Sea-breezes and waves: the 'Kalgoorlie sea-breeze' and the 'Goondiwindi breeze'

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The Pielke numerical model has been used to investigate the wind surge often seen in summer on Kalgoorlie (350 km inland) anemograms at about 2300 h. The evidence provided by the model shows conclusively that the Kalgoorlie surge is activated by the sea-breeze, but that by the time it reaches Kalgoorlie it has degenerated to an internal long wave propagating on the nocturnal inversion. It cannot be deduced from the model whether the long wave develops undulations near its leading edge, but such structures are likely to be a fruitful source of solitary wave trains in the continental interior.

The model has proved successful in determining the origin of a summertime evening northeasterly wind surge often noticed at Goondiwindi, Queensland (315 km inland behind a range of mountains). It transpires that the sea-breeze front cannot be detected ascending the ranges. A surge starts near and to the lee of the top of the ranges in the early afternoon. It is this surge which reaches Goondiwindi at about 2100 h. By this time, however, sea air has actually penetrated inland as far as Goondiwindi. Three-dimensional modelling with orography shows that a surge line parallel to the coast reaches Goondiwindi at about 2100 h. It is a gravity current at this stage, but it also is evidently destined to degenerate, after midnight, to a long wave of elevation with solitary waves.

Introduction

Maxworthy (1980) deduced, as a result of his laboratory experiments on the gravitational collapse of mixed regions in fluid systems, that 'if a physical system is capable of supporting solitary wave motions, then such motions will invariably arise from quite general excitations'. This conclusion certainly seems to be applicable to the atmosphere at certain times (but not always, for a given set of conditions, as implied by the word 'invariably') and places, and we are concerned to investigate in detail which excitations produce the various wave trains observed in the atmosphere with a view to understanding their genesis and forecasting their occurrence.

Although attempts have been made to quantify the structure and behaviour of the solitary wave systems observed in the atmosphere (see Noonan and Smith 1985; Christie 1989; the extensions to the BDO theory elaborated by Grimshaw 1981; and Clarke 1989), full success has not yet been achieved. A number of questions concerning atmospheric solitary waves, their generation and properties remain unanswered.

Morning glory research in Australia (see e.g. Clarke et al. 1981; Clarke 1983b, 1984; Noonan and Smith 1986, 1987; Smith 1988) has shown that the exciting factor for the easterly morning glories occurring around the coasts of the Gulf of Carpentaria is the collision of two sea-breezes over Cape York Peninsula, when the easterly sea-breeze becomes transformed into an undular bore and propagates over the Gulf and adjacent land. This is evidently a special case of the encounter of an atmospheric gravity current with a suitably stratified medium. This encounter occasionally happens when a southern cold front impinges onto a sea-breeze preconditioned boundary layer south of the Gulf of Carpentaria, and results in a 'southerly morning glory' (although this mechanism seems not to account for all such morning glories. See Smith et al. 1986). A similar transformation may occur when a thunderstorm outflow encounters a suitably stratified boundary layer (Smith 1986; Haase and Smith 1984).

The author (Clarke 1984, Fig. 18(a)), with the
aid of his numerical model, has shown how a sea-breeze front or surge may degenerate during the night, when it is propagating into a stable environment, into what can be described as a long wave of elevation.

Christie et al. (1978) have measured many surface pressure signatures from what are evidently nocturnal boundary-layer waves, at Warramunga, in the vicinity of Tennant Creek, NT. The origins of these waves are obscure. Some, from their direction of movement, appear to have arisen inland of the Gulf of Carpentaria coast, and may be of sea-breeze origin; others may be excited by southern cold fronts and many must be traceable to thunderstorm outflows. Others have no obvious source and appear to come from high ground, but their precise mode of excitation has not been at all adequately explored. It seems unlikely that the Warramunga waves are remnants of morning glory waves from Cape York Peninsula because such a hypothesis would require them to be transmitted over a heated land surface by day when, in general, no surface inversion is available for them to propagate on.

The first objective of this communication is to describe and explain the Kalgoorlie sea-breeze, and the second to investigate the Goondiwindi breeze, by means of a numerical model.

The Kalgoorlie sea-breeze

In 1955 the author (Clarke 1955) claimed that he had demonstrated, by driving his car on a number of occasions on the Esperance-Norseman-Kalgoorlie road, that the sea-breeze in summer not infrequently penetrated inland from the south coast of Western Australia as far as Kalgoorlie, a distance of about 350 km. This claim was treated with disbelief by many, and with obvious scepticism by Atkinson (1981, p. 125). As far as is known there are no references in the literature to such deep penetrations, although the Snellius Expedition (Visser 1936) found apparent sea-breeze influences in the wind 370 km out to sea from Kalimantan. For a bibliography of some 536 publications on sea and land breezes, see Jehn (1973).

The known facts about the Kalgoorlie breeze have now been checked against predictions of the Pielke model (McNider and Pielke 1981) which has been widely used in mesoscale studies. The 1955 expedition showed that sea-breeze effects are usually quite strong between at least the coast and Norseman, some 160 km inland, which the sea-breeze reaches frequently at about 2000 h WST (UTC + 8 h), with an onshore component of wind of 10-15 m s\(^{-1}\) at 200-300 m above the surface. The mean speed of propagation on the days when the surge reached Kalgoorlie was found to be 9 m s\(^{-1}\) or more, and typical times of arrival in Kalgoorlie were about 2300 h. It was admitted (Clarke 1955) that ‘the sudden 2000-2400 h freshening of wind at Kalgoorlie has not been sufficiently studied’.

January 1986 anemograms, dry and wet thermograms and weekly barograms, and the Australian region surface weather maps for the month have been examined in detail. Five days (11th, 12th, 20th, 23rd and 26th) have been selected as typical ‘Kalgoorlie sea-breeze’ days on the basis of the anemograms. No response is evident from the other autographic instruments on these days except for a slight sharp rise (about 1°C) in both wet and dry-bulb temperature at 2230 h on the 12th. Times of arrival of the sea-breeze at Kalgoorlie varied from 2210 to 2335 h, with a mean of 2300 h. A specimen anemogram is shown, for 12 January 1986, in Fig. 1. The MSL isobars at 2000 h WST for this day show an anticyclone of central intensity 1017 hPa located in the Bight at 35°S, 131°E, with isobars parallel to the south coast (orientation 071-251°) of Western Australia, indicating a geostrophic wind of about 7.5 m s\(^{-1}\). Maps for the other four selected days were very similar. On occasions when a summertime trough or col lies in the Kalgoorlie-Esperance area, frontogenesis and sea-breeze effects usually combine to form a vigorous cold front-like disturbance, as noted in the 1955 paper. When this disturbance reaches Kalgoorlie it is similar in many ways to the Kalgoorlie sea-breeze, but it typically arrives earlier in the evening, is stronger, and from a more southerly direction; it is known locally as the ‘Esperance doctor’. Such cases are not considered here, although their essential features could almost certainly be successfully numerically simulated by
Modelling the Kalgoorlie sea-breeze

Two-dimensional modelling

This was done for no orography and for steadily rising land (Kalgoorlie has an altitude of 360 m) with 30 grid-points in the vertical and a horizontal grid length of 10 km, from 450 km offshore to 450 km inland. Typical January conditions were prescribed, with fairly dry ground, an initial temperature and humidity profile as averaged from the five 0600 h daily Kalgoorlie radiosoundings, a constant sea surface temperature of the climatological value (20.5°C), and a geostrophic wind of 7.5 m s\(^{-1}\) from 071°.

These two-dimensional model runs returned similar results but, with rising terrain, the sea-breeze travelled more rapidly inland; in terms of vigour, as measured by the vertical velocity component at its leading edge, it was weaker. At midnight, with rising land, the surge had travelled 316 km inland, its maximum vertical velocity was only 0.048 m s\(^{-1}\) (at 500 m) and its speed 10.7 m s\(^{-1}\). These values may be compared with the no-orography experiment, where the penetration was 282 km, the vertical component 0.059 m s\(^{-1}\) at 550 m, and its speed 10.0 m s\(^{-1}\). In neither case did the model produce an arrival time at Kalgoorlie near the observed mean time of 2300 h, but rather at 0100 and 0200 h respectively. In neither case could the disturbance be described as a gravity current late in the evening. In the ‘sloping land’ case the speed of the surge exceeded that of the forward wind component at any level behind it by 2200 h, and in the no orography case this was so by 2300 h. Figures 2 and 3 show streamlines relative to the surge and isentropes for the ‘sloping land’ case at 2000 and 2200 h respectively. During the two hours from 2000 to 2200 h the sea-breeze surge degenerated from being part of a closed horizontal vortex, with a length of over 100 km and the forward wind component behind the leading edge rising to \( u = 13.7 \text{ m s}^{-1}\) at 200-300 m, to a decaying wave-like perturbation with maximum \( u \) behind it of only 11.2 m s\(^{-1}\). The computation shows that the wind behind the surge remains of the same strength during the two hours but Coriolis effects have turned it anticlockwise through 9°, suggesting that the transition from a horizontal vortex to a mere wave is due in large part to earth rotation. This transformation, from vortex to wave, and the accompanying flattening of the isentropes has been described by Clarke (1984, Fig. 18(a)) for tropical latitudes, and the present Figs 2 and 3 respectively correspond to the ‘early degenerative’ and ‘late degenerative’ stages in the author’s 1984 classification. The degeneration evidently occurs more rapidly in the Kalgoorlie area than in the tropics, where Coriolis effects are less.

Effects of the passage of the surge near the ground (height 2 m above the surface) according to the model are shown in Fig. 4 for two points, respectively 185 and 295 km inland. The surface effects of the surge are predicted by the model to be fairly well-marked in wind and pressure in the former case but not in the latter. The finite grid length of 10 km inevitably produces smearing of modelled changes compared with observation, especially in the near-surface wind which is observed to typically rise from nil to 5 m s\(^{-1}\) in a minute or two. Surface temperature and humidity are clearly not good indicators for the passage of such a surge.
Fig. 4 The computed responses at two fixed points (a) 185 km inland and (b) 295 km inland at the lowest model level (2 m) to the passage of the surge, which occurs at 2030 and 2330 h respectively. Variation with time is shown for temperature, specific humidity, pressure and two components of wind. u is the inland-directed component, v the coast-parallel one.

The ‘origin’ of the air behind the surge was investigated by tracing the trajectories of parcels of air initially (at 0600 h) offshore. Some 60 such trajectories were traced. Only two such parcels were keeping up with the surge by 2000 h and none at all thereafter. The parcel penetrating furthest inland (277 km) by midnight, when the surge was 317 km inland, had started at 0600 h at a height of 300 m and a distance of 60 km offshore. Laterally, it had drifted (parallel to the coast) a distance of 585 km by midnight.

Summing up the results of the two-dimensional studies we conclude that the model agreed qualitatively with observations but the large drift of parcels along the isobars and parallel to the coast probably meant that the assumption of uniform conditions in the coast-parallel direction was unrealistic, and was responsible for the modelled surge arriving at a point 350 km inland some hours later than is normally observed at Kalgoorlie. To test this hypothesis, a three-dimensional model was set up with the best available orography.

Three-dimensional modelling
A horizontal grid length of 20 km, as used by Noonan and Smith (1987), and a time-step of 60 s were chosen with horizontal coordinates pointing east and north. The inner area consisted of a 33 x 36 grid with 20 points in the vertical, the highest above 9 km. Conditions chosen were the same as were used in the two-dimensional experiments. Values of wind components and potential temperature at several levels were recorded hourly for analysis.

It turns out that the irregular topography introduces a considerable amount of noise into the vertical velocity components so that it is not possible, with the information available, to locate the leading edge of the modelled sea-breeze surge in the early hours of its existence. By 2000 h, however, the picture is becoming increasingly clear. A surge line is propagating inland, as shown in Figs 5 and 6, being well-marked by the vertical velocity. By 2200 h the easterly part of this surge line, lying very nearly east-west, is probably being affected by the proximity of the northern boundary, but the western portion is propagating towards northwest as a line oriented approximately 065-245° at about 12 m s⁻¹. This line passes over Kalgoorlie at precisely 2300 h. The 2300 h fields of horizontal wind speed and direction, at a height of 100 m above the surface are shown in Fig. 7.

Wind components normal to the surge and just behind it show without doubt that, during the period 2200-2300 h, the line is moving at a speed greater than the normal component of the wind at any level behind it. The normal components at 2230 h at 10, 100, 200 and 350 km above the surface were 4.4, 8.2, 8.5 and 6.5 m s⁻¹ respectively.

Fig. 5 Map showing the coast and the inner area of computation, except for the seaward extension of the area, which is truncated. Isochrones show the location of the surge at hourly intervals from 1900 to 2400 h. The sharp bend in the surge at 1900 and 2000 h is evidently due to the topography.
General comments
It would seem that the proper classification of the Kalgoorlie sea-breeze is as the leading edge of a finite-length wave of elevation and not as a gravity current. The development of waves behind its leading edge, as noted by e.g. Christie (1989), or like the pressure waves recorded by Christie et al. (1978), cannot be deduced from the present coarse hydrostatic model, but it is likely that post-surge waves of modest amplitude do develop. The pre-surge and post-surge potential temperature profiles at 2300 h are shown in Fig. 8. Low-level cooling in the former has been the result of radiative and turbulent heat flux diver-

Fig. 6 Map showing the distribution of vertical velocity w (cm s⁻¹) at a height of 700 m above the surface at 2300 h.

Fig. 7 Map showing the modelled wind speed (m s⁻¹) and direction (degrees) at 100 m above the surface at 2300 h.

Fig. 8 The vertical distribution up to 1300 m of potential temperature at a point 40 km ahead of the advancing surge at 2300 h, and that at a distance of 40 km behind it. The lower model levels are also shown. Humidity was computed but not recorded.
verts the available potential energy, produced mainly by heat flux from the ground, into atmospheric kinetic energy largely directed parallel to the coast with an efficiency, averaged over the period from sunrise to 2200 h as computed by Clarke (1973) for latitude 36°, of about 1.2 per cent. This results in the quite strong boundary-layer winds shown in Fig. 7 for the 100 m level. Even stronger winds are computed for 200 and 350 m, at 2300 h being well in excess of 20 m s⁻¹, although the imposed initial geostrophic wind is only 7.5 m s⁻¹. Some of the energy remains in the early morning hours as a propagating wave which, when examined in detail, would probably turn out to be a packet of solitary waves.

The Goondiwindi breeze

Jacquie and Nigel Killalea (personal communication) of ‘North Callandoo’, near Goondiwindi, Queensland, have provided information that a breeze from the northeast springs up on many summer evenings. Goondiwindi is 315 km inland from the central Queensland coast at about latitude 28°S. It is well known that a summertime northeasterly or easterly surge commonly occurs at Oakey, about 140 km inland, and there is plenty of evidence concerning this surge from autographic meteorological records taken there.

The Goondiwindi breeze has been treated in a similar fashion to the Kalgoorlie one. Two and three-dimensional simulations were carried out in the Brisbane-Goondiwindi area. It had been reported that the breeze was observed at 2230 and 2030 h on 29 and 30 December 1988 respectively, when the surface geostrophic wind in the area could be approximated by $V_g = 7.5$ m s⁻¹ from a direction of 020°, the sea surface temperature was about 23.5°C, and the temperature and humidity profiles measured at Brisbane at 0900 h EST (UTC + 10 h) could be taken as representative.

Two-dimensional modelling

One significant difference between the Goondiwindi and Kalgoorlie cases is that in the former a pronounced ridge, up to 600 m high and roughly parallel to the coast, bars the way of an inland-penetrating sea-breeze. It has been pointed out by the author (Clarke 1983a) that the presence of an escarpment of this magnitude near Canberra does not prevent a sea-breeze from occurring commonly there; also that the hilly ground near the eastern coast of Cape York Peninsula does not prevent the easterly sea-breeze from flooding across the Peninsula (see also Noonan and Smith 1986).

A simulation for the Goondiwindi area with the hill in place demonstrates that the hill has quite a profound influence on the sea-breeze front and its penetration inland. Figure 9 shows that the sea-breeze surge moves normally, propagating about 100 km inland, until it comes hard up against the ridge, and then cannot be traced beyond about 1500 h. At approximately 1300 h another discontinuity (marked by a vertical velocity and isallobaric maximum) begins to develop in the lee of the hill and continues to develop and propagate down the hill on to the plain where Goondiwindi lies, reaching the latter at 2118 h. The succession of events is suggested by Figs 10, 11 and 12, showing the inland-directed wind component $u$ as a function of height and distance inland at 1000, 1400 and 1900 h. The sea-breeze maximum appears to interact with the wind maximum near the top of the hill and this results in the downhill and inland migration of this wind maximum. By the time it reaches Goondiwindi the associated surge is a strong gravity current disturbance, propagating at 8 m s⁻¹ and accelerating, with a maximum $w$ (vertical velocity component) of 0.24 m s⁻¹, at about 1400 m. By midnight it is just as strong and its speed is over 10.0 m s⁻¹.

An experiment with no orography shows the sea-breeze propagating steadily inland, as shown in Fig. 9, reaching Goondiwindi at 2250 h. It is considerably weaker than in the ‘hill’ case, maximum $w$ being only 0.14 m s⁻¹, and by midnight has decayed to the stage where it is a long wave of elevation (the normal wind behind it being less at all levels than the propagation speed of 11.8 m s⁻¹). The presence of the hill results in the breeze springing up earlier and being stronger than it would otherwise be, as found by Noonan and Smith (1986) for Cape York Peninsula.
Fig. 10 The distribution of u, the wind component normal to the coast, as a function of distance inland and height at 1000 h. The coastal wind maximum is the incipient sea-breeze; the other is due to temperature differences induced by the hill.

The remaining question is: is the Goondiwindi breeze a sea-breeze? In order to find the answer we computed trajectories for parcels of air lying out to sea (between 100 and 30 km offshore and 50 to 400 m above the surface) at 0600 h. Two such trajectories are shown in Fig. 13. They show that the air arriving at Goondiwindi with the breeze after 2100 h has indeed come from the sea and is lifted dramatically when it overtakes the frontal line. Thus, although the surge in its earlier history did not contain air which had been over the sea at 0600 h (the gap between the most advanced trajectory and the surge narrowed steadily from 96 km at 1300 h to zero at about 2100 h), by the time it reached Goondiwindi at least some of the air in the surge had come from the sea and this continued to be the case until 2400 h.

Fig. 13 Cross-section showing the hill barring the way from the coast to Goondiwindi (315 km inland) and the trajectories of two parcels of air, A and B, tracked from respectively 60 and 30 km offshore and 50 m above the sea at 0600 h. Both penetrate inland to Goondiwindi and overtake the 'breeze' or surge which the two-dimensional model predicts should reach Goondiwindi at 2118 h. The numbers in brackets near the 2100 h locations show lateral (coast-parallel) displacements of the parcels at 2100 h.

Fig. 11 As for Fig. 10 but at 1400 h. The sea-breeze circulation and that on the hill have both expanded inland. The surge or front in the lee of the hill is detected by a pressure tendency and vertical wind velocity maximum.

Fig. 12 As for Fig. 10 but at 1900 h. The wind maxima have pushed further inland while intensifying and the surge or front in the lee of the hill is gathering both speed and intensity.

Three-dimensional modelling
As before, a 20 km grid was used with axes pointing towards west and south and the best available topography. The inner mesh consisted of 39 x 21 grid-points.

Pressure tendency fields showed that a line of maxima roughly parallel to the coast developed by about 1800 h and moved steadily inland (Fig. 14). This line was associated with a line of maxima in w at heights of 1000-1500 m, with an advancing northeasterly wind maximum at 100-300 m above the surface. The wind and potential temperature fields at 2130 h and 100 m are shown.
Fig. 14 Map showing the coast near Brisbane and the inner area used for three-dimensional simulation, with orography, of sea-breezes under cloudless and dry conditions in January. The lines marked 18 to 23 show the locations of maxima in the surface pressure tendency indicating an inland-propagating surge line. The three dots mark, from left to right, the locations of Goondiwindi, Oakey and Brisbane.

Fig. 15 As for Fig. 14 but showing the speed (m s⁻¹) and direction (degrees) of the 100 m wind at 2130 h.

Fig. 16 As for Fig. 14, but showing the potential temperature (degrees C) of the air at 100 m above the surface at 2130 h.

Conclusions

The Pielke model captures many of the essential ingredients of the sea-breezes and waves considered here and is thought to provide some very good insights into the mesoscale behaviour of the real atmosphere in the virtual absence of clouds.

It demonstrates beyond doubt that the Kalgoorlie sea-breeze has in fact, by the time it reaches Kalgoorlie, ceased to be a genuine sea-breeze since no sea air can be found behind it; the evidence shows that it is a propagating wave, the heir of the sea-breeze front, which in the course of the evening becomes transformed from a gravity current to a long wave of elevation. An important factor in this transformation is the Coriolis acceleration which prevents the wind from keeping up with the surge front by continually turning its direction, anticyclonically in the southern hemisphere. Thus the time of the transformation is dependent on latitude, acting more slowly in lower latitudes. The speed of the surge is apparently determined by its character as a wave.

The Goondiwindi breeze turns out to be more complex than expected, the sea-breeze front apparently being blocked by the substantial hill (600 m high, 115 km inland). A new breeze (surge) develops in the lee of the hill before the sea-breeze could possibly penetrate there, so that the breeze is not initially a sea-breeze at all. It appears to separate potentially cooler air originating on the lower seaward side of the hill from the warmer air on the highlands. It propagates down the hill and is eventually overtaken by cooler air which has come from the sea. Thus, by the time it reaches Goondiwindi it can with some justification be labelled a sea-breeze. Eventually it too will be transformed into a wave, as in the case of the
Kalgoorlie surge. It is perhaps surprising that the presence of high ground strengthens and hastens the onset of the surge, rather than inhibiting it.

References

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