NUMERICAL MODELLING OF THE PROPAGATION ENVIRONMENT IN THE ATMOSPHERIC BOUNDARY LAYER OF LITTORAL AREAS

Summary of Findings from Phase 2

R. S. Plant and B. W. Atkinson

Department of Geography
Queen Mary and Westfield College
University of London

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Contents

Abstract

We present a brief summary of the findings from the project *Numerical Modelling of the Propagation Environment in the Atmospheric Boundary Layer of Littoral Areas.*

1 Introduction

This project is concerned with assessing the capability of mesoscale numerical models for predicting the propagation environment in coastal areas. Phase 1 covered the testing of a non-hydrostatic, numerical model in idealized and realistic situations (Li and Atkinson, 1997a,b, 1998a,b). The realistic cases (Li and Atkinson, 1998b) were run to simulate conditions in the Persian Gulf in a period when aircraft observations had been taken (Brooks *et al.*, 1997, 1999; Brooks and Rogers, 2000). The results were encouraging and showed that the model was capable of capturing the essential features of the propagation environment. A marine boundary layer (MBL) over the Gulf was well simulated in both its depth and the gradients of temperature, humidity and refractivity therein. In addition to the important vertical gradients at the top of the MBL, well-developed sea-breeze circulations were found which exhibited a strong horizontal gradient at the boundary between sea and land air. It is tempting to call this gradient the sea-breeze front (SBF), but care in nomenclature is required here as observations of such fronts show them to be hundreds of metres, rather than several kilometres, wide.

In the light of the results from Phase 1, it was decided to pursue several aspects of the project in greater detail (Atkinson, 1999). The reports produced during Phase 2 (Plant and Atkinson, 1999, 2000a,b,c) have discussed the effects of grid resolution (1999), the development of the marine internal boundary layer (2000a), the application of the `TERPEM` model (2000b) (a code that allows calculation of the response of electromagnetic radiation to the refractivity environment produced by the meteorological model) and the effects of the initial conditions (2000c). Results from this project are also presented in Atkinson *et al.* (2000) and Plant and Atkinson (2000d). In the present report we offer a summary of the findings of this project. Since a summary of the Phase 1 findings is already available (Li and Atkinson, 1998c) we concentrate here on the work of Phase 2.

The report also includes an Appendix. This is included for reference purposes and contains a summary of mesoscale model runs performed during the project.

2 Physical Issues

As stated in the Introduction, the main aim of the project has been to investigate the extent to which a mesoscale meteorological model can be used to predict the propagation environment over a littoral area. The quality of the prediction available is connected with many practical and numerical issues such as the choice of grid resolution, the initial conditions and the detailed transfer of refractivity data to a radar propagation model. Questions of this sort are discussed in Sec. 3. Here we summarize the physical description of the propagation environment that has been obtained in the course of the project. This provides an indication of the physical effects that can and cannot be captured using the mesoscale–model approach.

The simulations have been divided into low- and high-wind cases, following the division of the observations made by Brooks *et al.* (1997). The SHAREM-115 research flights gathered data a couple of hundred kilometres or so downwind of the Saudi Arabian coastline, within a marine boundary layer that was well-adjusted to sea-surface conditions. Although there was "considerable variability on a scale of 10 to 20 km" (Brooks *et al.*, 1997), any longer–range trends across the observation region were found to be modest, certainly in comparison with the horizontal evolution of the MBL that might be expected within a hundred kilometres or so of the coastline. The short–scale variations could not be captured by the mesoscale model (Plant and Atkinson, 2000a, p5). There may be numerical obstacles to this due to the limited vertical resolution and the strong horizontal smoothing in the model (Li and Atkinson, 1998b, p17). However, the main reason for the failure to simulate short–scale variations seems to be the absence of certain physical mechanisms from the modelling. Explicit resolution of entrainment at the MBL top may be necessary. Inhomogeneities in the sea-surface temperature (SST) may also be an important factor. It has been shown that realistic spatial variations of SST can force short–scale, low-level variations in the humidity (Plant and Atkinson, 2000c).

By contrast, the main properties of the mature MBL were fairly well captured by the model, provided that the initial conditions included some information on the MBL (Plant and Atkinson, 2000c). The definition of an MBL height is somewhat ambiguous (Stull, 1988; Plant and Atkinson, 2000a, Appendix A) but mid-afternoon heights of around 100 m in the low-wind case and of 300–400 m in the high-wind case were in good agreement with observations (Brooks *et al.*, 1997, 1999). The strong horizontal and vertical gradients that mark out the marine internal boundary layer (MIBL) were reasonably well reproduced (Plant and Atkinson, 2000c, p14) and were correctly predicted to be stronger in the low-wind case. Some aspects of the long–range variations in the mature MBL could also be distinguished (Plant and Atkinson, 2000c, p16). Ducting properties, such as the depth, character and trapping strength, were found to be in good agreement with the observations (Plant and Atkinson, 2000b, p12).

Conditions immediately downwind of the coast could not be compared with observations but the model predictions accorded with general expectations from existing experimental and theoretical studies (Atkinson, 1981; Simpson, 1984; Garratt, 1990, 1992). In particular, a sea-breeze circulation (SBC) developed, consistent with the model resolution. It is important to obtain a good representation of the SBC since this has been found to have some significant effects on the distribution of refractivity within the lowest few hundred metres of the atmosphere. Some examples of this are:

- Uplift at the sea-breeze front (SBF) transports marine air upwards resulting in an isolated moist region above the MIBL around the position of the front (Plant and Atkinson, 1999, p9);

- Advection of the SBF inland moves marine air landwards in the early evening (Li and Atkinson, 1998b; Plant and Atkinson, 2000a, p22). This smooths out the horizontal gradients between the land and sea air masses and has important effects on the propagation around the coast. Radar signal trapping is enhanced, signals sent from land to sea being more easily captured by the growing duct and signals sent from sea to land being more strongly retained within the decaying duct (Plant and Atkinson, 2000b, p21, p23);

- Onshore and near-stationary velocities in the SBC of the low-wind case perturb the humidity distribution in the MIBL (Plant and Atkinson, 2000a, p23; 2000c, p17);

- In the high wind case, the SBF lies several tens of kilometres out to sea. The precise representation of the SBC is sensitive to numerical factors but if the circulation is modelled as being strong enough to reverse the synoptic wind at low levels then the MIBL depth undergoes a hydraulic jump just beyond the front. This occurs because air-mass adjustment to sea-surface conditions can occur over a short distance within near-stationary flows. This was explained by Plant and Atkinson (2000a) using a generalization of the MIBL growth model of Garratt (1987); Garratt and Ryan (1989). Although there is no corresponding jump in the duct depth, there are manifest changes to the refractivity difference across the duct at the SBF (Plant and Atkinson, 2000b);

- The depth of the trapping layer is reduced through the action of subsidence in the tail of the SBC (Plant and Atkinson, 2000b, p18);

- At high altitudes, there is a dip in the isolines of refractivity at the position of the SBF (Plant and Atkinson, 1999).

The shape of the potential temperature profile confirms that the MIBL formation in the model is driven by turbulent rather than radiative cooling (André and Mahrt, 1981; Plant and Atkinson, 2000a, p10). It consists of a well-mixed layer near the surface, overlain by an inversion, above which one finds the decaying remnants of the overland convective boundary layer. At short fetches, only a surface–based inversion occurs. As the fetch increases the inversion deepens, reaching a constant depth which is maintained out to long range. Further growth of the MIBL then occurs through elevation of the inversion as the mixed layer is developed. The MIBL profiles are not suitable for power-law fits (Plant and Atkinson, 2000a, p11), as have been suggested elsewhere[1] (Mulhearn, 1981; Garratt and Ryan, 1989), but the potential temperature contours are found to be approximately parallel. This is a fundamental assumption of Garratt and Ryan's (1989) MIBL growth model (Plant and Atkinson, 2000a, p11) and it is interesting that it appears to hold in the mesoscale model results despite the perturbing effects on the MIBL of the strong SBC.

Quite small details in the vertical profiles of modified refractivity can have significant effects on the propagation environment (Plant and Atkinson, 2000b), even to the extent of altering the duct classification (Burk and Thompson, 1995). The low-wind case exhibits a shallow simple surface duct throughout. The refractivity difference across the mature duct is large ($\sim 80\,M$-units), resulting in strong trapping over the full extent of the duct. By contrast, the duct in the high-wind case is about three times as deep, but with a refractivity difference about half as large, which results in less powerful trapping. Moreover, around 100 km from the coast there is a transition from a simple, surface–based duct in the evolving MIBL to an S-shaped duct in the mature MBL. The base of the trapping layer in the S-shaped duct lies about 200 m above the sea surface. This transition has a significant impact on the high-wind propagation environment since trapping within the two types of duct is very different (Plant and Atkinson, 2000b). This means that

- Trapping of signals sent through the growing MIBL becomes much stronger once the S-shape has developed;
- Movement of the S-shape duct further out to sea during the day has noticeable effects on the propagation environment, the vertical distributions of signal strength within the duct being very sensitive to the detailed evolution towards the S-shape;
- For signals sent from sea to land, disintegration of the region of trapped signals is strongly related to the position of the transition.

Subtle influences on the propagation environment, such as those related to the duct–type transition, have been successfully captured by the modelling. However, there are limits to the accuracy of the approach, since minor changes to the refractivity fields (well within the range of probable errors in the predicted field) can be important. For example, one cannot realistically predict the very fine-scale fluctuations within a duct caused by interference of waveguide modes (Plant and Atkinson, 2000b, p11).

[1]An alternative fit was proposed by Melas (1989, 1998) who considered an exponential function of the dimensionless height variable z/h. This would also not be appropriate for our model results although it would be an improvement over a power-law fit.

3 Numerical and Practical Issues

The numerical solution of a mesoscale model requires discretization of space and time. Along with an imperfect knowledge of the initial conditions, this may compromise its predictive power. Some practical issues arising from such considerations are summarized below.

3.1 Initial Conditions

Initial conditions for the model runs have been obtained from the SHAREM-115 data (Brooks *et al.*, 1997, 1999) and routine synoptic soundings from Kuwait International Airport (KIA) (KIA data, 1996). Once the model has spun-up, say by mid-afternoon, the overland conditions are found to be insensitive to the initial conditions (Plant and Atkinson, 2000c) presumably because of the strong forcing mechanism of the diurnal cycle. By contrast, the important forcing mechanism over the Gulf waters is much weaker, specifically the advection of land air out to sea. Not surprisingly, the response to this stimulus is sensitive to the initial specification of the atmosphere over the sea.

If the land–based soundings from KIA are used to provide the initial conditions over the Gulf then the land/sea contrasts are too weak, producing a thermal internal boundary layer which is too deep and bounded by vertical gradients that are too weak (Plant and Atkinson, 2000c, p13). Input data on the early–morning low-level atmosphere over the Gulf are therefore highly valuable and their incorporation yields dramatic improvements to the predictions. Model spin-up also suffers if good initial data over the sea is not available (Plant and Atkinson, 1999, p6; 2000c, p14) largely because time is required for evaporation to produce realistic amounts of water vapour in the MBL (Plant and Atkinson, 2000c, p13,15). Unfortunately, it is precisely such input data which are difficult to obtain on a routine basis — the quality of low-level data from Brooks *et al.* (1997, 1999); Brooks and Rogers (2000) will only rarely be available. Nonetheless, the results from this project emphasize that for accurate forecasting, all efforts should be made to incorporate as much data as possible on the low-level atmosphere over the sea.

The wind profiles used in the modelling were highly idealized, being simple, smoothed composites of the available data, and were used to introduce the wind through the boundary conditions (Li and Atkinson, 1998b). Specification of the wind could certainly be improved within an approach based on nested gridding, such as those adopted by Lystad and Tjelta (1995); Burk and Thompson (1995, 1997). If boundary conditions on the mesoscale grid were to be determined from the results of synoptic forecasting on a coarser grid more realistic wind profiles (and distributions of the wind in the horizontal) would be obtained. Such a procedure is common in operational forecasting but was not considered in this project.

3.2 Horizontal Resolution

The horizontal grid length used by the UK Meteorological Office in operational forecasting of mesoscale phenomena is typically about 15 km. Grid lengths used in this project have been considerably smaller, 3 or 6 km being the usual choices. However, finer (Plant and Atkinson, 2000a) and coarser grids (Plant and Atkinson, 1999) have also been investigated, with grid lengths ranging from 1 to 15 km. Important features such as the depth of the mature MIBL and the position of the SBF appear to be little affected by the choice of grid length (Plant and Atkinson, 1999), although the model spin-up is longer for a coarser grid. Thus, it may be possible to use coarse grids for qualitative studies of the refractivity environment. However, the use of a finer grid has been found to confer two important advantages. First, the strong horizontal and vertical gradients bounding the MIBL are more accurately captured (Plant and Atkinson, 1999, p9). Second, the model description of the SBC and its inland penetration are much improved. This is particularly true in the high-wind case where a grid length of 15 km smears out the boundary between the sea and land air masses to such an extent that the SBC is barely noticeable (Plant and Atkinson, 1999). A good representation of the SBC is important because it can influence ducting properties in several ways, as outlined in Sec. 2.

When studying the propagation environment using the `TERPEM` code (TERPEM User Guide, 1998), the ability to examine the effects of horizontal variations in the refractivity field is also limited by issues of horizontal resolution. `TERPEM` allows for specification of only ten different profiles of refractivity and therefore (unless the coverage region of interest is small) some of the information produced in the mesoscale–model simulations has to be discarded. This makes it difficult to obtain a good representation of the strong horizontal gradients associated with the SBF and possible enhancements to the input resolution of `TERPEM` have been suggested for this reason (Plant and Atkinson, 2000b). The errors associated with the transfer of mesoscale data to `TERPEM` can be reduced with the aid of an automated data–selection scheme or through the intervention of a skilled user (Plant and Atkinson, 2000b, p25). This can be valuable in some circumstances since quite small errors in representing the horizontal refractivity changes can have noticeable effects on the predictions for the propagation environment.

3.3 Vertical Resolution

Since ducts are shallow features, certainly in comparison with the tropospheric depth, and since they are often bounded by strong vertical gradients, it is important to have adequate vertical resolution if ducting characteristics are to be accurately modelled. This point was evident in the study of Lystad and Tjelta (1995) which appeared to suffer somewhat from the use of only 14 vertical levels. For most of the runs in this project, 33 levels were chosen with spacings that increased with altitude in order to ensure reasonable resolution within the duct itself. There were about 10 levels covering the mature MBL in the low-wind case which allowed for model description of its detailed vertical structure. Nonetheless, an increase to 41 levels for some of the runs did appear to be beneficial. In particular, an improved description of the SBC meant that the jump in the MIBL at the SBF in the high-wind case was uncovered using this finer resolution (Plant and Atkinson, 2000a). The improvements may be related to the fact that the turbulence closure scheme used in the model is sensitive to local gradients (Golding, 1986). Good vertical resolution is therefore necessary in order to realize an accurate representation of the important turbulence structure of the SBC (Arritt and Physick, 1989).

The limited vertical resolution was also an issue when passing data from the mesoscale model to `TERPEM`. The `TERPEM` code needs to make some assumption about the evolution of refractivity in between the mesoscale vertical grid points. The choice made can have a noticeable impact on its predictions of the propagation environment (Plant and Atkinson, 2000b). In practice, linear interpolation is chosen, which would appear to be a reasonable default method, but this may not be suitable for describing the profile close to the top of the MIBL. Alternative choices could be imposed by post-processing the mesoscale model output.

3.4 Some Miscellaneous Issues

- In some cases, mesoscale model runs were found to crash owing to the use of a timestep that led to numerical instabilities (see p7 of Plant and Atkinson, 2000a for example). Whenever an acceptable timestep was specified, however, there was very little indication of any dependence of the model results on the value chosen.

- The horizontal domain size was chosen to cover the central portion of the Persian Gulf. It was extended westwards and northwards from the SHAREM-115 observation area in order to permit modelling of the conditions in the air upstream that would later be advected into the observation area. It was also important for accurate predictions that the thermally–induced circulations were contained within the domain. The grid used by Li and Atkinson (1998b) covered an area of $600 \times 360\,\mathrm{km}^2$. In some of the fine-resolution runs performed for Phase 2 of the project, the grid was cut down to $300 \times 120\,\mathrm{km}^2$. This was convenient in order to produce practical model run times. The reduced size was determined from various numerical experiments (Plant and Atkinson, 2000a, p7). Since it only just encloses the SBC it is considered to be close to the minimum reasonable size. It is safer to work with a larger grid and this should be preferred for runs with grid lengths of 6 km or more.

- Horizontal diffusion is included in the mesoscale model as a mechanism for numerical smoothing (Ballard and Golding, 1991). This may have affected the ability of the model to capture strong horizontal gradients and short-scale variations in the MIBL (Plant and Atkinson, 2000c).

- The boundary conditions at the downwind lateral limit of the model domain seemed to cause some problems, with deviations to the isolines of various variables occurring just before the eastern boundary. These deviations were associated with strong vertical velocities[2]. This is not exactly an unusual problem to find at the boundaries of this model, as noted by Ballard (1989, p12). Fortunately there was little indication that the numerical effects seen close to this boundary had any impact on the results obtained over the rest of the model domain.

- The `TERPEM` model features a number of numerical techniques which are designed to speed-up its computations over parts of the modelled domain where conditions are favourable (Levy, 1989, 1995; TERPEM User Guide, 1998). The code can also be run with the simplifying techniques disabled in which case the full split-step Fourier transform method (Dockery, 1988) is applied throughout. Results obtained with and without the simplifying methods were found to be in excellent agreement, indicating that the quality of the results is not compromised by these techniques.

4 Conclusions, and Suggestions for Future Progress

At high frequencies, the range of propagation of radar signals is largely controlled by atmospheric absorption (Bogush Jr, 1989). However, this is a minor effect for many radar applications and is usually neglected for frequencies below ~ 1 GHz. At the lower frequencies, many other mechanisms of signal loss in propagation may have to be taken into account (Hall, 1979) such as the free-space transmission loss, the presence of localized scattering centres or turbulent fluctuations of refractivity (Battan, 1973; Gossard, 1983), multipath fading and diffraction around terrain features. Moreover,

[2] Such behaviour can be seen on many of the cross-sections produced in the project reports. Good examples would be Figs. 14a, 15a and 16a of Li and Atkinson (1998b). For examples of the strong, artificial vertical velocities that can be generated see Figs. 3a and 9b in the same report.

refraction is caused by spatial variations of the atmospheric refractive index. Under most atmospheric conditions, radar signals are refracted away from the surface of the earth (Turton *et al.*, 1988). However, situations can occur in which the vertical gradient of the refractive index is sufficiently large and negative that signals are refracted downwards, at least within some range of heights. Radar energy can then become trapped within a region of strong negative gradient, a phenomenon known as ducting.

Radar ducting is a long-established and well-documented phenomenon (Skolink, 1980) that can dramatically affect propagation. Although the range can be greatly extended within the duct, the signal strength outside of the duct may be significantly reduced, producing “holes” in the radar coverage. The weather conditions that can lead to ducting are well-known and occur quite frequently over the Persian Gulf (Hall, 1979; Cole, 1985; Abdul-Jauwad *et al.*, 1991). Propagation within a uniform duct is also well-understood, based on waveguide theory (Budden, 1961). However, important details of the propagation environment under ducting conditions are hard to predict, being sensitive to small changes in refractivity. Propagation within littoral environments presents a particularly difficult problem since the meteorological conditions can vary quite significantly over both space and time. It is not uncommon for predictions to be based on soundings taken at 12 hourly intervals, assuming horizontal homogeneity across distances of ~ 100 km (Rogers, 1995). Such an approach is scarcely adequate for accurate prediction in littoral regions.

Good prediction requires detailed knowledge of the refractivity field and its variations over space and time. It is also necessary to be able to calculate the propagation within a non-uniform field. Simple waveguide theory breaks down if conditions are non-uniform in the horizontal, but in recent years numerical models have been developed which directly solve a parabolic approximation to the electromagnetic wave equation (Dockery, 1988; Craig, 1988; TERPEM User Guide, 1998). Such models have been operationally successful to the extent that they are now standard when assessing the effects of meteorological conditions on naval radar applications (Dockery and Goldhirsh, 1995). In this project, the `TERPEM` model has been used (TERPEM User Guide, 1998).

With good propagation models now being available, the immediate issue is the specification of the refractivity field. This view was recently stressed by Christophe *et al.* (1995) who argued that obtaining meteorological profiles is currently a more important task than assessing them in the propagation models. Observational data tends to be both infrequent and widely-spaced, particularly over the sea. Work is continuing in order to ascertain acceptable space and time separations in recorded data that are required for useful prediction (see, for example, Dockery and Goldhirsh (1995); Rogers (1995); Brooks *et al.* (1999)). However, it seems unlikely that the 5 dB accuracy desired (Dockery and Goldhirsh, 1995; Goldhirsh and Dockery, 1998; Brooks *et al.*, 1999) could be achieved on a routine basis without major expansions of routine observational programmes. An attractive alternative is the use of a mesoscale model. Using the standard semi-empirical formula of Bean *et al.* (1970) one can translate from meteorological variables into refractivity which can therefore be studied at arbitrary times and places. Even if the available data are sparse, the model results could at least be regarded as offering an interpolation between data, allowing one to take account of space and time variations in a reasonably realistic way.

The studies reported by Lystad and Tjelta (1995) and by Burk and Thompson (1995, 1997) demonstrated the feasibility of predicting the refractivity field under ducting conditions using a mesoscale model. The models used were the Norwegian Met. Office model and the US Navy's NORAPS model (Navy Operational Regional Atmospheric Prediction System) respectively. Operational forecasting of propagation environments is now performed routinely by the UK Met. Office and by the US Navy. The operational model used over the Middle East (a domain extending from Italy to Afghanistan and from the Caspian Sea to the south of Arabia) by the UK Met. Office is hydrostatic with a horizontal grid length of about 17 km and 31 vertical levels (14 in the lowest 2 km). It is initialised by interpolation from a Global Model that has a horizontal grid length of 60 km. The US Navy now uses the COAMPS (Coupled Ocean/Atmosphere Mesoscale Prediction System) system (Hodur, 1997) in which a non-hydrostatic atmospheric model is coupled to an ocean model. The level of resolution available in operational refractivity forecasting using COAMPS is not known. However, we note that in an example surface–wind forecasting run presented by Hodur (1997, p1420) the horizontal grid length was 5 km and there were 30 vertical levels (11 in the lowest 2 km).

This project has attempted to improve the understanding of littoral propagation environments. A crucial advantage enjoyed by this study has been the availability of a high-resolution, high-quality data set taken over the Persian Gulf in conditions of strong ducting (Brooks *et al.*, 1997, 1999; Brooks and Rogers, 2000). By contrast, the studies of Lystad and Tjelta (1995) and Burk and Thompson (1995, 1997) had access to verifying data from only a few isolated, coastal points within the modelled domain. Therefore, the results of this study provide a much clearer indication of the ability of mesoscale models to predict duct characteristics and their horizontal variability. Moreover, and importantly for the study of ducts, the simulations performed in this project have had considerably finer vertical resolution in the lowest 2 km (either 22 or 33 levels).

The model used was the UK Met. Office's non-hydrostatic mesoscale model (Ballard and Golding, 1991). Although the use of a hydrostatic model would have been reasonable on the horizontal scales considered here (Martin and Pielke, 1983), the inclusion of non-hydrostatic effects in the model is reassuring. According to Yang (1991), such effects reduce the intensity of a strong SBC by opposing the hydrostatic pressure gradient. As described in Sec. 2 above, the strong SBC found in the simulations has important effects on the propagation environment and one would not want these to have been distorted by any exaggeration of the SBC.

Results from the project have been summarized in Sec. 2 above and further details can be found in the project reports. We believe that the results support the following general conclusions about the modelling of propagation environments using a mesoscale model.

1. The modelling of refractivity environments has been shown to be feasible using the non-hydrostatic model of the UK Met. Office (Ballard and Golding, 1991). This is in addition to other models that have been used in this context, as described above. At present, the limited number of studies reported does not enable one to make judgements the relative performance of the models.

2. Genuinely useful predictions of the propagation environment can be obtained when mesoscale model results for the refractivity environment are used as input to parabolic–equation models.

3. The evolution of a radar duct has been shown within the growing internal boundary layer. Changes in ducting conditions over time can also be captured by the model. This confirms the findings of Lystad and Tjelta (1995); Burk and Thompson (1995, 1997).

4. The availability of high-quality verifying data has provided a good indication of the level of agreement that might be expected between simulation and observation.

5. The model was correctly able to capture the effects of wind speed on the properties of an advection duct.

6. The model was not able to capture short-scale horizontal variations within the inversion. It has been shown that these variations, described by Brooks *et al.* (1997), may be related to inhomogeneities of SST.

7. A transition from a simple surface duct to an S-shaped duct can occur in an evolving MIBL. Although the transition arises from a subtle change in terms of the meteorological variables, it was nonetheless captured in the modelling. This has important effects on propagation.

8. The propagation environment is influenced in a number of respects (Sec. 2) by the development of a SBC.

9. The model was able to produce decent results from very crude initial conditions. Reasonable, qualitative results indicating duct formation were obtained using only a single overland sounding, taken several

hundreds of kilometres upwind of the model domain. Although improved initial conditions are required for good forecasting, the predictive power of the mesoscale model has clearly been shown.

10. The refractivity environment over the sea is sensitive to the initial specification of the marine atmosphere in the lowest kilometre or so. The information routinely available on the near-surface marine atmosphere is often quite poor, certainly compared to the wealth of data collected on the overland atmosphere. Initialization of the mesoscale model from a global model may not necessarily yield very significant improvements in this regard. For example, the global model used by the UK Met. Office, and referred to earlier, has a horizontal grid length of 60 km and therefore would cover the Persian Gulf with only 5 or 6 grid lengths. Results from this project stress the need to assimilate as much data as possible on the low-lying marine atmosphere.

11. The depth of an advection duct is no more than a few hundred metres. Moreover, as has been explicitly illustrated in this study (Plant and Atkinson, 2000b), the detailed vertical structure of refractivity within the duct can significantly affect radar propagation. Thus, for accurate prediction the vertical resolution used in a mesoscale model at low altitudes must be high. The results obtained in this study benefited from higher resolutions than are commonly used in mesoscale studies.

12. Important features of the ducting environment, such as the depth of the MIBL, were not sensitive to the horizontal grid length. However, a coarse grid length does not provide a good representation of the SBC.

13. In a question and answer session at an AGARD conference, following the presentation of Lystad and Tjelta (1995), a question was asked about how mesoscale modelling of ducting environments might be advanced[3]. Lystad and Tjelta suggested better parameterizations of the active surface layer, an increase in the number of low-lying model levels, better topographic information and an increase of available data. S. D. Burk also responded to the question and commented that the weakest aspect of the modelling was the specification of the initial moisture fields. The evidence from this project backs-up several of those points quite strongly. In particular, the benefits of increased vertical resolution and improved initial conditions have been clearly seen.

In the light of this project, some suggestions for possible future investigation are offered below. While such work could be conducted using the

[3]This is reported in the conference proceedings immediately after Lystad and Tjelta's paper.

same mesoscale model, improvements to the modelling could emerge from the use of the non-hydrostatic form of the Unified Model.

1. There are some indications that the `TERPEM` propagation model may not have been primarily designed to operate using high-resolution input data from a mesoscale model. Improvements to the modelling capability might be made by investigating the interface between the models, considering, for example, issues of horizontal and vertical interpolation. The work reported by Plant and Atkinson (2000b) would be a useful starting point for such studies.

2. The transition from a simple surface to an S-shaped duct merits further study. Although the occurence of such a transition is realistic, and the capture of a transition by a mesoscale model is encouraging, it is not clear whether the transition was captured accurately. If any suitable observational studies could be found, it would be very interesting to examine whether or not one could reliably model the locations of such transitions.

3. A systematic study of the effects of vertical resolution (similar to the analysis of Plant and Atkinson (1999) for the horizontal resolution) would be valuable in order to establish the optimum low-level grid separation.

4. Problems caused by the downwind lateral boundary conditions were described in Sec. 3.4. These may merit further attention.

5. Good representation of strong gradients in the mesoscale model is important for truly accurate prediction of ducting. There are a number of numerical issues that are important in this regard (examples are the smoothing due to horizontal diffusion and the numerical dispersion that is implicit in a finite–difference scheme).

6. This project has shown that it is possible to produce mesoscale simulations that agree well with observational data in many important respects. Now that this has been established, it becomes reasonable to study ducting environments more generally. The model could be used to try to improve our understanding of advection ducting by examining the sensitivity of the results to variations in the prevailing physical conditions[4]. As examples, it might be interesting to consider

[4]There may also be value in studying some artificial parameter variations. For example, the MIBL development is sensitive to the buoyancy parameter $g\Delta\theta/\theta$ (Garratt, 1990), and so competing MIBL models could be compared by varying this parameter. The variations could be imposed by changing the SST or the overland conditions, but they could also be implemented through purely artificial changes to the solar constant (altering $\Delta\theta$) or even to g.

the effects of varying the surface roughness length, the wind speed or direction, or the amplitude of the overland diurnal cycle (in terms of the albedo of the land surface, the time of year or the location of the model domain).

A Summary of Model Runs

A large number of mesoscale model runs were performed in the early stages of Phase 1 of this project in order to investigate properties of the mesoscale model and to study some idealized configurations for the littoral environment. Such runs were described by Li and Atkinson (1997b, 1998a) and were valuable in understanding the treatment of littoral phenomena by the mesoscale model. The first attempts at specific modelling of the refractivity environment within the Persian Gulf on the occasions of the SHAREM-115 flights were reported by Li and Atkinson (1998b). For Phase 2 of the project a number of model runs have been performed which are broadly similar to those of Li and Atkinson (1998b), but with some differences introduced in order to study the effects of numerical resolution, initial conditions etc. For reference purposes it may be useful to have a brief summary of the runs that have been performed in order to study conditions in the Persian Gulf. Such a summary is provided below.

Description:	**Original low wind run**
References:	Li and Atkinson (1998b); Plant and Atkinson (2000c)
Notes:	First attempt — set 1 initial conditions.
Resolution:	Δx=6 km; 33 vertical levels; Δt=20 s.

Description:	**Original high wind run**
References:	Li and Atkinson (1998b); Plant and Atkinson (2000c)
Notes:	First attempt — set 1 initial conditions.
Resolution:	Δx=6 km; 33 vertical levels; Δt=20 s.

Description:	**Low wind run at Δx=3 km**
References:	Plant and Atkinson (1999, 2000a)
Notes:	Test of sensitivity to Δx
Resolution:	Δx=3 km; 33 vertical levels; Δt=20 s.

Description:	**High wind run at Δx=3 km**
References:	Plant and Atkinson (1999)
Notes:	Test of sensitivity to Δx
Resolution:	Δx=3 km; 33 vertical levels; Δt=20 s.

Description:	**Low wind run at Δx=6 km**
References:	Plant and Atkinson (1999, 2000b)
Notes:	Initial conditions slightly altered from original run. Used in `TERPEM` studies.
Resolution:	Δx=6 km; 33 vertical levels; Δt=20 s.

Description: **High wind run at Δx=6 km**
References: Plant and Atkinson (1999, 2000b)
Notes: Initial conditions slightly altered from original run. Used in `TERPEM` studies.
Resolution: Δx=6 km; 33 vertical levels; Δt=20 s.

Description: **Low wind run at Δx=9 km**
References: Plant and Atkinson (1999)
Notes: Test of sensitivity to Δx
Resolution: Δx=9 km; 33 vertical levels; Δt=20 s.

Description: **High wind run at Δx=9 km**
References: Plant and Atkinson (1999)
Notes: Test of sensitivity to Δx
Resolution: Δx=9 km; 33 vertical levels; Δt=20 s.

Description: **Low wind run at Δx=12 km**
References: Plant and Atkinson (1999)
Notes: Test of sensitivity to Δx
Resolution: Δx=12 km; 33 vertical levels; Δt=20 s.

Description: **High wind run at Δx=12 km**
References: Plant and Atkinson (1999)
Notes: Test of sensitivity to Δx
Resolution: Δx=12 km; 33 vertical levels; Δt=20 s.

Description: **Low wind run at Δx=15 km**
References: Plant and Atkinson (1999)
Notes: Test of sensitivity to Δx
Resolution: Δx=15 km; 33 vertical levels; Δt=20 s.

Description: **High wind run at Δx=15 km**
References: Plant and Atkinson (1999)
Notes: Test of sensitivity to Δx
Resolution: Δx=15 km; 33 vertical levels; Δt=20 s.

Description: **Low wind run at Δx=1 km**
References: Plant and Atkinson (2000a)
Notes: Search for small–scale horizontal variations.
Resolution: Δx=1 km; 41 vertical levels; Δt=15 s.

Description:	**High wind run on reduced grid**
References:	Plant and Atkinson (2000a,b)
Notes:	Used to study MIBL growth. Also used to study selection of horizontal profiles for `TERPEM`.
Resolution:	Δx=3 km; 41 vertical levels; Δt=15 s.

Description:	**Low wind run using KIA data**
References:	Plant and Atkinson (2000c)
Notes:	Set 2 initial conditions.
Resolution:	Δx=6 km; 33 vertical levels; Δt=20 s.

Description:	**High wind run using KIA data**
References:	Plant and Atkinson (2000c)
Notes:	Set 2 initial conditions.
Resolution:	Δx=6 km; 33 vertical levels; Δt=20 s.

Description:	**Low wind run using data from KIA and the SHAREM-115 flights**
References:	Plant and Atkinson (2000c)
Notes:	Set 3 initial conditions.
Resolution:	Δx=6 km; 33 vertical levels; Δt=20 s.

Description:	**High wind run using data from KIA and the SHAREM-115 flights**
References:	Plant and Atkinson (2000c)
Notes:	Set 3 initial conditions.
Resolution:	Δx=6 km; 33 vertical levels; Δt=20 s.

Description:	**Low wind run with spatially–varying SST**
References:	Plant and Atkinson (2000c)
Notes:	Set 4 initial conditions.
Resolution:	Δx=3 km; 41 vertical levels; Δt=15 s.

Description:	**High wind run with spatially–varying SST**
References:	Plant and Atkinson (2000c)
Notes:	Set 4 initial conditions.
Resolution:	Δx=3 km; 41 vertical levels; Δt=15 s.

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