The importance of the boundary layer parameterization in the prediction of low-level convergence lines

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Abstract

We investigate the importance of the boundary-layer parameterization in the numerical prediction of low-level convergence lines over northeastern Australia. High-resolution simulations of convergence lines observed in one event during the 2002 Gulf Lines Experiment are carried out using the Pennsylvania State University/National Center for Atmospheric Research Mesoscale Model (MM5). Calculations using five different parameterizations are compared with observations to determine the optimum scheme for capturing these lines. The schemes that give the best agreement with the observations are the three that include a representation of counter-gradient fluxes and a surface-layer scheme based on Monin-Obukhov theory. One of these, the MRF-scheme is slightly better than the other two, based on its ability to predict the surface pressure distribution. The findings are important for the design of mesoscale forecasting systems for the arid regions of Australia and elsewhere.
1 Introduction

In the Gulf of Carpentaria region of northeastern Australia, low-level convergence lines occur with great regularity at certain times of the year (Goler et al. 2006, Smith et al. 2006, Weinzierl et al. 2007). During the dry season, the lines are often marked by cloud lines such as the morning glory and the North-Australian Cloud Line (NACL). 'Morning glory' refers to a low-level roll-cloud line or a series of such lines which arrive early in the morning in the southern gulf region. In this case the convergence line corresponds to a bore-like disturbance. Such disturbances occur elsewhere in the world, often in association with cold fronts, or following the collision of gravity-current-like flows such as sea breezes or thunderstorm outflows (Haase and Smith 1984, Smith, 1986, Hoinka and Smith, 1988). Their occurrence poses a threat to aircraft when taking off or landing, especially where they are not marked by cloud (Christie and Muirhead, 1983). Other reports of cloud lines similar to the morning glory have been given by Clarke (1986) and a few noteworthy observations in other parts of the world include the fog waves over Berlin (Egger, 1985) and the wave disturbance which occurred over southern England in 1914 (Geophysical Memoirs 1914).

The NACL is a line of convective cloud that forms along the west coast of Cape York Peninsula early in the evening and moves westwards across the Gulf of Carpentaria during night and following day. In this case the convergence line corresponds to the leading edge of a gravity current (Thomsen and Smith 2006, henceforth TS06). During the dry season the clouds are mostly capped by the trade-wind inversion at about 3 km, but during the moist season, they may develop as lines of thunderstorms that pose a significant forecasting
problem in the region. A recent review of the various cloud lines is given by Reeder and Smith (1998).

The possibility of forecasting the convergence lines was examined by Jackson et al. (2002) using the mesoscale version (mesoLAPS) of the Australian Bureau of Meteorology’s Limited Area Prediction System. Their study was seen as a first step towards being able to forecast the formation and movement of lines of thunderstorms that the convergence lines sometimes trigger. Unfortunately, only satellite images were available for verification of the model forecasts, a fact that prompted the organization of the Gulf Lines field EXperiment (GLEX). Two phases of the experiment were carried out, the first in the period September-October 2002 and the second in November-December 2005. The overall aim of GLEX was to document the convergence lines and their accompanying clouds in as much detail as possible and to provide a suitable data base with which numerical predictions of the lines could be assessed. Details of the 2002 experiment are described in papers by Goler et al. (2006), Smith et al. (2006) and Weinzierl et al. (2007).

High-resolution numerical simulations of two of the most interesting events from GLEX are described by TS06. For that study, which used the MM5 model, it was necessary to determine the most appropriate boundary-layer scheme to use from the many schemes available in the model. The choice of parameterization has a significant impact on the simulation since the processes leading to the generation of the lines, namely the sea-breeze circulations around Cape York Peninsula, occur within the boundary layer. Although morning-glory cloud lines are unique in that they occur relatively frequently in a particular geographical location, the generation of such disturbances is not confined to the Gulf-of-Carpentaria region.
Moreover, the sea-breeze circulations in this area are representative of those in a semi-arid, coastal tropical climate. For these reasons, the results of our study are relevant to mesoscale simulations for many other regions.

Several recent studies have examined the capabilities of the boundary-layer parameterizations available in MM5 in different situations. Tombrou et al., 2007 describe simulations using the Blackadar, Gayno-Seaman, MRF and Pleim-Xiu schemes. The MRF-scheme was applied both in its original form and in a modified form more suitable for urban environments. Tombrou et al. examined a case for an urban area in a semi-humid maritime subtropical climate and found that during night-time stable conditions there is a need for improvements in all the parameterizations. However, the overall performance of schemes in predicting the heights of the boundary layer during day-time was found to be close to the observations. Lee et al., 2005 focused on the night-time stable conditions in a middle-latitude continental case employing only the Blackadar-scheme, the MRF-scheme and a version of the latter scheme with a modified night-time module. They found that the MRF- and Blackadar-schemes over-predict the turbulent diffusion of heat during night-time stable conditions and thereby the height of the mixed layer. Berg and Zhong, 2005 compared the Blackadar, Gayno-Seaman and the MRF-scheme in two cases, one being the same as in Lee et al. and the other being in a subtropical continental environment. They found that the mixed-layer depths were over-predicted by the MRF-scheme, under-predicted by the Gayno-Seaman, and were closest to those observed using the Blackadar-scheme. The surface sensible-heat flux was over-predicted by all schemes, an aspect attribute to inappropriate values for the soil moisture. Deng and Stauffer, 2005 focused their study mainly on the Gayno-Seaman scheme.
and a modified version thereof with the vertical mixing of turbulent kinetic energy enhanced. A few calculations were carried out also using the MRF-scheme. They selected a middle-latitude case in a maritime warm-temperate climate. They found that the MRF-scheme over-predicted mixed-layer heights. The most comprehensive assessment of schemes was made by Zhang and Zheng (2004), who examined the Burk-Thompson, Eta, MRF, Gaynor-Seaman, and Blackadar-schemes. They describe model results for a subtropical continental case. Their methodology provided inspiration for our work and therefore Zhang and Zheng’s study is the most relevant to our paper. We discuss this paper in more detail in Section 4. None of the cases described in any of these studies addresses climatic conditions similar to those in our case.

This paper presents a summary of the results of our investigation. We begin with a brief overview of the five schemes investigated and compare the model predictions using them with observations made for one significant event, that of 9 October 2002. On this day, four disturbances were observed as seen in the satellite image shown in Fig. 1: these include morning glories moving from the northeast, the southeast and the south as well as an NACL. This event provides not only a suitable challenge for the model, but is representative of other GLEX cases. Four other GLEX cases are discussed in Thomsen (2006). The processes leading to the formation of the convergence lines and their behaviour were very similar in all cases, suggesting that the boundary-layer parameterizations behave similarly as well.

The paper is organized as follows. Section 2 contains a brief description of the model configuration including two land-surface schemes which interface with particular boundary-layer parameterizations. In the subsections of Section 2 we give an overview of five of the boundary-
layer schemes in MM5 and follow in Section 3 with a comparison of calculations using these schemes. In Section 4 we attempt to isolate the properties of the more superior schemes that are responsible for their skill and in Section 5 we present the conclusions.

2 The model configuration

Stull (1988) defines the planetary boundary layer as that part of the troposphere that is directly influenced by the presence of the earth’s surface and which responds to surface forcing with a timescale of about an hour or less. Over dry land surfaces in the tropics, the boundary layer can be as deep as 4 km. In our model, there are 23 $\sigma$-levels providing relatively high resolution in the boundary layer. The 17 below 4 km are centered at heights of approximately: 18, 54, 109, 182, 157, 332, 445, 599, 754, 994, 1322, 1662, 2016, 2383, 2767, 3168, and 3588 m. Thus the layer thickness in the lowest 3 km vary from $\sim$40 m to $\sim$400 m and increase with height.

The calculations are carried out on two horizontal domains shown in Fig. 2. The outer domain has $221 \times 221$ grid points with a horizontal grid size of 9 km and the inner domain has $301 \times 301$ points with a grid size of 3 km. The terrain land use and topography is taken from the United States Geological Survey data set implemented in MM5 and has a 5’ resolution in the outer domain and 2’ resolution in the inner domain. The time step is chosen as 27 s for the outer domain and 9 s for the inner domain. The coupling of both domains is done every time step of the outer domain.
The Grell cumulus parameterization scheme (Grell, 1993) is used in the outer domain, but no such scheme is used in the inner domain as the phenomena of interest involve predominantly dry processes. The Dudhia scheme is chosen as a parameterization for the microphysics (Dudhia, 1989). The short- and long-wave cloud and ground radiation scheme takes into account diurnal variations. Analysis data from the European Centre for Medium Range Weather Forecasts (ECMWF) with a horizontal resolution of 0.25° are used to provide initial and boundary conditions for the calculations.

The most energetic boundary layer eddies are tens of metres to 1-2 km in size in either the horizontal or vertical direction. The smaller eddies are not adequately resolved by the foregoing horizontal and vertical resolution, which is typical for this type of model. In order to compensate this lack of resolution, a parameterization of the boundary layer is required. Five of the seven such parameterizations available in MM5 are investigated here. Those not considered are the Pleim-Xiu scheme, which is unavailable in a suitable version (a massive-parallel version does not exist and the scheme is too demanding of memory for a single-processor run) and the Bulk scheme, which led to numerical instability. The questions addressed below are: how do the remaining schemes compare and which one(s) have the most skill in forecasting low-level convergence lines over northeastern Australia?

In contrast to the simulations described in TS06, the ones here are carried out without a representation of moist vertical diffusion and without a soil-moisture scheme. This is necessary since only a few boundary-layer parameterizations in MM5 support both these schemes. Moreover we wish to isolate effects resulting solely from the choice of parameterization. Without the use of a soil moisture scheme, the soil moisture is held constant. The
difference in runs using, or not using, this scheme can result only from changes of the soil moisture during the integration time. The average moisture availability in the inner domain reduces only little (from about 0.45 to 0.44) in 24 h in the configuration used by TS06 (see Thomsen 2006, page 104). The moist vertical diffusion option has its main impact in cloudy environments, in contrast to the case discussed here. The influence of this option has been assessed in Thomsen (2006, page 77) and was found to be negligible. Thus the present study is of direct relevance to that in TS06.

Each parameterization requires a land-surface scheme of which four are available in MM5. These have various levels of sophistication, but not all of them can be interfaced with all the parameterizations. The two that interface with several parameterizations are the force/restore (Blackadar) scheme and the five-layer soil model. The former treats the soil as a single slab, which is assumed to span the depth over which there is a significant diurnal temperature variation (approximately 10-20 cm). The slab temperature is based on the energy balance at the surface and the substrate-temperature is fixed. The latter predicts the temperature in layers of depth 1, 2, 4, 8 and 16 cm using a vertical diffusion equation and assuming a fixed substrate temperature at below the 16 cm deep layer. The thermal inertia is derived in a similar way to the force/restore scheme except that the diurnal temperature variation is computed separately in the different layers, allowing for a more rapid response of the surface temperature. The five-layer soil model is computationally more stable and allows for a larger time step than the force/restore scheme. Both schemes use a "look-up" table for the surface characteristics like albedo, roughness, emissivity and thermal inertia. These quantities are held constant during the model integration.
All simulations start at 1000 EST on 08 October and the integration time is 24 h. We review now the main characteristics of the five boundary layer schemes investigated here.

2.1 The MRF scheme

The MRF scheme was developed initially for the United States National Centers for Environmental Prediction (NCEP) Medium Range Forecast system by Hong and Pan (1996) and was implemented in MM5 by Dudhia and Hong, as stated in the corresponding piece of code. This scheme applies nonlocal $K$-mixing for potential temperature and water vapour mixing ratio in the mixed layer, moist vertical diffusion in clouds, and local $K$-mixing above clouds. The nonlocal mixing is implemented following a nonlocal diffusion concept by Troen and Mahrt (1986). The term ”nonlocal” as it appears in the literature is a little misleading. It refers here to the flux of a particular quantity between adjacent layers calculated by applying a correction term for the local gradient. This correction term incorporates the contribution of the large-scale eddies to the total flux, thus allowing for counter-gradient fluxes. The eddy exchange coefficients, $K$, are calculated from a prescribed profile function of boundary layer heights and scale parameters. The surface fluxes are calculated in the same way as in the Blackadar scheme. The four boundary-layer stability states are determined using only the bulk Richardson number: In the night-time stable state ($R_i b \geq 0.2$), all scaling parameters at the surface and all turbulent fluxes are set equal to zero. In the nocturnal damped mechanical turbulent state ($0 < R_i b < 0.2$), the scaling parameters are determined by $R_i b$ and $L$ (the Monin-Obukhov length). In the nocturnal, forced-convection state ($R_i b = 0$), the
scaling parameters are determined by the local Richardson number $Ri$ only (local $K$-theory). When $Ri_b < 0$, the daytime module is used and the counter-gradient terms take effect.

2.2 The Blackadar scheme

The Blackadar scheme (Blackadar 1976) was first introduced as a representation of the nocturnal boundary layer. The version used here was extended by Blackadar (1978, 1979) and Zhang and Anthes (1982) to account also for the daytime boundary layer. The present scheme has two modules: one for the day-time convective state and one for the night-time stable states. The module that is invoked depends on the vertical temperature gradient in the lowest model layer and on the magnitude of $|z_h/L|$, where $z_h$ is the height of the mixed layer and $L$ is the Monin-Obukhov length. The vertical temperature gradient in the lowest model layer is characterized by the bulk Richardson number $Ri_b$. In the nocturnal module, the atmosphere is assumed to be stably stratified, or at most slightly unstable, and a first-order closure scheme is used. To account for the largest gradients, which generally occur in the lowest layer, a surface layer of 10 m depth is used, based on Monin-Obukhov similarity theory. The module for the nocturnal boundary layer is subdivided into three stability states, which are the same as those described in the MRF-subsection. The night-time stable state is assumed when $Ri_b \geq 0.2$, the damped mechanical turbulent state when $0 < Ri_b < 0.2$ and the forced convection state when $Ri_b \leq 0$ and $|z_h/L| \leq 1.5$. The daytime module allows for free convection and is active when $Ri_b \leq 0$ and $|z_h/L| \geq 1.5$. Discrete matrix forms of nonlocal theory are then used to parameterize convective circulations. In nonlocal theory,
the vertical transfer of momentum, heat and moisture is not determined by the local mean
gradient, but by the thermal structure of the whole mixed layer. The Blackadar scheme is
the only one of those studied that applies transilient mixing in any of the stability states, i.e.,
which allows mixing between non-adjacent vertical layers. It is also the only boundary-layer
parameterization in MM5 that works with both the force/restore- and the 5-layer surface
scheme.

2.3 The Mellor-Yamada-based schemes

All three Mellor-Yamada-based schemes described here use a one-and-a-half-order closure,
which refers to level-2.5 in the Mellor-Yamada hierarchy (Mellor and Yamada, 1974). A
comprehensive summary of the different closures is given by Stull (1988). In a one-and-a-half-order closure the eddy exchange coefficient of an adiabatically conserved quantity is
related to the predicted turbulent kinetic energy (TKE). This kind of scheme is often referred
to as a "TKE scheme".

2.3.1 The Gayno-Seaman scheme

The Gayno-Seaman scheme is a level-2.5 Mellor-Yamada-based scheme. In order to repre-
sent cloud water in a consistent way, the model uses liquid water potential temperature,
$\theta_L$, and total water mixing ratio, $q_T$, which are both conserved thermodynamic variables in
non-precipitating clouds (Betts, 1973). The turbulent vertical transport of $\theta_L$ is parameter-
ized using a counter-gradient heat flux term, based on the sensible heat flux, boundary layer
height, and the convective vertical velocity scale (Therry and Lacarrere, 1983). The Gayno-Seaman scheme is the only one in MM5 for which TKE is treated as a prognostic quantity and for which TKE is advected. The scheme interfaces with the 5-layer soil model. The surface fluxes for the Gayno-Seaman scheme are based on the same Monin-Obukhov similarity parameterization used with the Blackadar scheme and the stability states are determined using the same criteria (Shafran et al., 2000). The boundary-layer heights are calculated for all stability states except for the stable state.

2.3.2 The Burk-Thompson scheme

The Burk-Thompson scheme was originally designed for the marine boundary layer (Burk and Thompson, 1982) and incorporated both level 2.5 and 3.0 schemes. The early versions of the scheme, which were implemented in the US-Navy’s Navy Operational Regional Atmospheric Prediction System (NORAPS), apply a higher vertical resolution than that in the model and include a counter-gradient flux term for temperature. These two features are not implemented in MM5 and only the level 2.5 version is available. The Burk-Thompson-scheme has its own force-restore ground temperature scheme and does not interface with any other MM5 soil models or land use schemes. The Louis (1979) scheme is used to parameterize the surface layer and applies an empirical fit to the Businger profile functions. Neither horizontal advection, diffusion, or vertical advection of TKE are included in this scheme.
2.3.3 The Eta-scheme

The Eta-scheme was originally implemented by Janjić (1990, 1994) in the NCEP Eta (step-mountain) model. It is based on the level 2.5 Mellor-Yamada scheme above the surface layer. The treatment of the surface layer is different over land and over the sea. In the original version, a Mellor-Yamada level-2 scheme was used for the surface layer, but in the MM5 version, the surface fluxes are calculated according to similarity theory. As in the Burk-Thompson scheme, horizontal advection, diffusion, and vertical advection of TKE are ignored. The Eta-scheme interfaces with the MM5 5-layer soil model, a requirement arising from the long time step of the Eta-scheme.

3 Results

A prerequisite for the TS06 study was to determine the optimum boundary-layer scheme for forecasting low-level convergence lines that develop over northeastern Australia. It was necessary to compare the predictions using the different schemes and to determine the sensitivity of the forecasts to the choice of scheme. We report on these questions below.

A qualitative assessment of the model skill is provided by comparing the location and orientation of the convergence lines in the model with the cloud lines observed in satellite imagery. Surface pressure is an appropriate quantity to assess the quality of the model results because surface observations during GLEX showed that the passage of the cloud lines coincides with marked change in the wind speed and direction and in the surface pressure (TS06, Fig. 4).
On the other hand there is no coherent signature in the temperature or dewpoint. Figure 3 shows the sea-level pressure at Karumba during in the simulation. The peak at about 0600 EST corresponds to either the northeasterly or southerly morning glory or both, since both lines arrived at Karumba at nearly the same time.

A quantitative measure of the model skill is obtained by calculating a correlation coefficient between the model predicted surface pressure and that observed. The correlation coefficient is defined by

\[ r_{MSLP} = \frac{\sum (p_{obs} - \bar{p}_{obs})(p_{mod} - \bar{p}_{mod})}{\sqrt{\sum (p_{obs} - \bar{p}_{obs})^2 \sum (p_{mod} - \bar{p}_{mod})^2}}, \]

where the average is taken over the stations shown in Fig. 2b. The index 'obs' denotes a measured value, 'mod' refers to the model value, and variables with an overbar are averaged over the 24 h forecast period. There were no AWSs in the gulf, except for the two situated on Sweers Island and Mornington Island in the southern gulf, but morning-glory cloud lines are more or less straight and occur over land as well as the sea. Therefore the data obtained should be adequate to capture the essence of the cloud lines. The Australian Bureau of Meteorology does maintain a few additional AWSs in the Gulf-of-Carpentaria region, but the data at the time of GLEX were available only every 3 h, which is too unfrequent for our study.

Table 1 lists properties of the boundary-layer schemes as well as the MSLP correlation coefficients for the experiments with the different boundary-layer parameterizations described in the previous section. The results can be subdivided into three groups in terms of the
magnitude of this coefficient. The Blackadar, MRF and Gayno-Seaman schemes give the highest correlation, the Burk-Thompson and Eta schemes give a lower correlation, and explicit modelling of the boundary layer gives the worst correlation. The crucial differences between the best schemes and those with a more modest skill are discussed below.

Figure 4 shows the low-level divergence field and wind vectors at 0600 EST\(^1\) on 09 October for calculations with each of the five parameterizations and for one calculation in which no such scheme was used.

The panels are arranged in descending order of the MSLP correlation coefficient. The convergence line corresponding to the NACL is marked A in each panel and those corresponding to the northeasterly morning glory and the southerly morning glory are marked B and C, respectively. The position of the cold front to the south of the gulf is marked D.

Two tests of the Blackadar scheme were made, one using the force/restore land surface scheme and the other using the five-layer scheme. The value of \(r_{\text{MSLP}}\), 0.93, turned out to be the same time for the two calculations and the convergence patterns are so similar, that we show only the results for the force/restore scheme. One deduction from the similarity of the convergence patterns is that the surface fluxes with both surface schemes must be very similar.

The first available visible satellite image was that at 0632 EST, 32 min after the time shown in the plots. In this image, the NACL is located along the western side of the 141° meridian.\(^1\)All dates and times are given in Eastern Australian Time (EST), which is 10 h ahead of Universal Time Coordinated (UTC).
Based on backward extrapolation using the images at 0632 EST and 0825 EST, its location at 0600 EST would have been approximately 12 km east of this meridian. All model runs captured a convergence line too far west of the cloud location, indicating that the line travels too fast in all simulations. The line was captured closest from the estimated position with the Eta scheme (12 km) and farthest with the Burk-Thompson scheme (57 km) and without a PBL scheme (64 km). In the runs with the MRF-, Gayno-Seaman-, and Blackadar schemes, the line was 38 km too far west. The error in assessing the position of the lines is estimated to be ±10 km. There are large differences also in the structure of the convergence line between the runs. The line is most coherent when using the MRF scheme and, rather surprisingly, in the run without any scheme, but it is rather fragmented at its northern end in the other four simulations.

In the satellite image at 0632 EST, the northeasterly morning glory passes through 140°E, 17°S and the backward extrapolation with the later image leads to an estimated position at 0600 EST which is 13.5 km to the northeast. The corresponding convergence line in the model is captured most accurately, about 12 km from the observed position by the MRF-scheme. In comparison, the location in the simulations using the Gayno-Seaman, Blackadar, Burk-Thompson and Eta-schemes is about 25 km, 31 km, 70 km and 84 km too far to the northeast, respectively. The line is displaced only about 38 km to the northeast using no scheme, but its Y-shaped northwestern end predicted using this scheme was not observed. The error in determining the position of the lines in the model are estimated to be at most ±10 km. The length of the convergence lines cannot be compared with those in satellite imagery because the length in the divergence plots depends on the contour interval chosen.
The most striking difference between the model results is the convergence line corresponding to the southerly morning glory. The three simulations with the largest values of $r_{MSLP}$ produced a well-pronounced line. Using the Burk-Thompson and Eta schemes, the convergence line is barely perceptible. Its position in panel (d) is revealed by a small break in the convergence line corresponding to the northeasterly morning glory and some smaller regions of increased convergence. In panel (e) it is only just detectable by a small bulge in the northeasterly-morning-glory convergence line. Plots of the field before and after, also with different contour intervals, show that the bulge definitely corresponds to the southerly morning glory. However, at this time, the position closely coincides with the position of the NACL as well and the bulge could be related to the NACL also. The convergence line corresponding to the southerly morning glory is located about 200 km too far south in the run without a scheme. No scheme was able to distinguish between the southerly and southeasterly morning glories that are seen in Fig. 1.

The cold front to the south of the gulf is not marked everywhere by strong convergence, but it is marked by a strong change in wind speed and direction. The western side of the convergence line corresponding to the southerly morning glory is connected to the cold front using the MRF and especially the Gayno-Seaman scheme, but this southwest to northeast oriented part of the line is located too far west to be interpreted as a southeasterly morning glory.
4 Discussion

The three boundary-layer schemes giving the highest values of $r_{MSLP}$ are the Blackadar scheme, the Gayno-Seaman scheme and the MRF scheme. The value of $r_{MSLP}$ varies only little between these three schemes and is greater than 0.90. These schemes have two features in common:

- the treatment of the surface layer, and
- the representation of counter-gradient fluxes in the daytime convective module.

In the Blackadar scheme, the counter-gradient fluxes of water-vapour mixing ratio, potential temperature, and horizontal wind speeds are represented by the transilient scheme. In the Gayno-Seaman scheme, the turbulent fluxes of liquid water potential temperature are calculated using a counter-gradient heat flux term. In the MRF scheme, the turbulence diffusion equations for potential temperature and water vapour mixing ratio apply a counter-gradient correction term. The common feature of the schemes is that they all allow for counter-gradient fluxes of a form of the potential temperature, which suggests that the counter-gradient flux of this quantity is more important than the flux of moisture and momentum.

The Burk-Thompson and Eta schemes differ from the above three in the treatment of the surface layer and the fact that they do not have any representation of counter-gradient fluxes. The value of $r_{MSLP}$ for these schemes is 0.86 and 0.85, respectively. The simulation without a
boundary-layer parameterization rates poorly in comparison with all schemes giving a value of \( r_{\text{MSLP}} = 0.60 \).

The difference between the values of \( r_{\text{MSLP}} \) for the MRF scheme and for the Burk-Thompson and Eta schemes is about 0.08. We try now to quantify the relative effects that the treatment of the surface layer and the representation of counter-gradient fluxes have on the skill of the MRF scheme as measured by the value of \( r_{\text{MSLP}} \). Both counter-gradient mixing and surface-layer scheme, have in common that they transport heat from the surface or lower levels to higher levels and thus affect the sea-breeze circulation. The correct timing of the sea breezes, in turn, has a paramount impact on the formation and orientation of the low-level convergence lines corresponding with the morning glories and the NACL. Morning glories and sea-breeze fronts have a strong surface-pressure signature and it seems appropriate, therefore, to focus on \( r_{\text{MSLP}} \).

First we assess the importance of the counter-gradient fluxes by suppressing their effect in the MRF scheme. To do this we carried out two additional experiments with this scheme, one with the nocturnal stable state only and the other with the free convective state only. With the nocturnal state switched off, the results were essentially the same, indicating that it is the inclusion of the free convective state that is of paramount importance. When only the nocturnal state is invoked, the convergence line corresponding to the northeasterly morning glory at 0600 EST on 09 October is located about 100 km too far northeastwards, but with little difference in intensity. The convergence line corresponding to the southerly morning glory arrives at the gulf coast at about the same time as observed, while its intensity is weaker in this calculation than with the unmodified MRF configuration. Switching the
counter-gradient fluxes off reduces the value of $r_{MSLP}$ by 0.02. Thus, the counter-gradient fluxes account for approximately a quarter of the difference between $r_{MSLP}$ for the MRF and the Burk-Thompson and Eta schemes.

We turn now to the surface-layer representation, which is important because the surface sensible heat fluxes have a major influence on the sea-breeze circulations. In turn, the intensity of these circulations affects the intensity and propagation speed of the morning glory convergence lines. This dependence is shown in a sensitivity study on the effects of soil moisture carried out by Thomsen (2006). In general, the relation of sensible to latent heat flux becomes smaller as the surface becomes the moister, but it is the sensible heat flux that directly drives the sea-breeze circulation.

Zhang and Zheng (2003) performed a sensitivity study of MM5 to the different boundary-layer parameterizations. They found that the maximum temperature in the lowest model layer was underestimated by 1-2°C when using the Burk-Thompson and Eta schemes. They attributed this underestimate to the surface-layer scheme, which differs from those in the parameterizations which showed no such underestimate. In the present calculations, the spatial average of the temperature in the lowest model layer at 1600 EST on 08 October is about 1 K lower in the Burk-Thompson and Eta schemes than in the other three (see third column in Table 2), which is in line with Zhang and Zheng’s findings.

We attempt to quantify the importance of the surface-layer representation by reducing the mean temperature of the lowest model layer in the MRF scheme to the same as that in the Burk-Thompson and Eta schemes and examining the change in the value of $r_{MSLP}$. One
way to reduce the near-surface temperature is to increase the soil moisture. We apply the results of Thomsen’s (2006) study of the sensitivity to soil moisture to quantify the effects of the reduced near-surface temperature. This study used the MRF scheme together with the bucket soil-moisture scheme, but all other parameters were the same as those here.

Figure 5a shows the average temperature in the lowest model layer at 1600 EST on 08 October as a function of the initial moisture availability (MAVA), the quantity that is used in MM5 instead of the soil moisture (SOILM) itself. The soil moisture is defined as a dimensionless ratio of the volume of liquid water to that of soil. The two quantities are linked by the formula $\text{MAVA} = \text{SOILM} \times 2 + 0.09 \times (0.5 - \text{SOILM})$. The average surface-layer temperatures using the Burk-Thompson and Eta schemes would require initial values of MAVA of 0.28 and 0.27, respectively, for the MRF scheme.

Figure 5b shows values of $r_{\text{MSLP}}$ for model runs using the MRF scheme, but with different initial values for MAVA. The values given in the fourth column of Table 2 have been derived from the fit function plotted in Fig. 5b. MAVA values of 0.28 and 0.27 lead to values of $r_{\text{MSLP}}$ of 0.89. Thus the value of $r_{\text{MSLP}}$ would decrease by about 0.05 if the sensible heat fluxes in the surface-layer were as low as in those in the Burk-Thompson or Eta scheme. We conclude that the treatment of the surface-layer scheme has an effect about $2\frac{1}{2}$ times as large as the inclusion of counter-gradient fluxes in improving the MSLP correlation in the MRF scheme.

Finally we should remark that the use of the MSLP-correlation is only one of many conceivable measures of model skill. It has advantaged here because accurate surface pressure
measurements were available at all the AWSs and surface pressure is less influenced by local
effects than, for example, surface (i.e. 2 m) wind speed and direction.

5 Conclusions

We have shown that the skill of MM5 in predicting low-level convergence lines in the Gulf
of Carpentaria region of northeastern Australia depends on the boundary-layer parameter-
ization that is chosen. We used a quantitative measure of skill based on the correlation
of surface pressure between model predictions and the observations. Of the six schemes
examined, the three best were those that have: (1) a representation of counter-gradient
fluxes in the convectively well-mixed layer; and (2) a treatment of the surface layer based
on Monin-Obukhov theory. Of these, the MRF scheme performed marginally better than
the Blackadar and Gayno-Seaman schemes. The Burk-Thompson and Eta schemes were less
skillful and the model without a scheme was comparatively poor. The improvement in skill
by including the Monin-Obukhov theory in the MRF-scheme was found to be more than
twice that by including the daytime counter-gradient fluxes. While other measures of skill
could be devised, the measure based on the MSLP correlation coefficient is consistent with
subjective judgements based on a comparison of the spatial patterns of low-level convergence
with the cloud lines in satellite imagery in the case examined. The findings reported here
raise important considerations for modelling the planetary boundary layer over tropical and
subtropical Australia as well as in other arid regions of the world.
References


Figure captions:

Figure 1
Visible Geostationary Satellite image of the cloud lines at 0632 EST on 09 October. Arrows indicate the northeasterly morning glory (NEMG), the southeasterly morning glory (SEMG), the southerly morning glory (SMG), and the north Australian cloud line (NACL).

Figure 2
Map of north-eastern Australia showing (a) the outer domain of the model with places mentioned in the text, (b) the inner domain with the locations of AWSs in the southern gulf region marked by crosses.

Figure 3
Sea-level pressure at Karumba during the simulation time.

Figure 4
Low-level wind vectors (scale 10 m s$^{-1}$ below panels) and divergence (shaded, unit s$^{-1}$) at $\sigma = 0.955$ at 0600 EST on 09 October. The capital letters stand for convergence lines corresponding to an NACL (A), a northeasterly morning glory (B), a southerly morning glory (C) and a cold front (D).

Figure 5
Left panel: Average surface-layer temperatures for different MAVA initializations with the MRF scheme. Right panel: MSLP correlation coefficients for different MAVA initializations.
with the MRF scheme. The crosses indicate actual values while the lines are (linear in the left panel, quadratic in the right panel) fits to these values.
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Table 1: Experiments with the different PBL schemes, important groups of their properties and mean sea-level correlation coefficients. Here, $\theta$ refers to the potential temperature, $q$ to the water-vapour mixing ratio, $u$ to the zonal wind, $v$ to the meridional wind and $\theta_L$ to the liquid-water potential temperature.

<table>
<thead>
<tr>
<th>Exp.</th>
<th>PBL scheme</th>
<th>Closure (Order)</th>
<th>Surface fluxes</th>
<th>Counter-gradient fluxes$^1$</th>
<th>Land-surface scheme</th>
<th>$r_{MSLP}$</th>
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</thead>
<tbody>
<tr>
<td>1</td>
<td>MRF</td>
<td>profile (1)</td>
<td>M.-O.- similarity</td>
<td>$\theta, q$</td>
<td>Five-layer</td>
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<td>local $Ri$ (1)$^2$</td>
<td>M.-O.- similarity</td>
<td>$\theta, q, u, v$</td>
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<td>TKE (1.5)</td>
<td>M.-O.- similarity</td>
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<td>Burk-Thompson</td>
<td>TKE (1.5)</td>
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<td>Eta</td>
<td>TKE (1.5)</td>
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<td>6</td>
<td>Explicit</td>
<td></td>
<td></td>
<td></td>
<td>Force/restore</td>
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</tr>
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$^1$only in daytime convective stability state

$^2$only in night-time stable states
Table 2: Experiments with the different boundary-layer schemes, average surface-layer temperature (ASLT) at 1600 EST on 08 October and MSLP correlation coefficient ($r_{MSLP}$) which the MRF scheme would produce in an experiment in which the surface-layer temperature was adjusted to this value by the soil moisture.

<table>
<thead>
<tr>
<th>Exp.</th>
<th>PBL scheme</th>
<th>ASLT (°C)</th>
<th>$r_{MSLP}$ (MRF) with ASLT</th>
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<tr>
<td>1</td>
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<tr>
<td>3</td>
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<td>Burk-Thompson</td>
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<td>Eta</td>
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<td>7</td>
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