael Fritsch, Dr. Johannes Verlinde, and two anonymous reviewers provided many helpful suggestions. Funding for this research, which was conducted as the lead author’s M.S. project while at The Pennsylvania State University, was provided by the Department of Energy (Grant DE-
FG02-94ER61773) and the National Science Foundation (Grant ATM-9414322).

REFERENCES


Sommeria, G., and J. Testud, 1984: COPT 81: A field experiment designed for the study of dynamics and electrical activity of