9.1 THE GENERATION OF THE MORNING GLORY

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1. INTRODUCTION

The morning glory is a dramatic low-level roll cloud or series of roll clouds observed around the southern part of the Gulf of Carpentaria in northern Australia. These roll clouds occur in the early hours of the morning with their passage accompanied by a sudden wind squall ($10 - 15\ ms^{-1}$) and a pressure jump of the order of $1 - 2\ hPa$. Although morning glories form at all times of the year, they are far more frequent during the dry season months of September to mid-November, the average during this period being about one every two days. For further details see the review by Reeder and Smith (1998).

Northeasterly morning glories, which form over Cape York Peninsula, are believed to be generated through the collision of the east and west-coast sea breezes, (*e.g.* Clarke 1984). Recently, Porter and Smyth (2002) have suggested that the disturbance forms through the resonant interaction of the west-coast sea breeze and the topography. The aim of this study is to clarify the mechanism by which morning glories are generated, through a series of very high-resolution numerical modelling experiments.

2. THE NUMERICAL MODEL

The numerical model used in the present study was originally described in detail by Clark (1977). It is formulated in terms of terrain following height coordinates and employs the non-hydrostatic, anelastic form of the equations of motion. The finite difference approximations are second order in both space and time. All calculations are done in two dimensions. The horizontal grid spacing is $200\ m$, and there are 60 unevenly spaced levels in the vertical, with the lowest level at $2\ m$ and the highest level at $15\ km$. The model domain is $640\ km$ wide, with a strip of land $440\ km$ wide located between two $100\ km$ wide bodies of water. The model is initialised at sunrise using an early morning sounding from Willis Island, and imposing a $5\ ms^{-1}$ easterly geostrophic flow.

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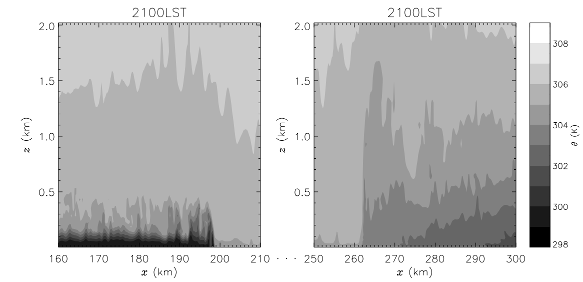

Figure 1: Control experiment. Potential temperature, shaded in $1\ K$ increments, showing the two sea breezes at 2100 LST, with a $40\ km$ gap between the plots. The peninsula is located from $x = 100\ km$ to $x = 540\ km$.

3. THE MODEL RESULTS

The sea breezes that develop over Cape York Peninsula are highly asymmetric with the east-coast sea breeze being both deeper and warmer than the western counterpart. Figure 1 is a plot of potential temperature showing the sea breezes at 2100 LST. The asymmetry is due to the easterly flow over the peninsula. When the sea breezes meet, the east-coast sea breeze rides over that from the west coast and in the process produces a series of waves that propagate on the west-coast sea breeze. Figure 2 shows this process and the resulting morning glory.

The results of various experiments, which are summarized in Table 1, show that when the phase speed of these waves matches the westward propagation speed of the east-coast sea breeze, the waves grow to large amplitude thus forming the morning glory. When the east-coast sea breeze propagates too fast relative to the waves, the waves do not amplify. This suggests that wave growth may be due to a resonant interaction between the wave and the east-coast sea breeze. Table 1 lists the Froude number, $Fr = c/c_e$, where c is the phase speed of the waves created immediately after the east-coast sea breeze rides over the west coast sea breeze, and c_e is the speed of the east-coast sea breeze, indicates whether or not a morning glory develops, and if so, how many waves are present at 0100 LST. The num-

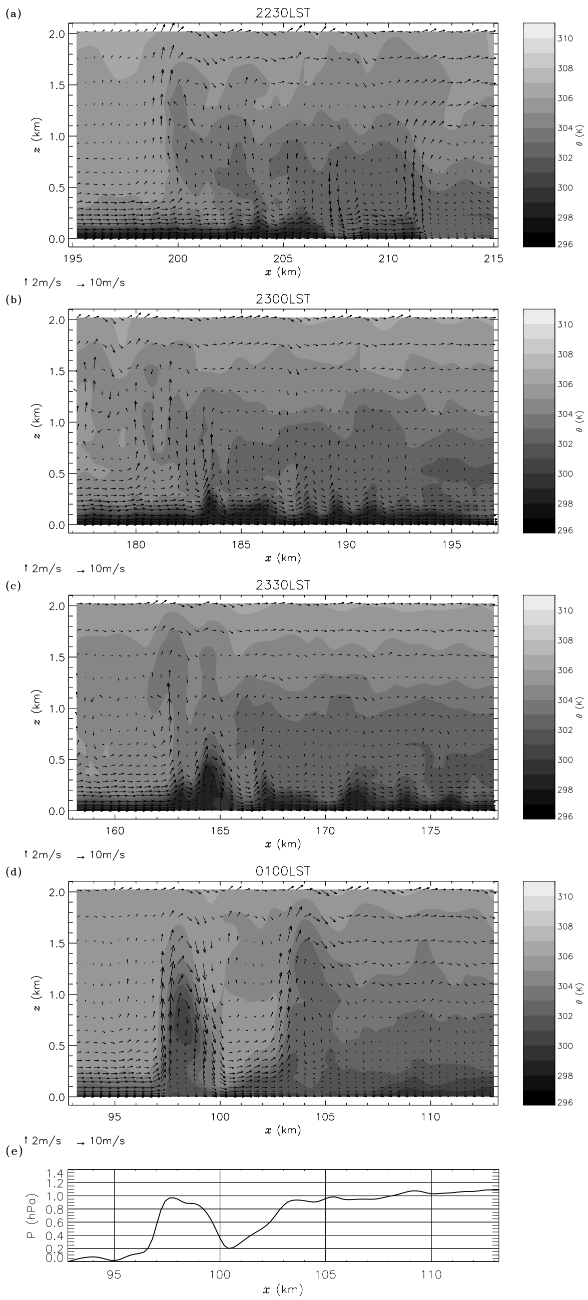

Figure 2: (a)-(d) The east-coast sea breeze overriding the west-coast sea breeze with a morning glory being produced. The velocity vectors are plotted relative to the east-coast sea breeze. For clarity they are only shown at every second horizontal gridpoint. (e) Surface pressure trace for panel (d).

Experiments	Fr	mg?	No. of waves
Control	0.77	Yes	2
No nocturnal cooling	0.63	No	-
2× nocturnal cooling	0.88	Yes	5
3× nocturnal cooling	0.94	Yes	7
Half surface heating	0.83	Yes	3
10.0 ms^{-1} easterly	0.46	No	-
2.5 ms^{-1} easterly	0.86	Yes	3
Thin peninsula	0.57	No	-

Table 1: Table comparing quantities from the various experiments conducted. This shows the Froude number, $Fr = c/c_e$ where c is the phase speed of the initial waves produced, and c_e is the speed of the east-coast sea breeze; the success or failure of the experiment to produce a morning glory; and the number of prominent crests that were present at 0100 LST.

ber of waves produced depends on the stability of the west-coast sea breeze and the strength of the east-coast sea breeze.

The inclusion of orography representative of Cape York Peninsula does not change the overall result with a morning glory forming in much the same way as in the case without orography. The main difference is that the sea breezes meet earlier when orography is included. An isolated hill on the west coast is considered also with westward propagating waves of smaller amplitude being generated by the west-coast sea breeze alone. However, the amplitude of these waves is much smaller than the morning glory that results from the interaction of the east-coast and west-coast sea breezes.

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