NOTES AND CORRESPONDENCE

Mesoscale Eddy Development over South Auckland—A Case Study

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ABSTRACT

Evidence is presented confirming the existence of a late-afternoon mesoscale eddy primarily caused by local diabatic heating. Simulations with the Colorado State University (CSU) mesoscale model show that the eddy forms in a zone of strong sea-breeze convergence under light southeasterly gradient flow. Although showing good agreement with simulations in respect to the timing and location of eddy development, observations from two days demonstrate that eddy formation may be complicated by mesoscale interactions that result in concurrent cloud development and precipitation in the vicinity of eddy genesis. The ability of the CSU model to capture the salient mesoscale features in the region, and the association of the cyclonic eddy and sea-breeze convergence in south Auckland with a preferred synoptic regime give cause for optimism in forecasting such phenomena.

1. Introduction

Complex interactions associated with benign phenomena such as sea breezes frequently trigger spectacular weather events that test the skill of forecasters. Examples include thunderstorms that develop within sea-breeze convergence zones over south Florida (Pielke 1974) and the "Morning Glory" associated with the collision of sea breezes across the Cape York Peninsula in northern Australia (Noonan and Smith 1987). Recently, attention also has been directed toward improved understanding of mesoscale cyclonic eddies that develop as a result of sea-breeze and/or slope-wind interactions. Well-documented examples include the Melbourne (Mel-II) eddy (Abbs 1986; McGregor and Kimura 1989) and the nocturnal Kanto Plain eddy (Harada 1981; Kimura 1986). Similar features also are noted by Wendell (1972) and Carpenter (1979). These vortices typically have horizontal length scales on the order of 100 km, vertical scales of up to 1000 m, and lifetimes of 6 to 12 h.

The Auckland region of New Zealand (Figs. 1 and 4a), with its convoluted coastline and narrow peninsulas, provides an ideal location for the study of sea-breeze–induced mesoscale phenomena. Previous studies (McGill 1987; McKendry 1989, 1991) have concentrated on the migratory sea-breeze convergence zones that develop due to the collision of sea breezes across the north Auckland peninsula on approximately 20% of days in summer. These features often produce significant cloud development and, occasionally, precipitation (McGill 1987).

The primary objective of the present study is to verify the existence of a mesoscale cyclonic eddy previously predicted in numerical simulations of local sea breezes during southeasterly gradient flow (McKendry 1991). Supportive evidence is presented from numerical simulations and observations for two consecutive days in 1973, while a numerical sensitivity analysis is used to investigate mechanisms responsible for eddy development. The two days were chosen for analysis because of the availability of a set of carefully recorded visual observations of cloud, wind (smoke plumes), and precipitation (supported by photographs) near Pukekohe that are unmatched to date. When combined with observations from the sparse regional network, these data permit a coarse meso-analysis for an area ordinarily devoid of surface wind observations. In describing the two case-study days, attention is also drawn to some unusual interactions between mesoscale phenomena that result in the spatial and temporal coincidence of convective precipitation and eddy genesis. Consequently, this study has important implications not only for local forecasting guidance but also forecasting in other locations where such phenomena may occur.

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2. Numerical simulations

a. Model description

The CSU mesoscale model has been described in detail by Pielke (1974), Pielke and Mahrer (1975, 1978) and Mahrer and Pielke (1976, 1977, 1978). In summary, the model, which was developed for the study of thermally forced, terrain-induced mesoscale phenomena, is hydrostatic and consists of the equations of motion, moisture, and continuity written in a three-dimensional terrain-following coordinate system. It also includes a surface heat budget and detailed planetary boundary-layer parameterization.

Relevant applications and verification studies of the model at other locations are described in McKendry (1989, 1991), and a summary of model setup and inputs for the Auckland region simulations are also described in those papers. Consequently, only a brief summary will be given here.

The terrain used in the model is shown in Fig. 1. Maximum terrain heights are found in the Coromandel Peninsula (600–800 m), the Hunua Range (450–600 m), and the Waitakere Range (250–500 m). Computations were performed on a $49 \times 42 \times 17$ (x, y, z) grid with a grid spacing of 5 km, except at the outermost grid points, where it expands linearly to 20 km (only the innermost grid is shown in the figures). Vertical grid spacing was variable, with greatest resolution near the surface. The top model level was at 6000 m.

The model was initialized using the mean vertical profiles of temperature and specific humidity derived from the 1100 LST (subtract 12 hours to obtain times

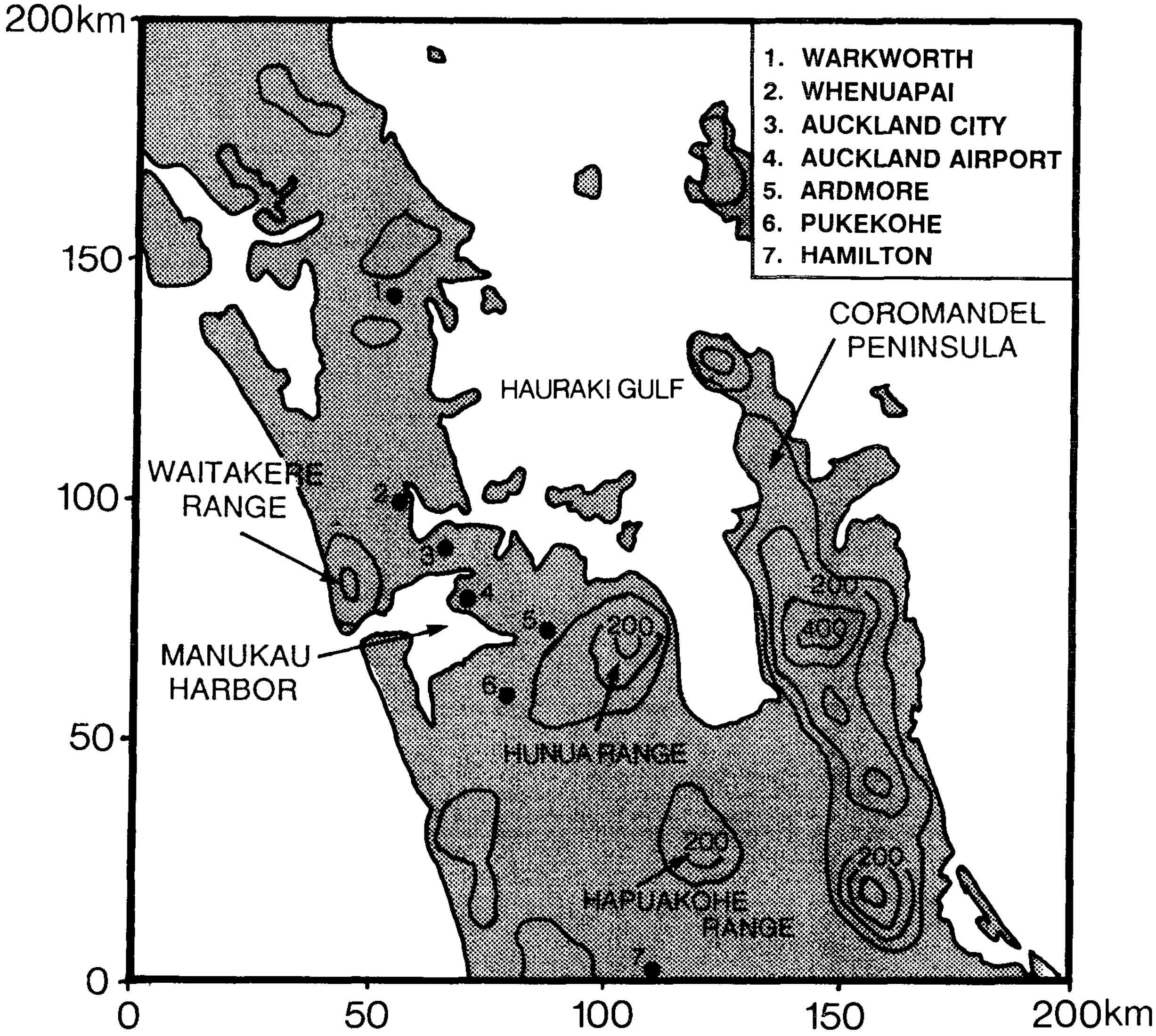


FIG. 1. Map of the Auckland Region (modeling domain), terrain (100-m contours), and locations mentioned in the text.

UTC) radiosonde ascents from Auckland Airport for 17–18 February 1973 (Fig. 2). Vertical wind shear was included in order to approximate the vertical variations shown in Fig. 5. Winds increased from 4 m s^{-1} at 1000 m to 7 m s^{-1} from the southeast at the upper boundary.

b. Simulation—moderate southeasterly winds

The predicted surface wind field for 1700 LST (Fig. 3a) shows well-developed sea breezes along coastlines to the north of Auckland city and a complex flow pattern in the south Auckland region associated with convergence between northerly sea breezes from the Hauraki Gulf, the southwesterly sea breeze from the west coast, and the gradient flow. At this time, maximum vertical velocities (Fig. 3b) are associated with a continuous sea-breeze convergence line extending along the west coast, in which localized "pockets" of intense vertical motion occur (up to 60 cm s^{-1}). The most significant of these is associated with the southwesterly sea-breeze convergence zone approximately 50 km to the south of Manukau Harbor. Further north, an incipient eddy is apparent to the southeast of the eastern tip of Manukau Harbor. This appears as a region of enhanced cyclonic vorticity in Fig. 3c.

In the following 2 h, the flow becomes much more organized in the south Auckland area, and by 1900 LST (Fig. 3d) the cyclonic eddy is clearly apparent near Pukekohe. This development is associated with a marked decline in the intensity of the local sea breezes and, in particular, with the retreat of the southwesterly sea breeze to the south of Manukau Harbor. It is the replacement of these southwesterly winds with easterly flow (on the southern edge of the eddy) that completes the cyclonic circulation. The strong vertical velocities that characterized the sea-breeze convergence line at 1700 LST are now absent in the vertical velocity field (Fig. 3e). However, a small region of enhanced vertical velocities (greater than 20 cm s^{-1}) is evident near the center of the eddy. The shift from a pattern characterized by a shear line to a single cyclonic eddy also is shown in the relative vorticity field (Fig. 3f). Although relative vorticity values are of similar magnitude in the south Auckland area at 1700 and 1900 LST, the vorticity at 1900 LST is much more strongly concentrated in the developing eddy.

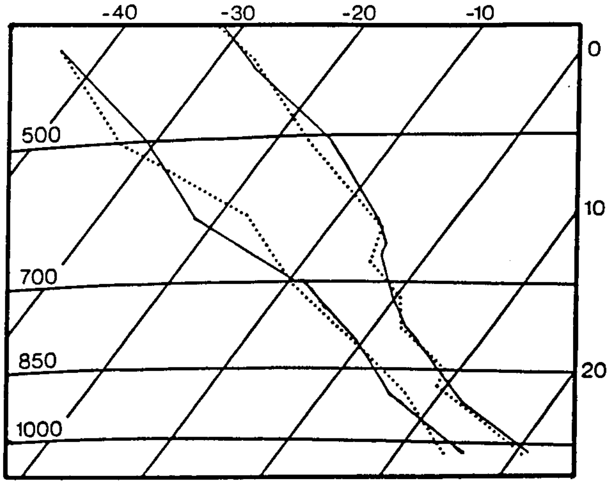


FIG. 2. Tephigram of vertical profiles of temperature and dewpoint from Auckland Airport for 1200 LST 17 February 1973 (solid line) and 1200 LST 18 February 1973 (dashed line).

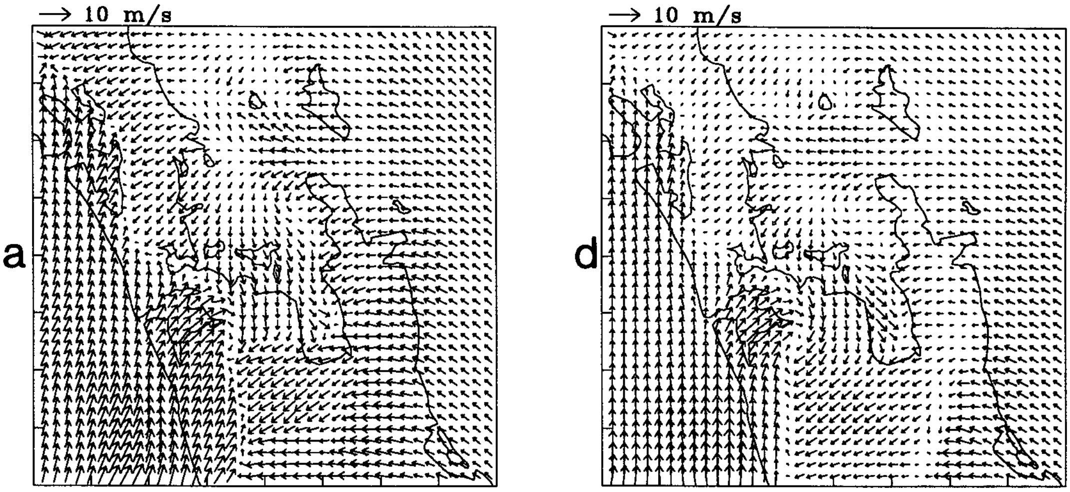
After 1900 LST, the eddy continued to assume a more conspicuous cyclonic appearance as winds decreased and vertical velocities within the eddy became virtually insignificant. During this stage, it decreased in depth from approximately 1000 m to about 500 m at 2400 LST. By midnight, the eddy was still discernible in the light surface flow immediately to the south of the entrance to Manukau Harbor, approximately 30 km to the west of its original position.

c. Sensitivity analysis

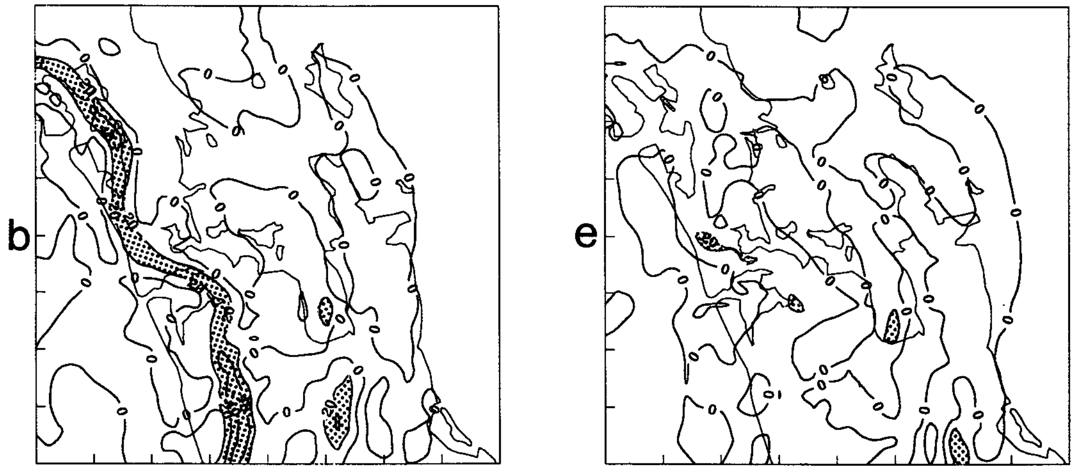
Several additional simulations were run in order to investigate the sensitivity of the eddy to gradient wind speed and direction, and to determine the role played by local terrain and Manukau Harbor in eddy genesis. These results are summarized in Table 1.

In those simulations in which gradient wind speed and direction were varied, an eddy only developed in relatively light gradient flow from a southeasterly direction. It is in these circumstances that the required combination of flows for eddy formation is present.

Studies elsewhere have shown that mesoscale eddies may form as a result of vortex shedding from terrain (McGregor and Kimura 1989). A representative Froude number, $Fr = U(Nh)^{-1}$, calculated at 1800 LST when the eddy developed, was 0.83. Here U denotes the fluid speed, h the obstacle height, and N the buoyancy frequency, $N = [(g/\theta)d\theta/dz)]^{0.5}$. Brighton (1978) has shown in laboratory experiments that vortex shedding from terrain is associated with stable conditions when Fr is less than 0.15, and, for values greater than 0.5, fluid flows over simple obstacles. On this basis, and the fact that the eddy developed in a well-developed mixed layer, wake effects from the Hunua Range were eliminated as a mechanism contributing to eddy formation for the two cases examined. This is confirmed by a simulation in which an eddy formed when terrain was excluded (Table 1). However, the eddy that developed was positioned approximately 15–20 km farther north and had a less well-defined cyclonic structure. It therefore appears that, although not a necessary precondition for eddy development, the presence of the Hunua Range acts to concentrate vorticity in the south Auckland area. The combined effects of sea breezes and anabatic flow on northfacing slopes of the range results in a strengthening and slight backing of the northerly sea breeze. The net effect is a more symmetric vortex displaced farther south.



VERTICAL VELOCITY (500m) VERTICAL VELOCITY (500m)



RELATIVE VORTICITY RELATIVE VORTICITY

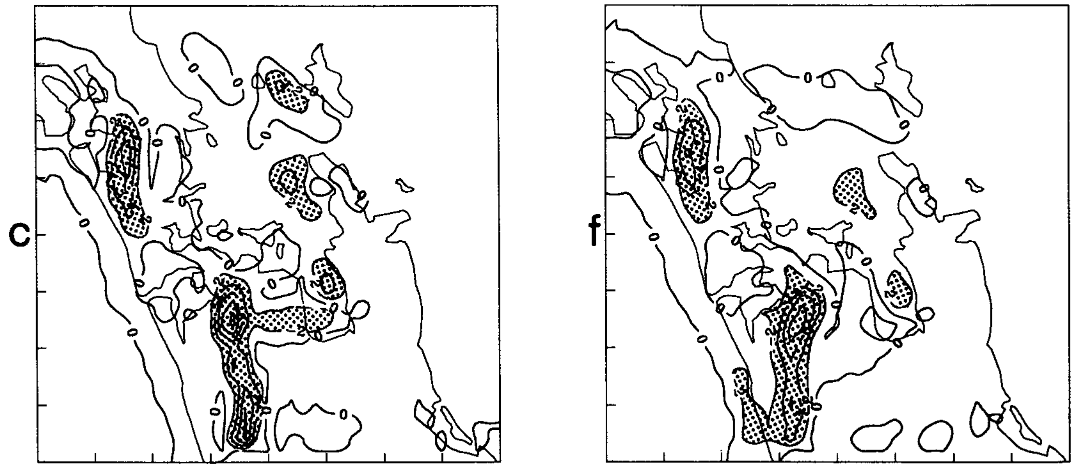


FIG. 3. Model predictions representing 17 and 18 February 1973, showing (a) and (d) wind field (10 m), (b) and (e) vertical-velocity field (cm s^{-1}) at 500 m (velocities greater than 20 cm s^{-1} are stippled), and (c) and (f) relative vorticity field ($\times 10^{-4}$ s^{-1}) at 10 m (values less than -4×10^{-1} s^{-1} are stippled), for 1700 and 1900 LST.

TABLE 1. Summary of sensitivity simulations.

Gradient wind	Terrain	Eddy development
SE, 3 m s^{-1}	Yes	Centered at $x = 80$ km, $y = 65$ km (Fig. 1)
SE, 3 m s^{-1}	No	Centered at $x = 80$ km, $y = 80$ km, less symmetric structure
SE, 6 m s^{-1}	Yes	None
E, 3 m s^{-1}	Yes	None
S, 3 m s^{-1}	Yes	None
SE, 3 m s^{-1}	Yes (NH*)	Centered at $x = 80$ km, $y = 80$ km, less symmetric structure

* Manukau Harbor replaced by land.

A notable feature of the eddy shown in Fig. 3d is the relatively strong southwesterly flow over the Manukau Harbor (up to 7 m s^{-1}). This is associated with the superimposition of the local harbor breeze on the larger-scale, west-coast sea breeze. Replacement of this water body by land did not change the location or timing of eddy development. However, wind speeds over the area of the harbor were reduced to approximately 4 m s^{-1}, and the circularity of the vortex was diminished as a result of more northerly winds (rather than northwesterly) in the northeastern quadrant of the developing eddy.

These results show that diabatic heating, resulting in local sea breezes, is the primary causal mechanism for the mesoscale eddy modeled over south Auckland. Both the Manukau Harbor and Hunua Range appear to play a secondary role in eddy genesis by reinforcing the cyclonicity of the flows that develop. The local harbor breeze enhances the larger-scale, west coast sea breeze, which forms the northwest quadrant of the eddy, while anabatic effects associated with the Hunua Range contribute to the cyclonic pattern in the eastern portion of the eddy.

3. Observations

a. Synoptic background

In mid-February 1973 the subtropical belt of high pressure extended from south of Australia across New Zealand and the South Pacific Ocean in latitudes 40°–45°S. The resulting southeasterly airflow over northern New Zealand was modulated by the passage of successive migratory anticyclones within the high-pressure belt. At 0000 LST 16 February, one such system was centered over the Chatham Islands (Fig. 4a), and a narrow frontal zone was approaching southern New Zealand ahead of the next anticyclone. Typically, such cold fronts become progressively more diffuse as they advance through the high-pressure belt, and they may be omitted from synoptic-scale analyses. Although the broadscale analysis did not show a continuation of the front north of latitude 39°S, evidence is presented in the following sections that an associated transitory disturbance advanced northward across the North Island on 17 February 1973. After 48 h, the associated front was located east of the Chatham Islands (Fig. 4b).

Upper winds from Auckland Airport (Fig. 5) show that throughout the period 17–18 February the synoptic-scale flow was consistently from the southeasterly quadrant. Late on 17 February the flow strengthened above 1000 m, with winds in excess of 9 m s^{-1} associated with the passage of the weak frontal disturbance. By late afternoon on 18 February, winds had decreased to predisturbance values in the lower troposphere. On 19 February winds again strengthened in the lower troposphere and backed to a more easterly direction. This change was sufficient to prevent significant sea-breeze development. Despite variations in the flow over the two case-study days, there was little difference in the vertical thermal structure between the two cases (Fig. 2). This provides support for the view that the passing

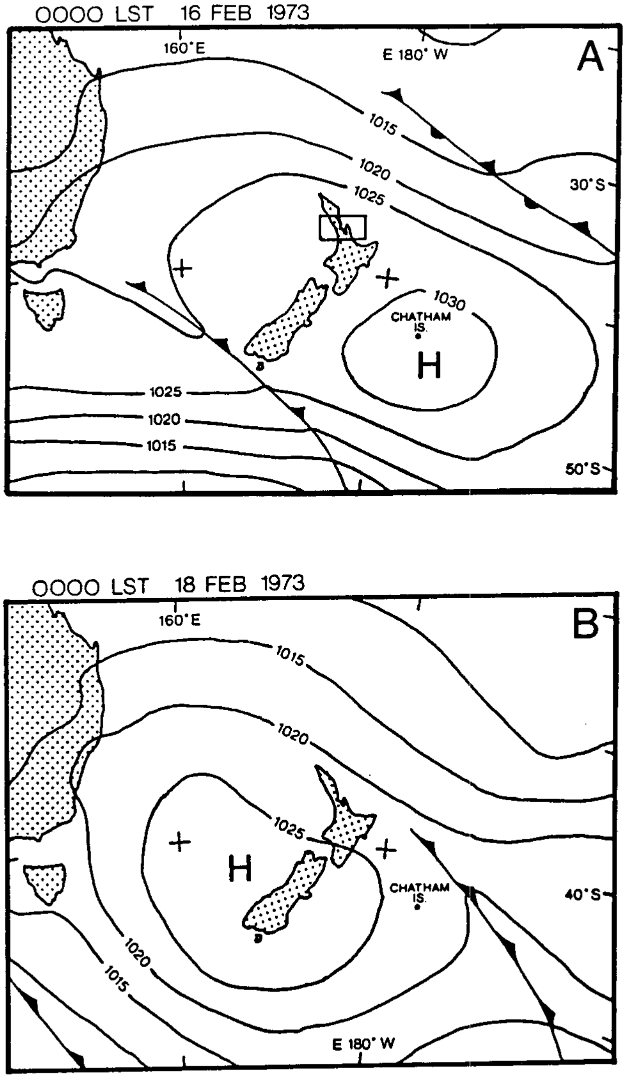


FIG. 4. Synoptic sea level pressure analysis for (a) 0000 LST 16 February 1973, (b) 0000 LST 18 February 1973. The study region is represented by the boxed area in (a).

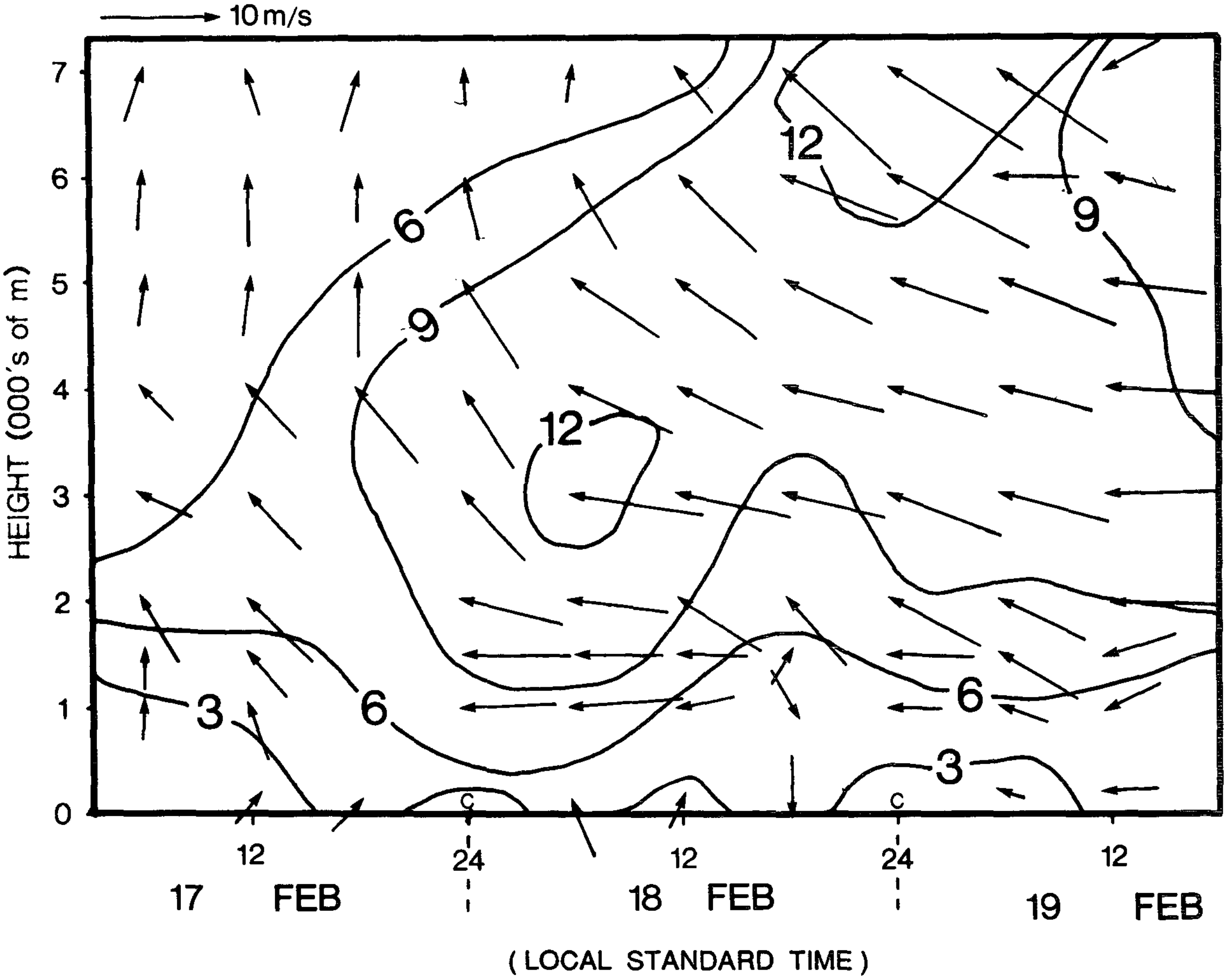


FIG. 5. Observed upper winds for Auckland Airport for the period 0000 LST 17 February 1973–2400 LST 19 February 1973. Arrows show wind direction and speed. Contours show wind speeds in meters per second.

disturbance on 17 February was only a minor perturbation embedded in the persistent southeasterly flow.

b. 17 February 1973

Weather over the Auckland region was characterized by scattered cumulus clouds (base 1200 m), with no particular organization and relatively warm temperatures (a maximum of 25°C in the vicinity of Auckland city). Sea surface temperature was approximately 21°C. Sea breezes developed during the day, and by 1600 LST the west-coast sea breeze had penetrated inland as far as Pukekohe. A surface streamflow analysis at this time (Fig. 6) shows easterly winds along the east coast of the north Auckland isthmus, and westerly winds at Auckland Airport. This suggests that a sea-breeze convergence line was present along the center of the peninsula, a typical pattern for southeasterly sea-breeze days (McGill 1987). Observations at Ardmore and Pukekohe in late afternoon show a complex flow pattern in the south Auckland area that is consistent with the development of a mesoscale eddy, as predicted in the simulations. Unfortunately, additional wind observations were not available to confirm that an eddy developed on 17 February. However, these data were available for 18 February and showed that, under virtually identical forcing conditions, the flow pattern around south Auckland was clearly cyclonic.

A notable aspect of events on 17 February was the late afternoon passage of a weak line disturbance. Since the version of the CSU model used is dry and does not permit an evolving synoptic state, interactions between the eddy and the weak disturbance were not resolved in the simulations. At 1630 LST, precipitating cumulus clouds were observed from Pukekohe to the south. The successive positions of this line disturbance as derived from radar returns are plotted in Fig. 6 (inset). The northwestward movement of this feature is also evident from analysis of the local pressure field (Fig. 7a). Deviations from the spatial average of hourly pressures

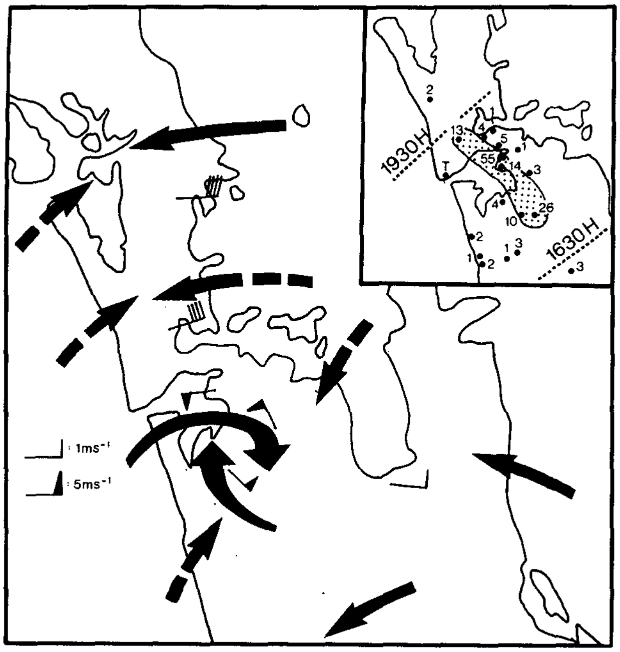


FIG. 6. Surface streamflow analysis for 1600 LST 17 February 1973. Large broken arrows signify uncertainty. Inset: Daily rainfall totals (millimeters) and successive positions of transitory disturbance.

at Whenuapai, Auckland Airport, Ardmore, and Hamilton reveal a slight pressure rise associated with the disturbance, which was evident at Hamilton between 1500 and 1600 LST (shown by the "0" isopleth). Both radar evidence and the pressure data indicate that the disturbance was traveling at a speed of approximately 11 m s^{-1}. Its passage over the Pukekohe area between 1700 and 1745 LST initially produced heavy rain, followed by thunder and lightning at intervals. With the passage of the system, winds backed to the southeast with gusts estimated at 10–12 m s^{-1}. Rain ceased at around 1745 LST. Daily rainfall records for the area show that precipitation was heaviest in a corridor extending from Pukekohe to west of Auckland city (Fig. 6, inset). Precipitation amounts elsewhere, particularly to the southeast, were relatively light. The highest precipitation amount was recorded at Mangere (54.9 mm). This seems anomalous in light of surrounding observations. However, it cannot be dismissed, given the spatial variability in precipitation that might be expected with intense convective activity.

c. 18 February 1973

Southeasterly flow still prevailed after the passage of the weak disturbance, and sea breezes again developed around the Auckland region on the next day with temperatures reaching 25°C under scattered cumulus clouds. In contrast to the previous day, the surface pressure analysis for 18 February (Fig. 7b) shows a rather static pattern characterized by relatively high pressures to the north and low pressures to the south. This reflects the development of a weak thermal low over the central North Island, a phenomenon previously described by McGill (1987). The late-afternoon streamflow analysis (augmented by smoke drift observations) shows a distinct mesoscale cyclonic eddy over the Pukekohe area in combination with a convergence line extending along the north Auckland Peninsula (Fig. 8). This pattern shows remarkably close agreement with the fields predicted by the model in Fig. 3. The eddy is clearly associated with convergence between the southwesterly sea breeze from the west coast, the northerly sea breeze from the Hauraki Gulf, and the southeasterly synoptic-scale flow. This pattern evolved in late afternoon and was associated with a pronounced change in cloud distribution. At 1225 LST the region to the southeast of Pukekohe was characterized by an irregular arrangement of cumulus cloud streets aligned parallel to the southeasterly low-level flow. These streets were most strongly developed downwind of the Hapuakohe Range. By 1645 LST,

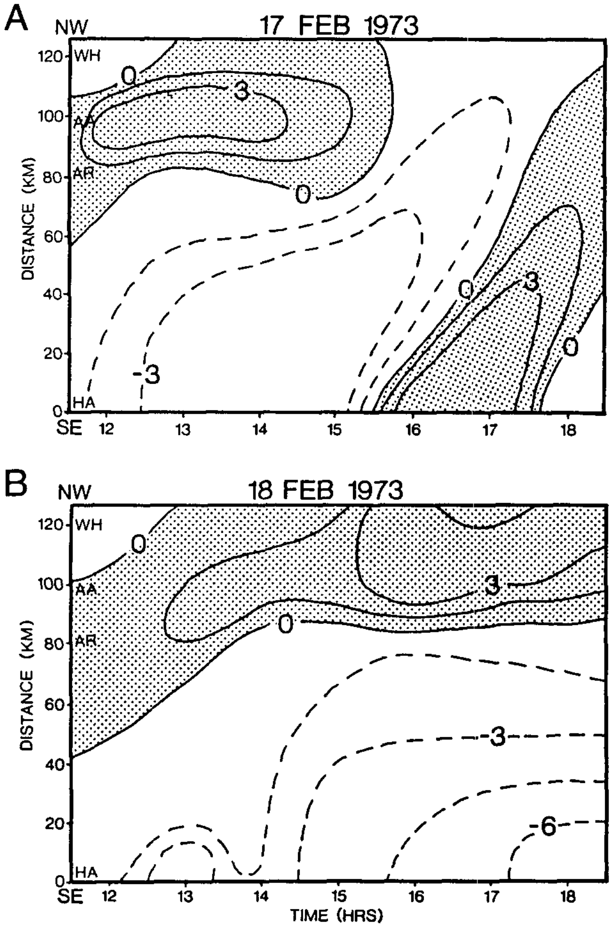


FIG. 7. Contoured (tenths of a millibar) deviations from the spatial average of mean sea level pressure for Hamilton (HA), Ardmore (AR), Auckland Airport (AA), and Whenuapai (WH). Values represent station value–spatial average of four stations. (a) 17 February 1973, (b) 18 February 1973.

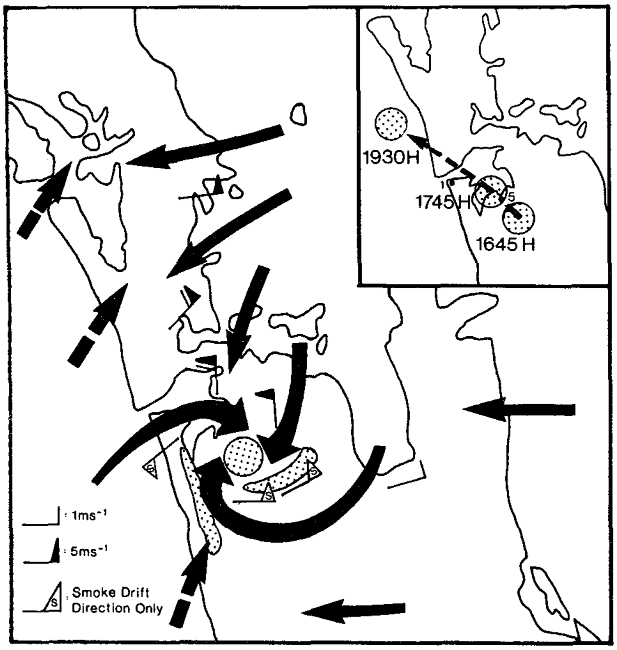


FIG. 8. Surface streamflow analysis for 1800 LST 18 February 1973. Cloud patterns are shaded. Inset: Daily rainfall totals and successive positions of towering cumulus cloud mass.

this pattern gave way to more complex banding oriented ENE/WSW in an otherwise clear sky. To the west of the Hunua Range, a solitary towering cumulus cloud mass over the Pukekohe area had developed (Fig. 9), while to the southwest of Pukekohe an isolated band of cumulus marked the position of the west-coast sea-breeze front (cloud positions are shaded on Fig. 8). The surrounding region, especially to the north and east, was essentially cloud free at this time. By 1745 LST, the cloud mass was producing showers as it followed a northwesterly trajectory across the western edge of the Manukau Harbor. Radar returns locate the feature (Fig. 8, inset) off the west coast to the northwest of Manukau Harbor at 1930 LST. The only precipitation recorded in the region was at the two stations along the path of the cumulus cloud mass.

4. Discussion and conclusions

Observations from two consecutive days confirm that a mesoscale cyclonic eddy forms when well-developed sea breezes occur under light southeasterly gradient flow in the south Auckland area. Close agreement between observations and model predictions with respect to the timing and location of eddy formation suggests that the CSU model is able to capture the essential dynamics of eddy genesis. However, the two examples presented demonstrate that eddy dynamics may be complicated by mesoscale interactions resulting in convective development and precipitation, aspects not incorporated in the simulations, and not documented in studies of mesoscale eddies elsewhere. The collocation of the eddy over south Auckland and the thunderstorm that developed subsequently within the line disturbance on 17 February raises the interesting possibility that the precipitation event was triggered by the same localized convection associated with eddy formation. The concurrent development of the eddy and the overlying solitary cloud mass on 18 February also points to a link between eddy genesis, convective development, and precipitation. A possible explanation is that convective cloud development and eddy formation are concurrent responses to late-afternoon sea-breeze convergence. Further work is required to investigate the exact relationship between eddy formation, sea-breeze convergence, terrain effects, and convective precipitation in this area.

For both case studies, a lack of observations extending beyond late afternoon means that the continued nocturnal development and advection of the eddy as predicted by the model cannot be verified. This is not important for the 17 February case, since the passing disturbance undoubtedly obliterated the eddy. However, the evolution of the eddy throughout the evening on 18 February remains uncertain. Although the convective cloud was advected offshore in the prevailing flow, it is possible that the low-level vortex remained in the south Auckland basin as predicted by the model. On the other hand, the inability of the CSU model to handle radiative and thermodynamic cloud processes might mean that the evolution of the eddy following significant cloud development is quite different from that predicted.

Results of the sensitivity analysis suggest that the south Auckland eddy has many similarities to the Mel-II eddy in the Melbourne area (Abbs 1986; McGregor and Kimura 1989). In particular, both eddies form in early evening with the most important precursors being well-defined sea breezes and a preferred wind direction. In both cases, eddy development is also enhanced by the presence of terrain, the importance of which has been noted by Carpenter (1979). He showed that the inclusion of terrain in mesoscale simulations results in the deformation and strengthening of the sea-breeze shear line and the development of a cyclonic vortex over the northeast coast of England. In this study, sensitivity analyses indicate that anabatic winds on the northern slopes of the Hunua Range, when combined with sea breezes from the Hauraki Gulf, are responsible for the location of the eddy on the southwestern edge of the Hunua Range. Notwithstanding, the simulation of an eddy over the eastern Manukau Harbor, with terrain excluded, is in broad agreement with south Australian results that show coastline curvature to be a sufficient cause of eddy development (Abbs 1986).

Future research will be directed toward a climatology of this phenomenon (based on satellite, rainfall, and radar data), and, perhaps most importantly from a forecasting perspective, elucidating the relationship between eddy development and convective precipitation. Notwithstanding, the present study provides

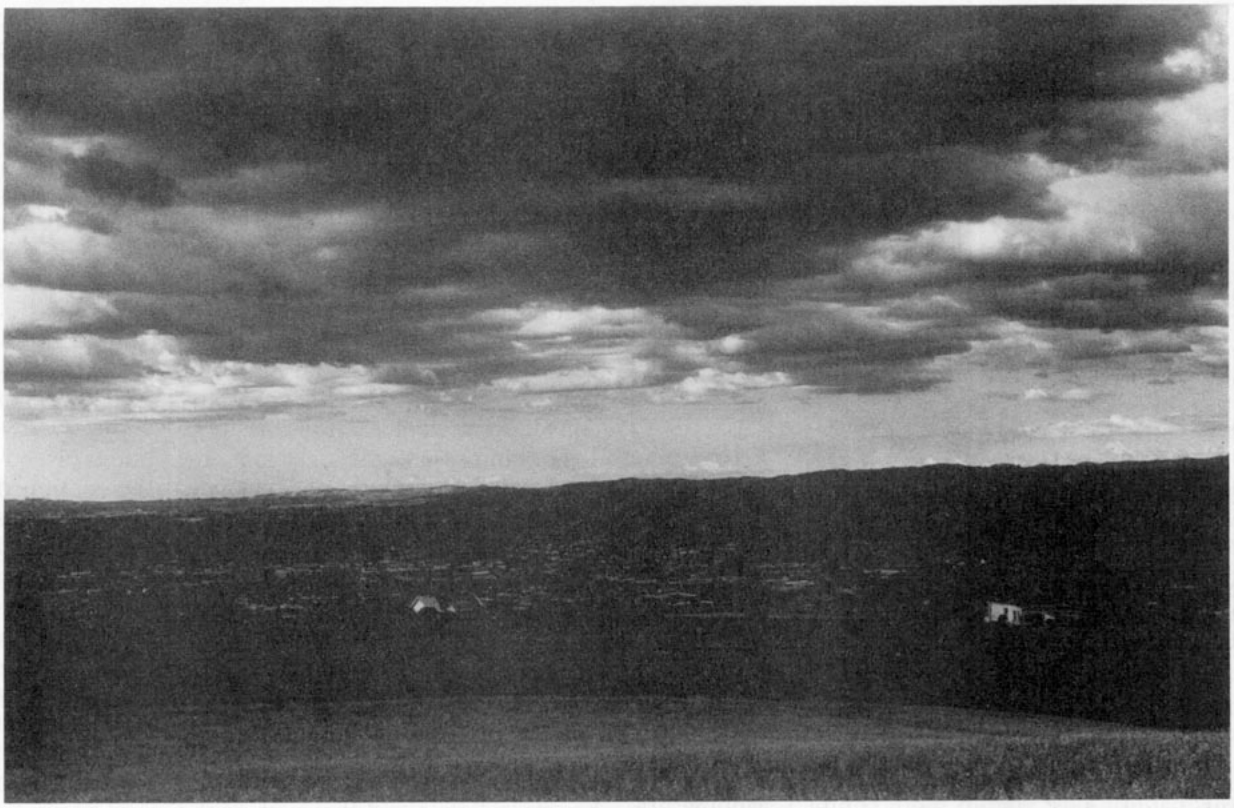


FIG. 9. Cumulus cloud mass photographed from Pukekohe looking northeast at 1645 LST on 18 February 1973.

forecasters with a further example of mesoscale interactions that may occur under sea-breeze conditions, and alerts them to the possibility of a link between meso-eddy development and convective precipitation. Association of the eddy and convective precipitation with a preferred large-scale wind speed and direction and a specific location gives cause for optimism in forecasting such phenomena.

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