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Numerical simulation of sea breeze interactions over the Auckland region, New Zealand

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Abstract The Colorado State University mesoscale model is used to investigate the influence of gradient wind direction on migratory sea breeze convergence zones (SBCZs) that develop over an irregular coastline incorporating two narrow peninsulas. Results, which are in good qualitative agreement with observations, reveal that SBCZ dynamics are strongly influenced by the extent to which flow is either subparallel or perpendicular to the orientation of the major coastlines. The local coastal configuration is also shown to be the dominant factor controlling the location of zones of intense vertical motion associated with SBCZs. A notable aspect of the study was the simulation of a late afternoon mesoscale cyclonic eddy caused by the interaction of sea breezes during south-easterly gradient flow. Further observations are recommended to verify the existence of this phenomenon.

Keywords sea breezes; Auckland; convergence zones; wind-field modelling; peninsulas; mesoscale atmospheric circulations

INTRODUCTION

Improved understanding and prediction of mesoscale phenomena remains an important challenge in meteorology. This is especially true in coastal environments where sea breezes strongly influence human activities. Over irregular coastlines, the development of sea breeze circulations is often associated with zones of strong vertical motion, which may be caused by the interaction of sea breezes from opposite sides of a peninsula or island, or simply the horizontally convergent flow associated with a convex coastline (Edinger & Helvey 1961; McPherson 1970). Often, these interactions create spectacular meteorological phenomena. For example, over Cape York Peninsula, Australia, the collision of sea breezes from opposite sides of the peninsula is responsible for the "morning glory" phenomenon and the North Australian Cloud Line (Clarke 1984; Noonan & Smith 1987). Over the south Florida peninsula, similar sea breeze convergence zones (hereafter referred to as SBCZs) have been shown in modelling studies to be the dominant control on the location of thunderstorm complexes on days not affected by synoptic scale disturbances (Pielke 1974).

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In this study, the Colorado State University mesoscale model is used to investigate the effect of gradient wind direction on the location, dynamics, and intensity of SBCZs that develop over the Auckland region. This mid-latitude coastal environment is characterised by two narrow peninsulas of a scale considered to be ideal for the development of strong sea breeze convergence features (Abe & Yoshida 1982). As well as having important implications for local forecasting, recreation (especially sailing), aviation, and air quality, this study provides an opportunity to examine sea breeze interactions that occur at a scale and complexity not previously investigated in the literature. Furthermore, in the absence of a dense mesoscale observation network over the region, application of a mesoscale model permits a high-resolution three-dimensional perspective on local airflow that incorporates those data-sparse regions (i.e. the Hauraki Gulf) which are of prime importance in forecasting.

BACKGROUND

The Auckland region is generally exposed to a succession of fast moving synoptic systems. Gradient winds, although most frequently having a westerly component, may come from any quarter. Auckland City is centred on a narrow isthmus

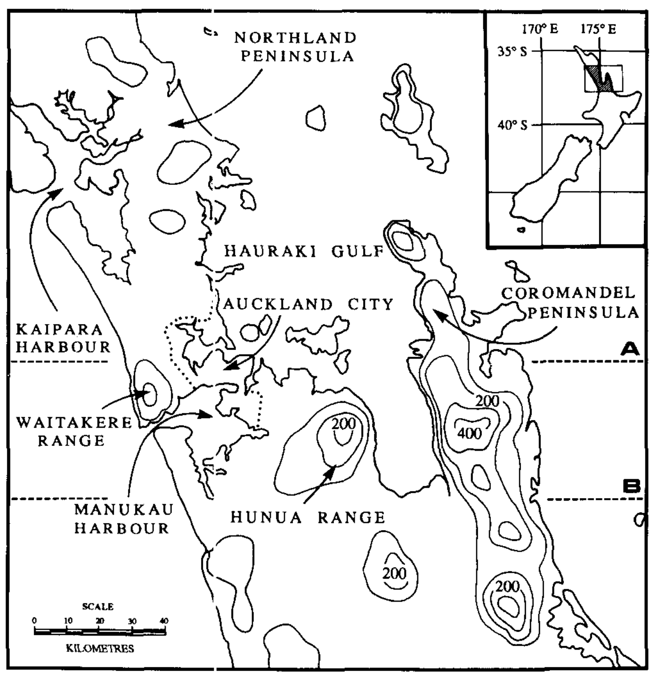

Fig. 1 Map of the modelling domain showing Auckland City and terrain (100 m contours). The cross-section used for Fig. 5, 7, 10 and 12 is denoted by the dashed line "A". The cross-section for Fig. 9 is denoted by dashed line "B".

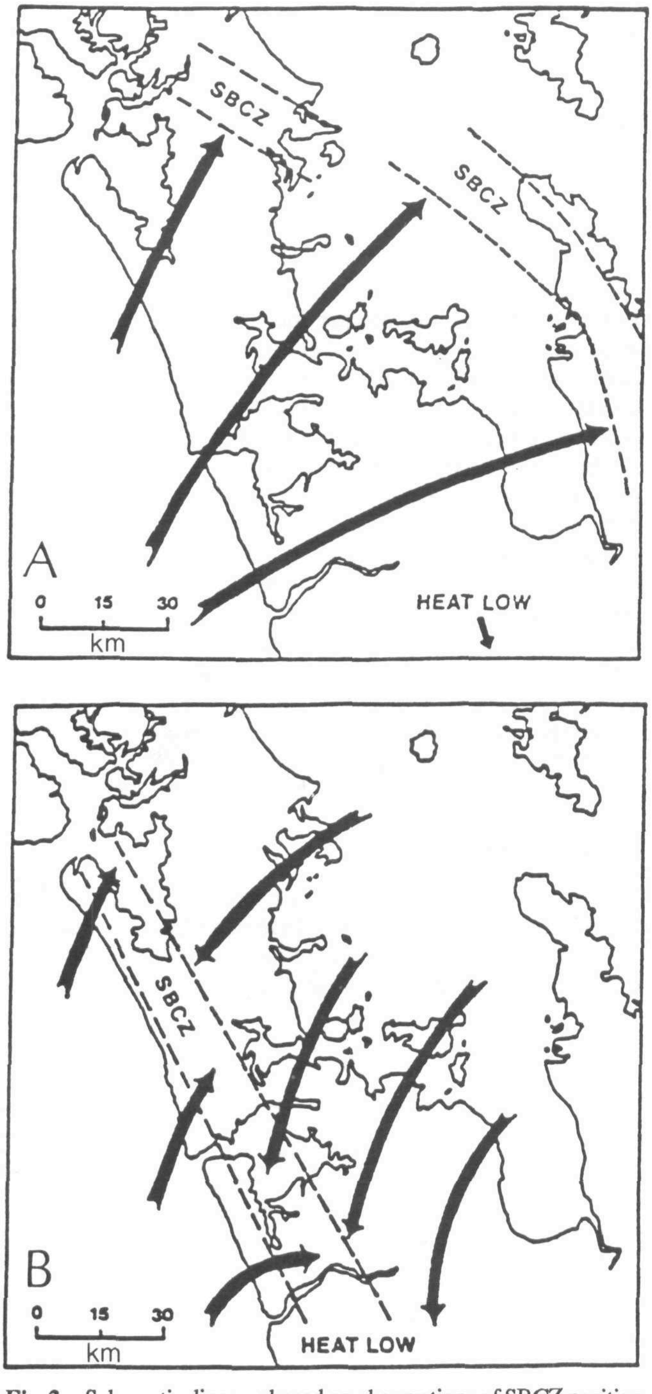

Fig. 2 Schematic diagram based on observations of SBCZ position under (A) southwesterly gradient flow and (B) northeasterly gradient flow. Large arrows represent the general low-level flow (after McGill 1987).

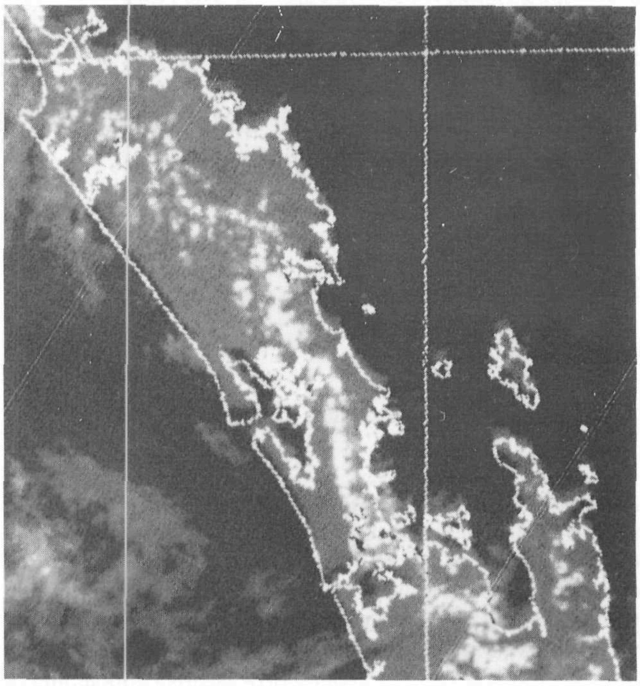

Fig. 3 Visible satellite image showing typical summertime SBCZs over the Auckland region.

separating the major portion of the North Island from the Northland peninsula which reaches a maximum width of 80 km and extends 320 km to the northwest (Fig. 1). Further east, the Coromandel Peninsula forms the eastern boundary of the Hauraki Gulf. Bounded by a long indented coastline, the region has a physical configuration which is conducive to the development of complex sea breeze interactions. This has been confirmed by observational studies (Revell 1978; McGill 1987) in the vicinity of Auckland City which show that SBCZs are an important feature of the summertime meteorology of the region and that their position and movement are strongly influenced by the strength and direction of the gradient wind. During the three summers of 1979–81, McGill (1987) observed sea breezes on 62 days (17% of all days). General characteristics of the SBCZs that developed on these days have been classified by McGill (1987) on the basis of gradient wind direction. For north to northwesterly gradient flow, the SBCZ was usually observed to migrate across the isthmus to the west coast. Conversely, southwesterly gradient flow was generally associated with a SBCZ near the the east coast of the isthmus (Fig. 2A). McGill (1987) noted that, in this case, the SBCZ was frequently observed to move back and forth across the coastline. With southeasterly gradient flow, the SBCZ was observed to remain inland between the coasts of the isthmus, although a tendency was observed for the SBCZ to migrate to the east coast in late afternoon. Cases of northeasterly flow were associated with movement of the SBCZ to the west coast during the afternoon (Fig. 2B). McGill (1987) observed variations in these patterns when gradient winds exceeded 6 m/s or changed markedly during the day.

Satellite imagery showing well-defined linear cumulus cloud features over the region confirms that the vertical motion within the SBCZs is sufficiently strong to develop significant cloud. Figure 3 shows a typical summertime example of a prominent SBCZ and its associated cumulus cloud line extending northward from Auckland City.

The sparse observational network over the Auckland region prohibits detailed validation of the predicted wind fields shown in the following sections. Instead, results are qualitatively compared with the broad patterns described by McGill (1987).

MODEL AND INPUT DATA

The CSU mesoscale model has been described in detail by Pielke (1974), Pielke & Mahrer (1975, 1978), and Mahrer &

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 co-ordinate system. It also includes a surface heat budget and a planetary boundary layer (PBL) parameterisation based on Deardorff's (1974) formulation as amended by Physick et al. (1989). Simulations are based on an iterative procedure beginning at an initial time (sunrise) in which the model equations are solved numerically by finite difference techniques. At the lateral boundaries, the horizontal gradients of pressure and the prognostic variables are set to zero.

The model has been used for a broad range of applications. Previous studies in Australasia include sea breeze investigations by Abbs (1986) and Physick et al. (1989) in the Melbourne region, Noonan & Smith (1987) for the Cape York Peninsula, McKendry et al. (1988) for the Canterbury Plains, and McKendry (1989) for the Auckland region. Verification studies have been carried out by Pielke & Mahrer (1978), Segal et al. (1982), and Steyn & McKendry (1988).

To investigate the effect of gradient wind direction on sea breeze convergence, four simulations (northwest, northeast, southeast, and southwest gradient flow) were carried out using identical initial vertical profiles of temperature and specific humidity based on the 1100 Local Standard Time (LST) radiosonde ascent from Auckland Airport on 29 January 1981. This day was chosen to be representative of all four gradient wind directions on account of its association with anticyclonic conditions (conducive to the development of sea breezes for all gradient flow directions) and the presence of a 2°C temperature inversion from 1.15 to 1.6 km. McGill (1987) indicated that such inversions are a characteristic feature of profiles associated with Auckland sea breezes.

Simulations commenced at sunrise and were preceded by a 4 h period of dynamic initialisation in which surface cooling was permitted to occur. This procedure enabled nocturnal flow features to be represented at sunrise and thereby permitted a more realistic initial state. To enable the model to be realistically initialised before sunrise, the 1100 LST PBL potential temperature profile was adjusted such that, after dynamic initialisation, surface temperatures matched observed values and the PBL was weakly stable at sunrise (Table 1).

Initial PBL depth over land was set at 150 m, a depth recorded by acoustic sounder near Auckland City and considered to be reasonably representative of nocturnal summertime conditions over the whole region.

The four gradient wind directions were chosen to reflect the broad range of observed gradient flows associated with sea breeze flow in the Auckland region. Observations by McGill (1987) suggest that the highest sea breeze frequencies are associated with flows from the northwest and east. Gradient wind speed was set at 3 m/s, a typical 900 hPa windspeed associated with sea breeze development in the region (McGill 1987).

The terrain used in the model is shown in Fig. 1. This was derived from a 1 km resolution digital terrain model (courtesy Geophysics Division, New Zealand Department of Scientific and Industrial Research) by averaging up to 5 km resolution and smoothing to removed 2 grid-length variability. Consequently, maximum terrain heights as found on the Coromandel Peninsula (600–800 m), the Hunua Ranges (450–600 m), and the Waitakere Ranges (250–500 m) are not resolved by the model.

Computations were performed on a 49 × 42 × 17 (x,y,z) grid with a horizontal grid spacing of 5 km, except at the outermost grid points where it expands linearly to 20 km (only the innermost 39 × 39 (x,y) grid is shown in the subsequent figures). Vertical grid spacing was variable with greatest resolution near the surface (Table 1). An absorbing layer was included above level 10 to control the reflection of vertical propagating wave energy (Klemp & Lilly 1978: Mahrer & Pielke 1978). Input parameters used to initialise the model are listed in Table 2. A lack of available data on grid square variations in surface and soil characteristics prevented the inclusion of spatial variations in these properties. Instead, a single landuse category was specified on the basis of known soil and surface characteristics for similar landuses elsewhere (Steyn & McKendry 1988).

RESULTS

For each gradient wind direction in the following analysis, one horizontal level (10 m) is used to show wind-field variations associated with sea breeze development over a diurnal cycle. Results are presented for four daytime hours, 0700, 1100,

Table 1 Initial vertical profile of potential temperature (°) and specific humidity (q) at model levels at 0600 LST.

Z (m)	°(K)	q (kg/kg)
10	290.7	.0102
40	290.9	.0101
100	291.3	.0099
250	292.5	.0097
500	292.6	.0093
750	293.2	.0090
1000	295.3	.0089
1500	301.5	.0040
2000	304.9	.0032
2500	307.9	.0024
3000	310.6	.0014
3500	314.0	.0014
4000	317.0	.0012
4500	318.0	.0011
5000	319.5	.0010
5500	321.0	.0008
6000	322.9	.0006

Table 2 Input parameters used to initialise the model.

Timestep	60 s
Horizontal filter coefficient	0.02
Mean latitude	37.0°S
Initial PBL depth	150 m
Initial surface pressure	101.6 kPa
Synoptic wind directions	315°, 225°, 135°, 45°
Synoptic wind speed	3 m/s
Free atmospheric lapse rate	6 K/km
Land surface:	
albedo	0.23
roughness length	.20 m
Soil characteristics:	
density	1300 kg/m^3
specific heat	1549.4 J kg^{-1} K^{-1}
diffusivity	5 × 10^7 m^2/s
wetness*	0.3

*A parameter between 0 and 1.

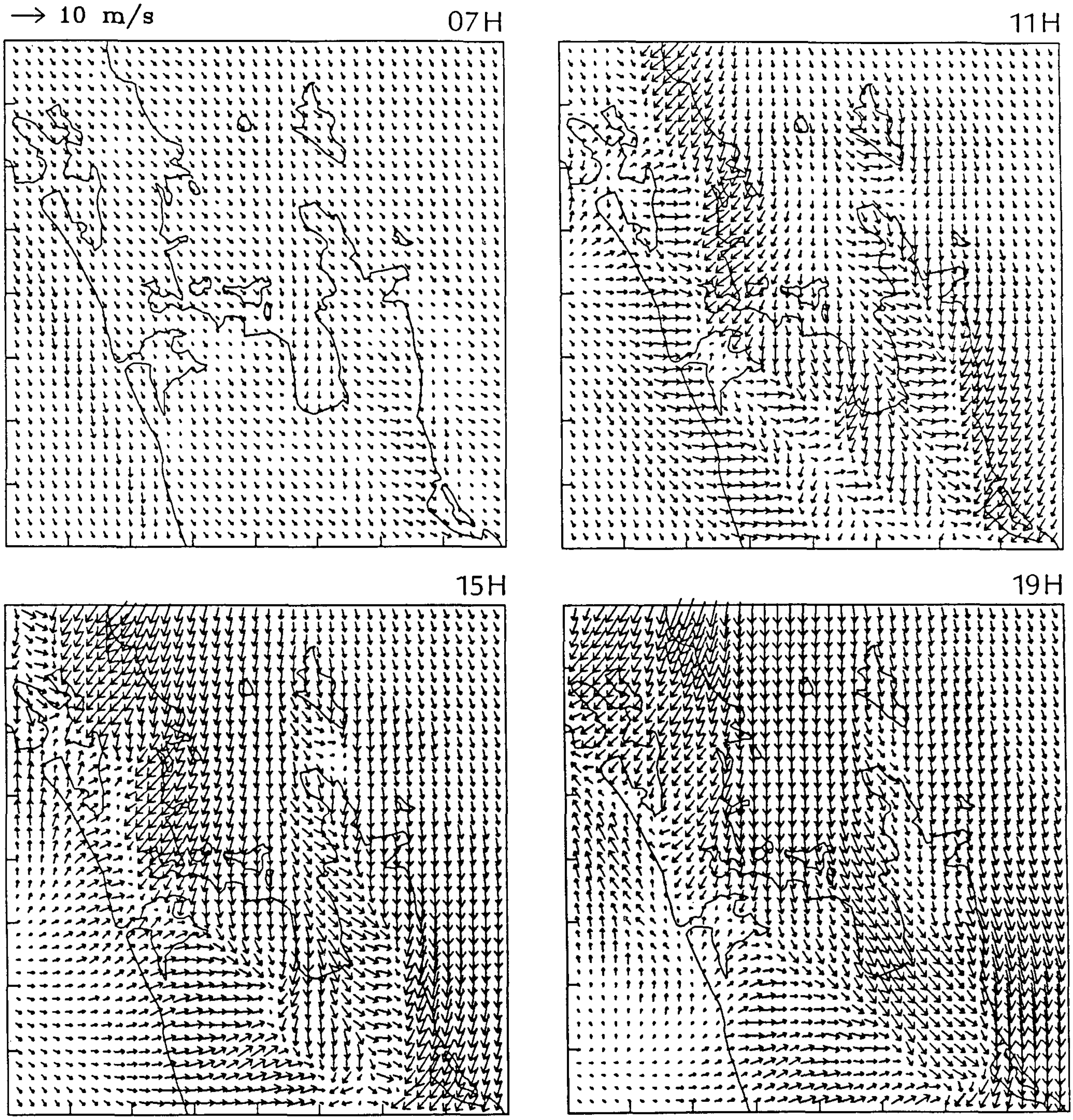

Fig. 4 Predicted wind fields at 10 m above ground level for 0700, 1100, 1500, and 1900 LST. Gradient flow is 3 m/s from the northwest.

1500, and 1900 LST. An east–west cross-section through Auckland City (shown in Fig. 1) is used to display variations in the depth and intensity of sea breeze induced convergence. The horizontal vertical velocity field at 500 m is also presented to highlight spatial variations in the position and intensity of sea breeze induced convergence. Vertical velocity fields are shown only for mid afternoon (1500 LST) and represent the time of maximum sea breeze development.

Northwesterly gradient flow

The evolution of the low-level wind field is presented in Fig. 4. By 0900 LST (not shown here), sea breezes are predicted along eastern coastlines and produce distinct convergence lines especially along the Coromandel Peninsula, to the southwest of the Hauraki Gulf, and to the north of Auckland. At this time, inland sea breeze penetration is of the order of 5–10 km. Sea breezes are well developed along all coastlines by 1100 LST and result in four distinct convergence lines. Over the centre of Coromandel Peninsula, marked convergence is predicted between the easterly sea breeze and the sea breeze augmented gradient flow from the Hauraki Gulf. To the north of Auckland City, convergence occurs between the east coast sea breeze, the gradient northwesterly flow (itself enhanced by sea breeze effects), and the local harbour breeze developed within the Kaipara Harbour. Finally, two convergence lines are predicted to the south of Manukau Harbour. One is

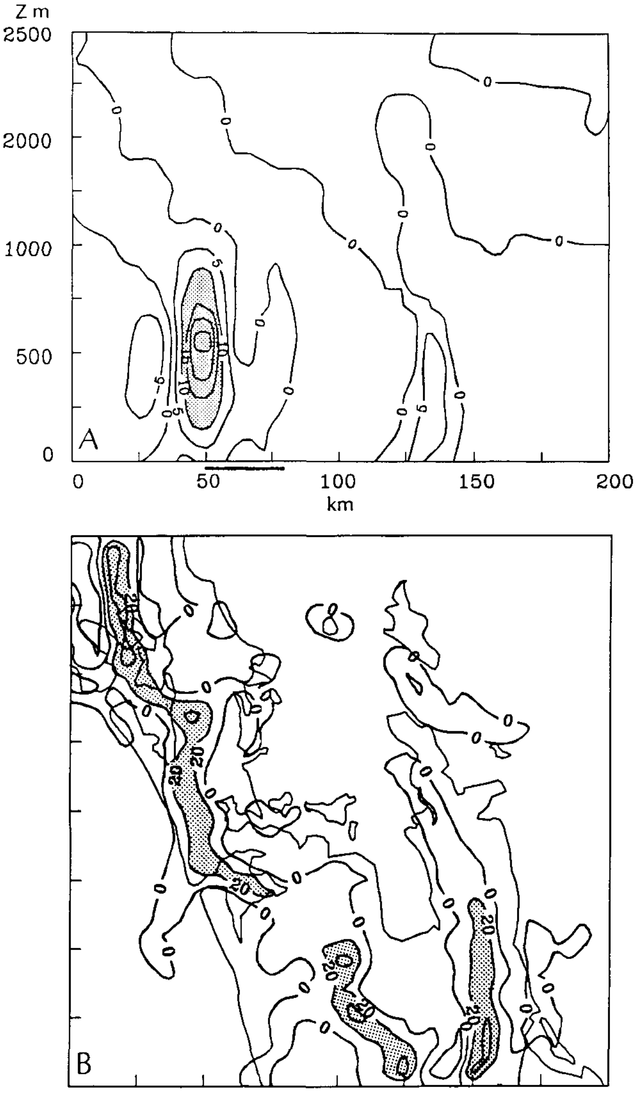

Fig. 5 Predicted vertical velocities (cm/s) for gradient flow of 3 m/s from northwest at 1500 LST. **A**, East–west cross-section ("A" shown in Fig. 1) through Auckland City (contour interval is 5 cm/s with shading representing upward velocities of >10 cm/s). The underscore denotes Auckland City. **B**, Horizontal field at 500 m a.g.l. (contour intervals 20 cm/s with shading representing upward velocities of >20 cm/s).

associated with the sea breeze from the east coast penetrating westward, and the other with the west coast sea breeze penetrating eastward. Between the two convergence zones, relatively light winds prevail. By mid afternoon, the two convergence lines to the south of Auckland have merged while that to the north of Auckland has pushed further westward. At this time, windspeeds at 10 m are of the order of 5–6 m/s over land and 3–4 m/s over the Hauraki Gulf. Finally, by 1900 LST, the convergence line to the north of Auckland has penetrated to within 10 km of the west coast. Elsewhere the dominance of the sea breeze circulations is diminished as thermal forcing decreases in late afternoon and winds become more northwesterly.

In Fig. 5A, contoured values of vertical velocity for an east–west cross-section through Auckland City show that maximum vertical velocities are associated with the surface convergence feature located to the west of the city. At the peak of sea breeze development in mid afternoon, a core of maximum upward velocities in excess of 30 cm/s is predicted to occur at c. 500 m. The sea breeze induced uplift is restricted to a layer c. 800 m in depth and is compensated for by weak subsidence over the west coast. Relatively weak uplift is predicted over the northern tip of the Coromandel Peninsula at this time.

The horizontal field of vertical velocities at 500 m (Fig. 5B) shows that the relatively strong uplift to the west of Auckland City is just one of several zones of more intense vertical motion associated with the SBCZs. Other zones are located to the south of the Hunua Ranges and over the southern Coromandel Peninsula. In each, the zones of enhanced vertical motion are associated with those areas where surface horizontal convergence is at a maximum.

Southwesterly gradient flow

In contrast to northwesterly gradient flow, which is subparallel to the broadscale northwest/southeast orientation of the Northland peninsula, southwest gradient flow is virtually normal to the major coastlines of the region. Consequently, this simulation is characterised by the eastward progression of sea breeze enhanced southwesterly flow across the model domain (Fig. 6). On eastern coastlines, opposing local sea breezes are only weakly developed, and their westward penetration is restricted by 6–7 m/s southwesterlies. No easterly sea breeze is predicted at Auckland City in this simulation. However, further north, a SBCZ develops along the eastern coastline and extends eastward into the Hauraki Gulf immediately to the north of Auckland City. During the afternoon, this marine convergence feature moves further northeastward and gradually weakens. In this simulation, flow within the Hauraki Gulf becomes generally northwesterly as opposed to the NNE flow evident under northwesterly gradient winds.

In the southeast of the model domain, sea breeze convergence is once again predicted along the centre of Coromandel Peninsula. By 1900 LST, this feature merges with the SBCZ associated with the sea breeze enhanced southwesterly flow which has migrated across the model domain from the western coastline.

The cross-section through Auckland City at 1500 LST (Fig. 7A) reveals only weak vertical motion since it does not intersect the major convergence zones developed in this simulation. However, zones of vertical motion of comparable intensity to those developed in the northwest case are evident in the horizontal field (Fig. 7B). These are restricted to localised areas immediately to the east of Kaipara Harbour and in the southeast corner of the model domain.

Southeasterly gradient flow

The evolution of the regional wind field for the case of southeasterly gradient flow is presented in Fig. 8. This case is similar to that for northwesterly flow in the sense that flow is subparallel to the orientation of the landmass. Consequently, neither east nor west coast sea breezes are able to dominate completely and the zone of sea breeze convergence remains over Northland. However, this is not the case over the Coromandel Peninsula. Here, sea breeze enhanced southeasterly gradient flow displaces the SBCZ that is normally developed over the peninsula eastward into the Hauraki Gulf. Along the Northland peninsula, the west coast sea breeze becomes more organised during the simulation and penetrates

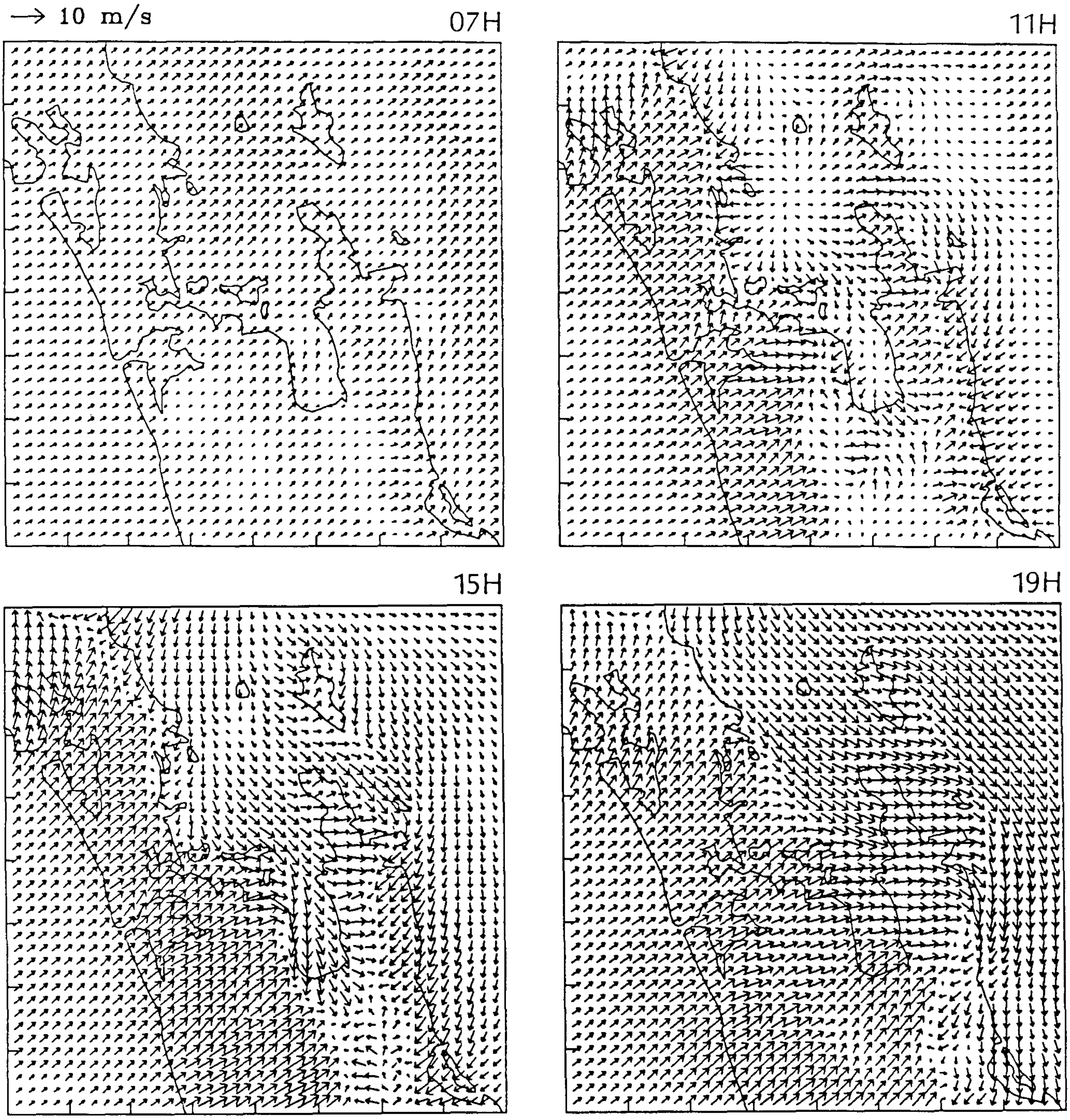

Fig. 6 As for Fig. 4 but gradient flow 3 m/s from southwest.

eastward toward the centre of the peninsula. This pattern appears to be enhanced by the development of local harbour breezes in the Kaipara and Manukau Harbours. These merge with the larger scale coastal sea breezes during mid afternoon resulting in windspeeds of 6–7 m/s and extension of the SBCZ further eastward. This pattern is opposite to that of northwesterly gradient flow (Fig. 4) when westward migration of the SBCZ takes place.

A notable feature of this simulation is the development in late afternoon (1500–1700 LST) of a cyclonic mesoscale eddy to the southeast of Manukau Harbour. This feature is 50–70 km in diameter and marks the convergence between onshore flow from the Kaipara Harbour, the larger scale west coast sea breeze flow, the onshore flow from the Hauraki Gulf, and the generally southeast flow in the southeast corner of the model domain. During southeasterly gradient flow, it appears that the topographic configuration of the region produces the exact combination of low-level flow which is conducive to the development of a cyclonic feature. The eddy continues to develop until 1900 LST and then gradually dissipates by 2300 LST. An east–west cross-section through the centre of the eddy at 1900 LST (Fig. 9A) shows vertical velocities of up to 30 cm/s with uplift extending through a depth of 1000 m. The secondary zone of uplift located further east of the mesoscale

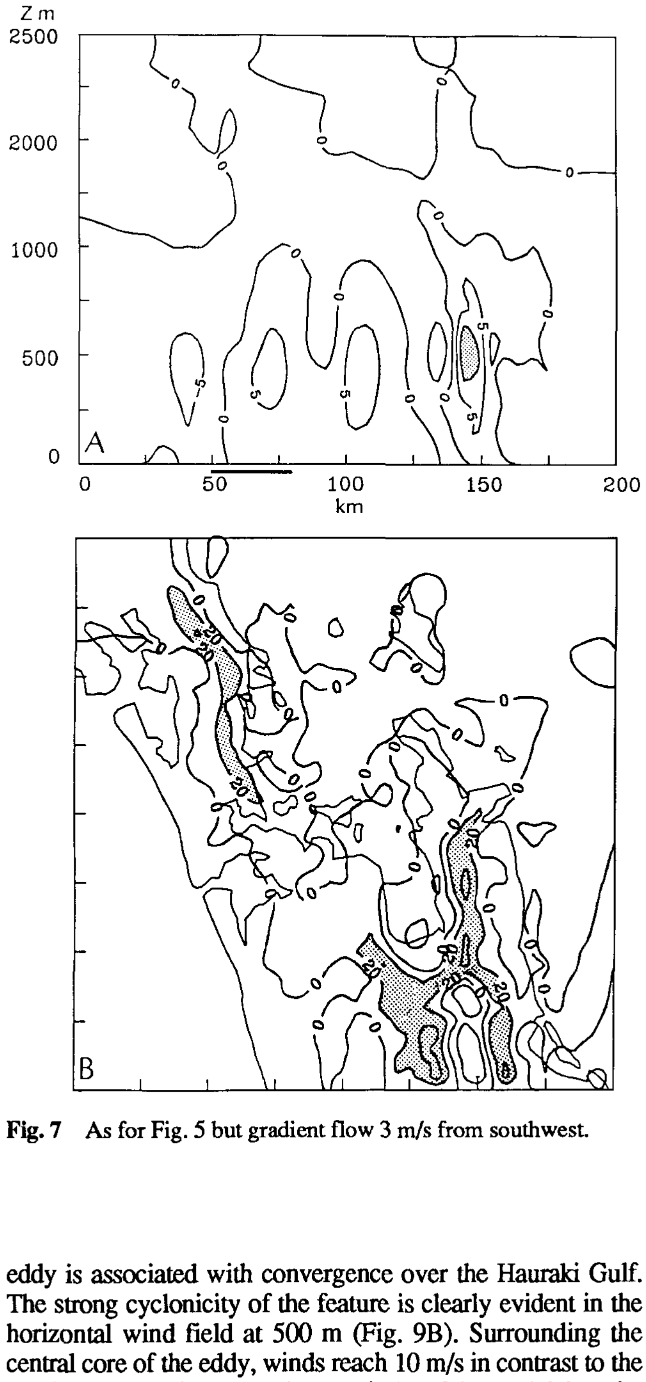

Fig. 7 As for Fig. 5 but gradient flow 3 m/s from southwest.

eddy is associated with convergence over the Hauraki Gulf. The strong cyclonicity of the feature is clearly evident in the horizontal wind field at 500 m (Fig. 9B). Surrounding the central core of the eddy, winds reach 10 m/s in contrast to the relatively light winds over the remainder of the model domain. At the 1500 m level (not shown here) the feature is characterised by marked divergence.

For southeasterly gradient flow, the vertical motion associated with sea breeze convergence near Auckland City (Fig. 10A) is not as intense or deep as that predicted for the northwesterly case. At 1500 LST, the core of upward motion is located slightly westward of that for the northwest case and is characterised by vertical velocities in excess of 10 cm/s extending to a height of 750 m. Again, the horizontal field of vertical velocities (Fig. 10B) shows the area immediately to the west of Auckland City to be a preferred zone of intense convergence. Other significant areas for this case include the eastern edge of the Kaipara Harbour and the region to the west of the Hunua Range which marks the location of the incipient mesoscale eddy. Here, vertical velocities reach 40 cm/s, the strongest for any of the simulations.

Northeasterly gradient flow

This case shares with the southwesterly situation large-scale flow which is approximately perpendicular to the main coastlines. As a result, sea breeze enhanced gradient flow dominates and opposing sea breezes are restricted to the western coastlines of the region throughout the simulation (Fig. 11). Consequently, persistent northeasterly winds of 4–5 m/s are predicted over Auckland City throughout the simulation. Only to the south of the Manukau Harbour does significant sea breeze convergence occur over inland areas. This is triggered by the interaction of sea breezes from the westerly coast and easterly flow deflected around the Hunua Ranges. By 1900 LST, the SBCZ which was located over the western coastline of the Northland peninsula for most of the simulation migrates offshore as the westerly sea breeze weakens in late afternoon.

The mid afternoon, east–west cross-section through Auckland City (Fig. 12A) shows upward velocities in excess of 10 cm/s associated with the SBCZ located over the western coastline. This vertical motion is not as intense as that associated with the northwesterly and southeasterly gradient flows. This is also evident in the horizontal vertical velocity field (Fig. 12B). Throughout the region, only localised zones of relatively weak vertical motion are predicted with the major features occurring to the west of Auckland City, to the south of Manukau Harbour, and over the southernmost portion of the Hauraki Gulf. The region surrounding Auckland City is characterised by weak subsidence at this time.

DISCUSSION AND CONCLUSIONS

For each gradient wind direction, the predicted location and movement of the SBCZs is in good agreement with observed patterns in the vicinity of Auckland City (Revell 1978; McGill 1987). With gradient flow perpendicular to the orientation of the Northland peninsula (northeasterly and southwesterly flow), SBCZs marking the boundaries between sea breeze enhanced gradient flow and opposing sea breezes are displaced toward the leeward coastlines. Studies elsewhere of the effect of offshore flow on sea breeze development attribute this pattern to the offshore advection of the temperature gradient responsible for sea breeze development (Atkinson 1981). Consequently, sea breezes that oppose the offshore gradient flow, although relatively strong, do not penetrate far inland. Horizontal temperature fields (not presented here for the sake of brevity) confirmed the presence of strongest land-sea temperature gradients along leeward coastlines.

For gradient flow subparallel to the Northland peninsula, the model successfully simulated the observed eastward migration of SBCZs across the peninsula to the north of Manukau Harbour under southeasterly gradient flow and the westward migration of SBCZs under northwesterly gradient flow. In these cases, the dominance of sea breezes from particular coastlines can be attributed to a combination of factors. The model results indicate that over the Northland peninsula the subparallel gradient flow initially causes advection of the temperature gradient responsible for sea breeze development toward the leeward coastline. This results in relatively strong sea breezes on the eastern coastline for northwesterly gradient flow and on the western coastline for southeasterly gradient flow. Conversely, the sea breeze that develops on the windward coastline is virtually perpendicular to the gradient flow and is forced by a relatively weak

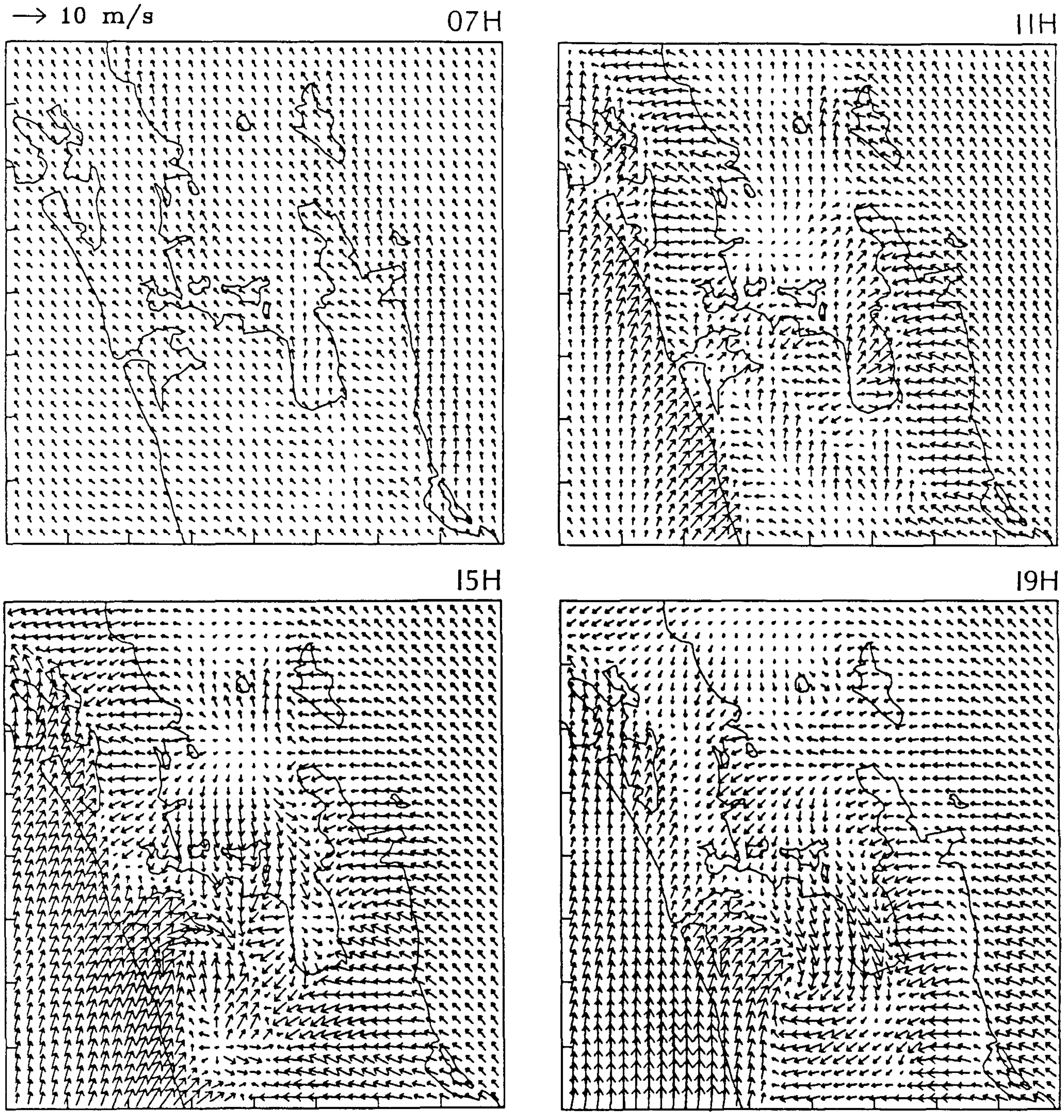

Fig. 8 As for Fig. 4 but gradient flow 3 m/s from southeast.

temperature and pressure gradient. This sea breeze is weaker and of shorter duration than that developed on the opposite coastline. It appears that it is the development of the relatively weak sea breeze on the windward coast that permits the stronger sea breeze from the leeward coast to migrate across the peninsula. In addition, it is likely that the augmentation of the upper level return flow by the offshore component of the gradient wind contributes to this pattern. For example, with northwesterly gradient flow, a component of the upper level flow is offshore along the eastern coastline. This strengthens the sea breeze return circulation along this coastline and inhibits that along the western coastline. Finally, it is apparent in the southeasterly case that local harbour breezes that develop in the Kaipara and Manukau Harbours play an important role in contributing to the eastward migration of SBCZs. During the afternoon, these local breezes merge with the large-scale coastal breezes, permitting considerable inland penetration. However, the simulations described herein do not incorporate the effects of the extensive tidal mudflats which form in both harbours as part of the normal tidal cycle. If exposed during sea breeze development, these mudflats may act to suppress inland penetration of the west coast sea breeze. Further studies are required to investigate the interactions between the tidal cycle and local sea breeze forcing in the region.

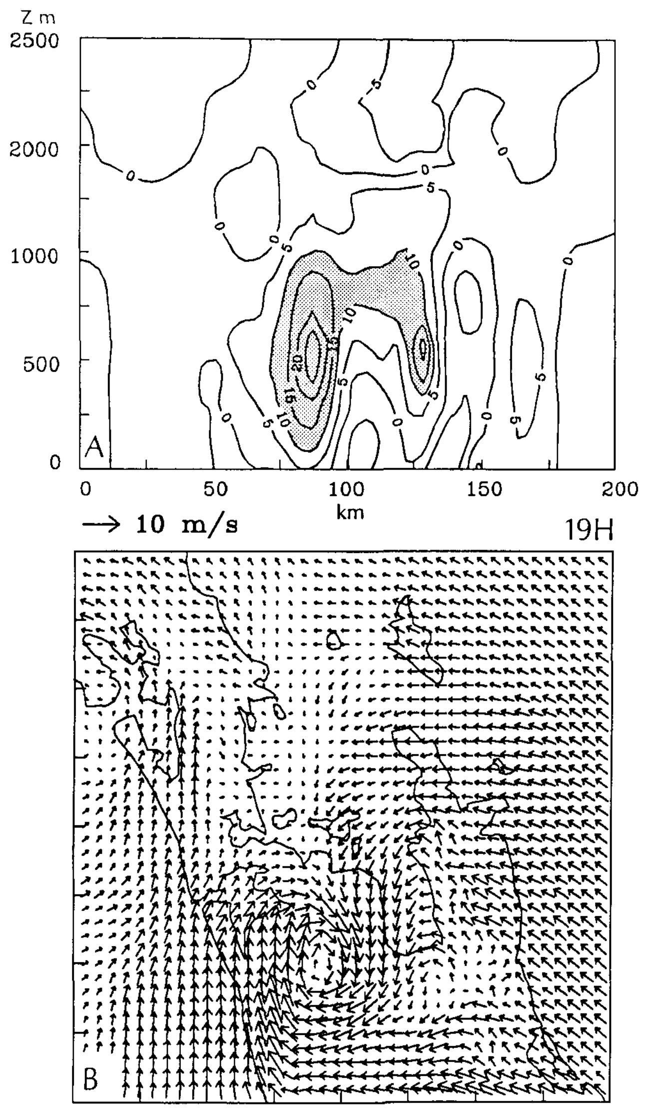

Fig. 9 Mesoscale eddy development under southeasterly flow at 1900 LST. **A**, Vertical velocities (cm/s) for cross-section "B" through centre of the eddy (shading and contour interval as in Fig. 5). **B**, Wind field at 500 m above ground level.

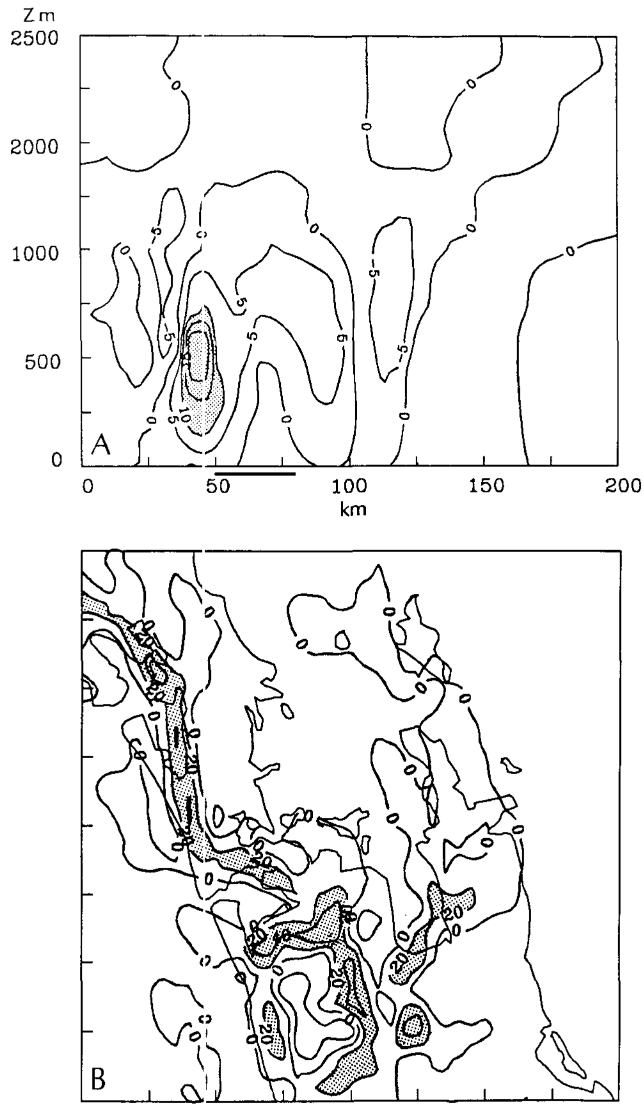

Fig. 10 As for Fig. 5 but gradient flow 3 m/s from southeast.

In summary, the numerical results indicate that gradient wind direction is a critical factor which determines the relative dominance of east and west coast sea breezes. With a northerly component of flow, the east coast sea breeze dominates, while for flows with a southerly component, the west coast sea breeze dominates. This suggests that a backing of the flow from southeasterly to northeasterly or northwesterly to southwesterly will result in a change in the relative dominance of east and west coast sea breezes in spite of the gradient flow remaining onshore with respect to one of the major coastlines.

Results of this study are in general agreement with previous modelling studies by Pielke (1974) and Noonan & Smith (1987) which show that, over peninsulas, localised zones of strong uplift may occur within sea breeze convergence lines. For example, Pielke (1974) has shown that these zones, which may develop in regions where the coastline curvature enhances horizontal convergence, are also zones of preferred cumulonimbus and thunderstorm activity. Although maximum vertical velocities in the Auckland SBCZs are generally less than those predicted for the South Florida case (Pielke's (1974) study predicted vertical velocities of up to 70 cm/s at 1.2 km), they are of sufficient magnitude to induce cloud development and precipitation under suitable conditions (McGill 1987). Unfortunately, there are few observations available to confirm the intensities of vertical motion predicted for the SBCZs or the dynamics of the sea breeze interactions away from the general locality of Auckland City.

A consistent feature of the simulations was the tendency for the Northland peninsula SBCZ to be located to the west of Auckland City in mid afternoon. Only during southwesterly gradient flow was the convergence zone located to the east of the city. Vertical velocities within this zone were strongest with northwesterly and southeasterly gradient flow. If the patterns and intensity of vertical motion predicted by the model are realistic, it is likely that this feature may significantly influence cloud and precipitation patterns around Auckland City. Research to investigate these effects is currently in progress.

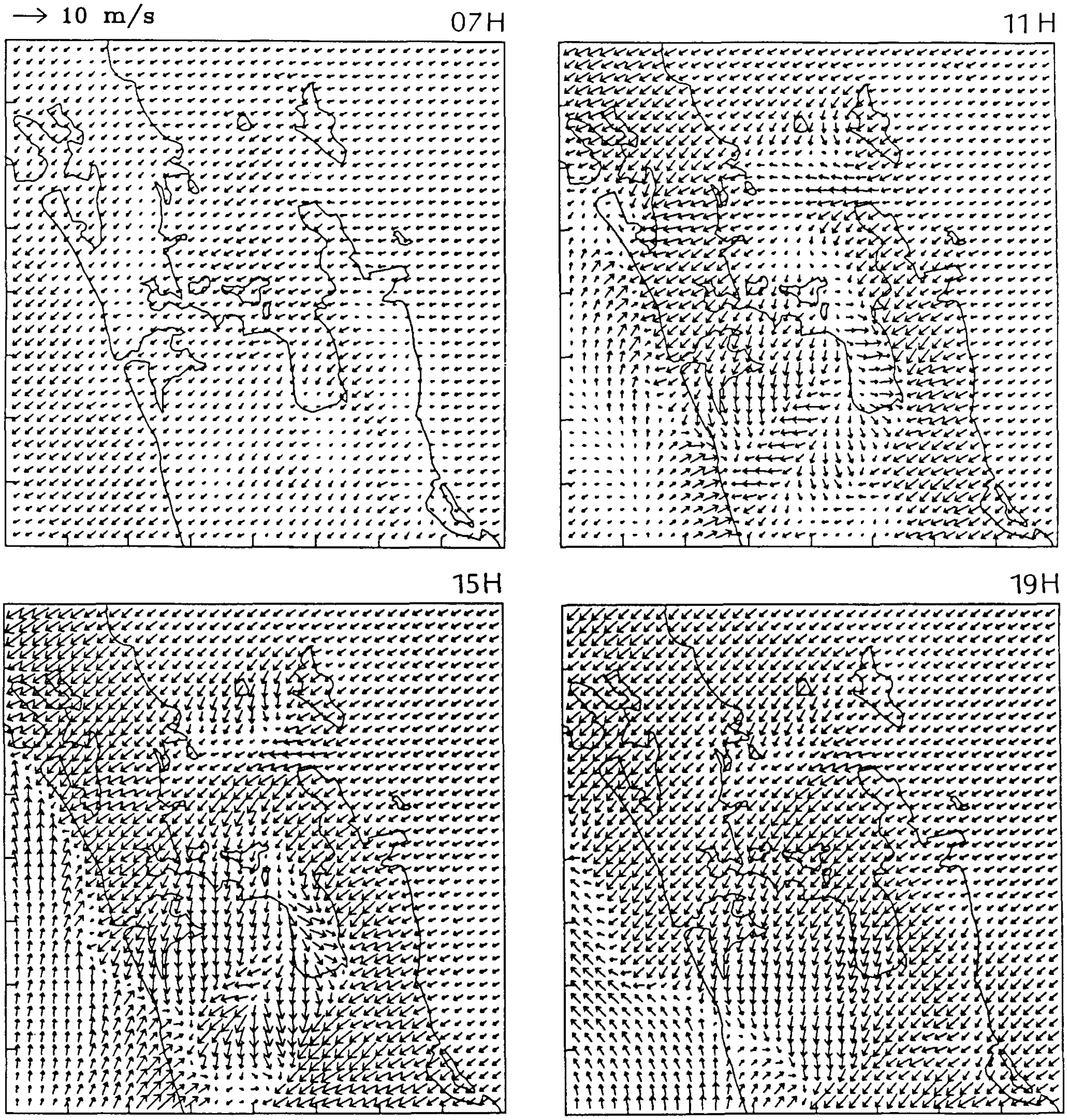

Fig. 11 As for Fig. 4 but gradient flow 3 m/s from northeast.

Prediction of a mesoscale cyclonic eddy during southeasterly gradient flow was a more surprising outcome of the simulations. Similar features, resulting from the convergence of boundary layer airflow and caused by a combination of differential heating and topographic effects, have been observed by Harada (1981) and Wendell (1972), and modelled by Carpenter (1979). More recently, a similar cyclonic eddy to that predicted in this study was observed and modelled over the Melbourne area (Abbs 1986; McGregor & Kimura 1989). There, the eddy was observed to develop during the early evening as a result of the interaction of "bay" and "ocean" breezes. Application of the Colorado State University mesoscale model showed the Melbourne eddy to have a depth of approximately 1000 m, strong ascent, and a duration of several hours. Only intensive observations in the Auckland area can determine whether the simulated cyclonic eddy occurs in reality. Location of the eddy in a region largely devoid of observations suggests that such an infrequent, ephemeral feature could easily pass unnoticed. However, Revell (pers. comm. 1990) did make detailed notes on what he believed to be a cyclonic eddy which occurred during southeasterly gradient flow on 18 February 1973. On that occasion, an eddy-like feature was observed in late afternoon in virtually the same location as the eddy simulated in the present study. Smoke plumes in the region suggested a cyclonic flow pattern which was surmised to be the result of

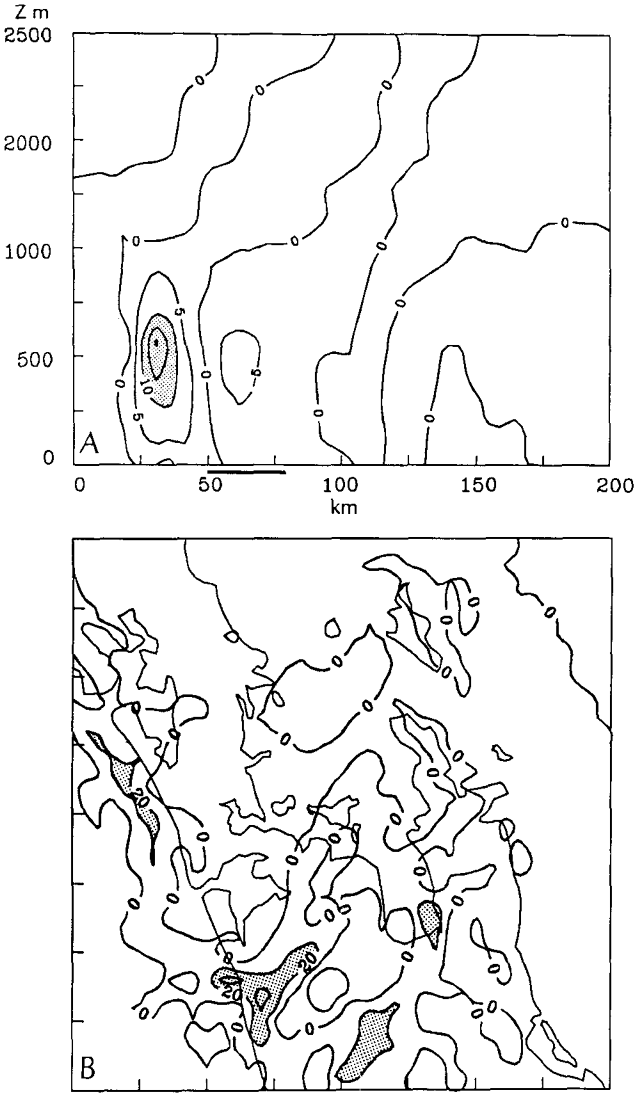

Fig. 12 As for Fig. 5 but gradient flow 3 m/s from northeast.

convergence between sea breeze flows and the predominant southeasterly gradient wind. By late afternoon (1745 LST), clouds associated with the feature had become organised into bands with a central concentration marked by precipitating towering cumulus.

Revell's observations provide solid evidence that on at least one occasion a mesoscale feature showing remarkable similarity to the simulated eddy developed under southeasterly gradient flow. However, other evidence (McGill 1987; Revell pers. comm. 1990) suggests that heat lows also occasionally develop over the central North Island during light southeasterly gradient flow. If the mesoscale eddy as simulated in this study develops under the same conditions that initiate a thermal low, either it may be obliterated under such a regime, or even more complex interactions may result.

Despite the good agreement between model predictions and available observations, several limitations of this study should be emphasised. The study has not considered variations in vertical thermal structure, gradient windspeed, or sea-surface temperature, all factors identified by McGill (1987) as influencing the character of sea breezes over the region. The exclusion of variable surface properties and the inability of the model to handle evolving synoptic situations are also major deficiencies in the approach adopted. Clearly, there is considerable scope for further modelling studies which address these shortcomings. However, intensive observational studies to investigate the existence, structure, and ultimately the meteorological significance of the mesoscale features identified in this study are a more immediate priority. A satellite climatology of SBCZs in the region would provide a useful first step in this direction. In addition, the installation of a surface mesoscale network in the region, complemented by a strong vertical sounding capability (weather radar, doppler sodar), marine observations, and enhanced satellite imagery, is imperative. The spatial and temporal variability in the regional wind field described in this study may provide an initial guide to the optimal location of stations within such a network.

The simulations described herein illustrate the complexity of sea breeze interactions that occur near irregular coastlines in a mid-latitude environment. The area studied is notable not only for the complexity of the coastline configuration and the small scale of the landmasses considered, but also for its strong synoptic variability. In this environment, the interaction between gradient wind direction and the complex coastal configuration is shown to be an important control on the intensity, location, and dynamics of migratory SBCZs, and on occasion may also induce the formation of a mesoscale cyclonic eddy. Within this context, the Colorado State University mesoscale model has successfully captured the salient dynamic aspects of mesoscale phenomena as previously observed in the area. Furthermore, results of these simulations provide an initial guide to the location of zones of significant vertical motion over the region. It is likely that these zones play a role in atmospheric dispersion, cloud development, and precipitation. In addition to having implications for local forecasting, dispersion studies, and recreation, further studies in this complex environment will undoubtedly contribute to an improved understanding of thermo-topographically induced mesoscale phenomena.

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