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Acoustic impact of upper ocean models

M. Porter, S. Piacsek, L. Henderson and F.B. Jensen

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Acoustic impact of upper ocean models

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Executive Summary: An important class of oceanographic models is the mixed-layer model which, simply stated, provides predictions of the temperature and salinity profiles in the upper ocean layers. These predictions take into account the surface winds, which drive the mixing, and the solar radiation, which heats the mixed layer. As interest has increased in using such models as a step in the process for making acoustic forecasts or nowcasts for predicting sonar performance, a recurring question has been that of what information is needed for accurate *acoustic* predictions. For instance, how precisely do mixed-layer depths need to be calculated? Is mixed-layer temperature important?

We first addressed these questions through a parameter study using synthetic sound-speed profiles as input to an acoustic model. A constant temperature offset was shown to have very little effect on transmission loss calculations. (Errors of $\sim 3\,^{\circ}$C in the mixed-layer temperature typically induce an error of less than 3 dB in transmission loss.) On the other hand, very slight changes in the sound-speed profile (SSP) gradient in the mixed layer led to large changes in transmission loss. In an idealized mixed layer such gradient changes are not possible, since the gradient is simply determined by the increase in sound speed due to pressure. However, in practice, fairly complicated mixed-layer structures can emerge due to successive heating and mixing cycles.

Next, these points were demonstrated in a somewhat more concrete form in a two-step process: the SSP was predicted using particular mixed-layer models and passed to an acoustic model that provides transmission loss calculations. The results were compared to predictions based on both measured and historical SSP measurements. These calculations illustrate that changes in the mixed layer as predicted by the upper ocean models can lead to very strong changes in the acoustic propagation relative to climatology. However, significant differences in acoustic propagation can also result from employing different mixed-layer models.

Additional work is in progress to examine 3-D mixed-layer modelling combined with a recently developed 3-D acoustic model. Apart from the problem of how to effectively fuse the two types of models, the objective will be to explore how 3-D variations in mixed-layer properties might be exploited in ASW tactics.

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Acoustic impact of upper ocean models

M. Porter, S. Piacsek, L. Henderson and
F.B. Jensen

Abstract: The upper mixed-surface layer of the ocean, with its homogeneous vertical temperature profile, provides a somewhat special acoustic propagation environment where the sound speed will increase (due to pressure) down to the bottom of the mixed layer, and then drop off due to temperature decrease until it reaches the minimum at the main sound channel. Above the velocity maximum at the bottom of the mixed layer, a surface 'duct' will develop, in which for all frequencies above a cut-off the acoustic energy will be trapped mostly near the surface, inside the mixed layer.

As an alternative to direct measurement of the mixed-layer profile, so-called upper ocean or mixed-layer models (MLM's) have been developed. The output of these mixed-layer models then becomes the input for an acoustic model that predicts the transmission loss.

In this memorandum, we examine this two-step modelling process with the objective of understanding what parameters must be accurately predicted by the MLM. We also consider the improvements that result compared to a simpler alternative (climatology) and, finally, the differences between particular mixed-layer models. The differences are considered not simply in terms of mixed-layer model accuracy, but in terms of the acoustic impact, which is the ultimate objective of the process.

Keywords: acoustic forecast ∘ mixed layer ∘ models ∘ ocenographya ∘ sonar performance ∘ sound-speed profile ∘ transmission loss

Contents

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1
Introduction

The surface layers of the ocean form a part of the ocean/atmosphere boundary layer system, and as such are dominated by turbulent mixing processes and the air-sea heat and momentum fluxes. These layers are referred to collectively as the 'mixed layer' because there is almost always present at least one homogeneous layer near the surface in which the temperature and salinity profiles are constant with depth (the result of mixing), and the sound-speed increases with depth due to pressure effects. The bottom of the mixed layer then most often represents the surface maximum of the sound-speed profile.

From the point of view of acoustic modelling, the mixed layer leads to a surface duct that can drastically alter the propagation of sound in the ocean. Mixed-layer models provide the details of the sound-speed profile, which are required for acoustic modelling. In a sense, they may be considered as sophisticated interpolators that provide the sound speed between times of, say, two weeks, when it might be practical to measure directly the mixed-layer structure. In between measurements, the mixed-layer structure is tracked by taking account of the surface wind and heat flux at the ocean/air interface.

Normally mixed layers are of interest only for the propagation of high-frequency sound, since there is a low-frequency cut-off below which the surface duct has negligible effect. However, at higher latitudes (for example, at the locations of the weather ships *Lima* (57°N, 20°W) and *Charlie* (53°N, 36°W) in the northeast Atlantic), mixed-layer depths of 300–400 m have been observed consistently in the December to April period [1]. Mixed layers of such depth influence even sound waves of lower frequencies, say, 200 Hz or so.

Although a great deal of work has been done on mixed-layer models and acoustic models, a fundamental issue remains. Mixed-layer models are principally validated on the basis of how well they match a measured temperature profile. However, a measure of 'goodness of fit' is difficult to motivate. For instance, if one model provides a more accurate prediction of mixed-layer depth and another provides a more accurate prediction of mixed-layer temperature, then which should be preferred?

Many times, however, the situation is more complicated, in that the 'mixed layer' is actually composed of a sandwich of several homogeneous layers, each the result of different mixing, cooling and heating epochs on the diurnal, synoptic (i.e. weather) and seasonal scales, or any combination of these. (Throughout this memorandum we shall use the term 'mixed layer' in this broader sense.) Since the ultimate objective is to provide an accurate transmission loss calculation, it is natural to make a judgment based on this same consideration.

Document overview In Sect. 2, we provide a brief overview of mixed-layer modelling. In Sect. 3, we consider which parameters of the mixed layer are most important to provide an accurate prediction of transmission loss. In particular, we address the sensitivity of transmission loss to offsets in the mixed-layer temperature, to errors in the gradient of temperature, and errors in mixed-layer depth. (For a good summary of errors that affect mixed-layer modelling, we refer the reader to Heathershaw and Codd [2].) Next, in Sect. 4, we examine the implications using a particular mixed-layer model compared to climatology and to direct XBT measurements, which provide 'ground truth'. In Sect. 5, we examine differences in particular mixed-layer models and, finally, we end with a summary and conclusions in Sect. 6.

2

The mixed-layer models

The boundary layer nature of the near-surface layers has strong implications for the models designed to simulate them. The principal requirement for these models is the correct specification of the fluxes of momentum and heat across the air-sea interface, and the correct simulation of the turbulent mixing due to surface wave breaking and shear of the wind-driven currents.

Due to the very large discrepancy in spatial scales between the horizontal extent of atmospheric cyclones and the depth of the mixed layer, mixed-layer models have been generally constructed as 1-D models, with pressure gradients and all horizontal gradients neglected. These assumptions are very similar to the usual boundary layer approximations in hydrodynamics.

The principal balance in the equations of motion comes from a balance of acceleration, vertical diffusion and the Coriolis force due to the Earth's rotation:

$$\frac{\partial U}{\partial t} = \frac{\partial}{\partial z}(K_{\mathrm{m}}\frac{\partial U}{\partial z}) + 2\Omega V, \quad (1)$$

$$\frac{\partial V}{\partial t} = \frac{\partial}{\partial z}(K_{\mathrm{m}}\frac{\partial V}{\partial z}) - 2\Omega U, \quad (2)$$

where U and V are the E–W and N–S components of the velocity, Ω is the rotation rate of the Earth ($7 \times 10^{-5}\,\mathrm{s}^{-1}$) and K_{m} is the coefficient of turbulent momentum diffusion. The transport equation for heat balances vertical diffusion of heat and incident solar radiation q_s in 1-D models, and also advection of heat in 3-D models. Thus,

$$\frac{\partial T}{\partial t} = \frac{\partial}{\partial z}(K_{\mathrm{h}}\frac{\partial T}{\partial z}) + (\vec{U} \cdot \nabla)T + q_s, \quad (3)$$

where T is the temperature. There is similarly a transport equation for salt,

$$\frac{\partial S}{\partial t} = \frac{\partial}{\partial z}(K_s\frac{\partial S}{\partial z}) + (\vec{U} \cdot \nabla)S, \quad (4)$$

where K_{h} and K_s are turbulent diffusion coefficients for heat and salt, respectively, and S is the salinity.

The derivation of the above transport equations involves generalized closure methods commonly used in the simulation of turbulent flows to relate the small-scale motions to the mean flow. An excellent review of these methods for geophysical flows is given in a survey by Mellor and Yamada [3]. Applying different order turbulence closures, one obtains formulas for the diffusion coefficients, which on the one hand, can be simple functional forms involving U, V, T and S, or involve the solution of additional evolution equations. A fuller discussion of higher-order closures applied to mixed-layer modelling may be found in [4, 5].

At this point we must introduce the concept of 'profile' models (also called 'diffusive' or 'differential') and 'bulk' (or 'integrated') models. The profile models solve the differential equations directly on a finite difference grid, yielding predictions of the evolution of the mixed layer in detail as a function of time and depth. The profile-type model considered here is the Mellor–Yamada model [6, 7] with various degrees of turbulence closure, known as the 'Level 2, 2.5, etc.' model.

In contrast, bulk models make the additional assumption that the mixed layer is uniform and predict its evolution in a depth-integrated sense. Momentum and heat added via entrainment at the surface and at the bottom are assumed to be distributed uniformly throughout the mixed layer. The bulk models considered in this memorandum will be the Niiler model [8, 9],and the Garwood model [10]. For a thorough examination and comparison of several models of each type, the reader is referred to the work of Martin [7], where observed fluxes and hydrography are used for the evaluation at the two weather ship sites Papa and November in the North Pacific. In general, it was found that bulk-type mixed-layer models mix much deeper than 'differential' models.

3
Sensitivity

A question that arises frequently in oceanographic modelling is that of which parameters are most important and how accurately must they be known for acoustic modelling purposes. In order to address this question, we take a particular mixed-layer profile as a reference solution and examine changes (in transmission loss) that result as the mixed-layer profile is varied in particular ways.

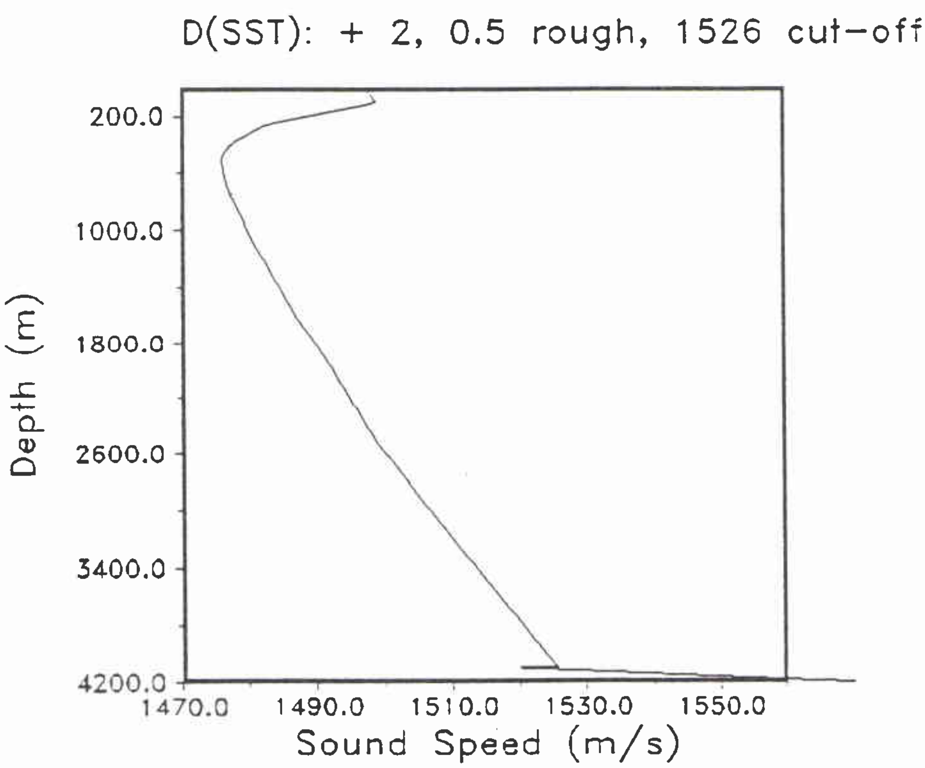

Figure 1 *Sound-speed profile used for the reference solution.*

The sound-speed profile corresponding to our reference solution is shown in Fig. 1. The upper 500 m of the profile have been extracted from XBT measurements from ocean weather ship *Lima* and mated to climatological data for the remaining portion of the water column. The salinity was also taken from climatology. Next, transmission loss (TL) has been calculated using a normal mode program [11] yielding the result shown in Fig. 2a. The frequency for this calculation is 600 Hz and the source depth is 25 m. As expected, the near-surface duct leads to trapping of acoustic energy in the upper 110 m. Note that transmission loss is plotted only in the upper 500 m of the water column.

In Fig. 2b we have modified the profile by increasing the mixed-layer sound speed by 12 m/s. In terms of mixed-layer temperature, this corresponds to a temperature offset of $\sim 3°C$. Interestingly, there is *negligible change* in the transmission loss. From time to time it has been proposed that satellite data be used to correct sea surface temperature. An implication of this result is that an *a posteriori* correction is not very useful in terms of acoustic impact. (However, such information may be quite useful in providing forcing functions for mixed-layer models.)

In Fig. 3a we have changed the gradient in the mixed layer so that the mixed layer has a *downward* refracting sound-speed profile with a gradient -1.75 m/s over the 110 m deep mixed layer.

The reference profile involves an isothermal mixed layer, which leads to an *upward* refracting sound-speed profile. This is due to the increase in pressure with depth and leads to a gradient of ~ 1.75 m/s over 110 m in depth. Note the tremendous change in the transmission loss associated with this slight change in sound-speed profile. To be more precise, the acoustic level within the duct is greatly reduced; however, receivers below the duct see very little change.

Finally, in Fig. 3b we demonstrate the effect of changing the mixed-layer depth. The reference solution involves a mixed layer of 110 m in depth while the perturbed solution has a mixed layer of 55 m in depth. We observe that for our 600 Hz source frequency the 55 m duct is much less effective at trapping energy. The transition from ducting to non-ducting is somewhat nebulous; however, as discussed in Urick [12], the formula $f = 1500/(0.008H^{3/2})$ gives a reasonable estimate of the lowest frequency f for which energy will be trapped in a duct of height H (in units of meters). (This formula assumes an isothermal mixed layer.) Thus, for our 55 m mixed layer 'significant' ducting occurs for a frequency of ~ 500 Hz.

One would like to derive from these kinds of results some general rule like 'mixed-layer depth must be known to ± 10 m'. This, however, involves some judgments that are somewhat subjective. Consider for instance a receiver located just below the *predicted* mixed layer, e.g. at a depth of 70 m in Fig. 3b. In this case, the receiver is in the shadow zone and the acoustic model predicts very high transmission loss. If the actual mixed-layer depth is 100 m, then such a receiver would be inside the duct and flooded by surface duct energy. On the other hand, if the source or receiver depth is uncertain by 20 m, then this may easily be the dominant source of error.

The above examples have been selected from a more complete parameter study to indicate the most important features. We mention in passing a few other points that emerged from this study. First, there is a particular case when a small change in mixed-layer temperature can make a big change in the resulting TL. This occurs when the duct is weak and the temperature change causes a transition between bottom limited (no depth excess) and non-bottom-limited (depth excess) propagation. Thus, a small change in ML temperature can destroy all convergence zone paths.

Secondly, we have examined the role of surface scatter. Mixed-layer effects like surface scatter become more conspicuous as frequency increases. Errors in TL are associated with errors in predicting the surface scatter as well as errors in the ML predictions, and if one dominates, then it should be considered preferentially. We find that for the particular scenarios described above, surface scatter due to RMS roughness of 0.5 m plays a negligible role in the TL. At higher frequencies (3.5 kHz), surface scatter is extremely important. (Roughly, surface scatter loss varies as the square of frequency times surface roughness.)

Obviously errors in mixed-layer predictions are not limited to the three parameters of temperature offset, gradient and mixed-layer depth. Nevertheless, an understanding of the sensitivity to these three basic parameters provides some useful insights. It is interesting that mixed-layer depth has become a fairly standard measure for comparing various models, yet it turns out that mixed-layer gradient is actually a much more important parameter in terms of acoustic predictions. Unfortunately, for mixed layers that are not strictly linear in sound-speed profile, the gradient is poorly defined. We could define a mixed-layer gradient based on the slope from top to bottom of the mixed layer; however, for profiles that vary nonlinearly with depth, this is not a useful measure of ducting. Thus, it is difficult to recommend a single parameter for characterizing the accuracy of a mixed-layer model.

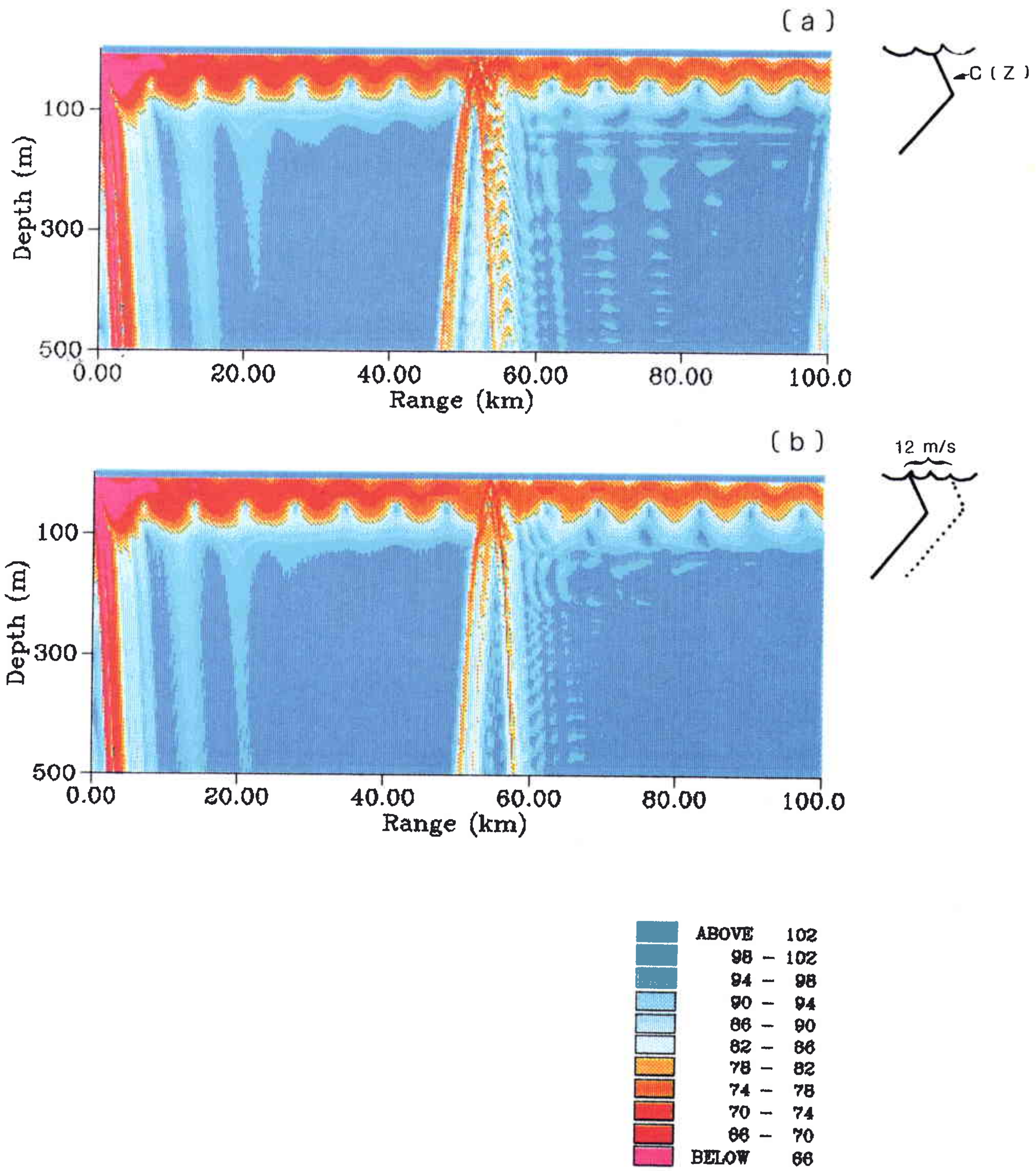

Figure 2 *Transmission loss calculations for (a) reference profile, and (b) profile with mixed-layer offset by 12 m/s. [The inset indicates schematically the difference between the perturbed profile (dotted) and reference profile (solid).]*

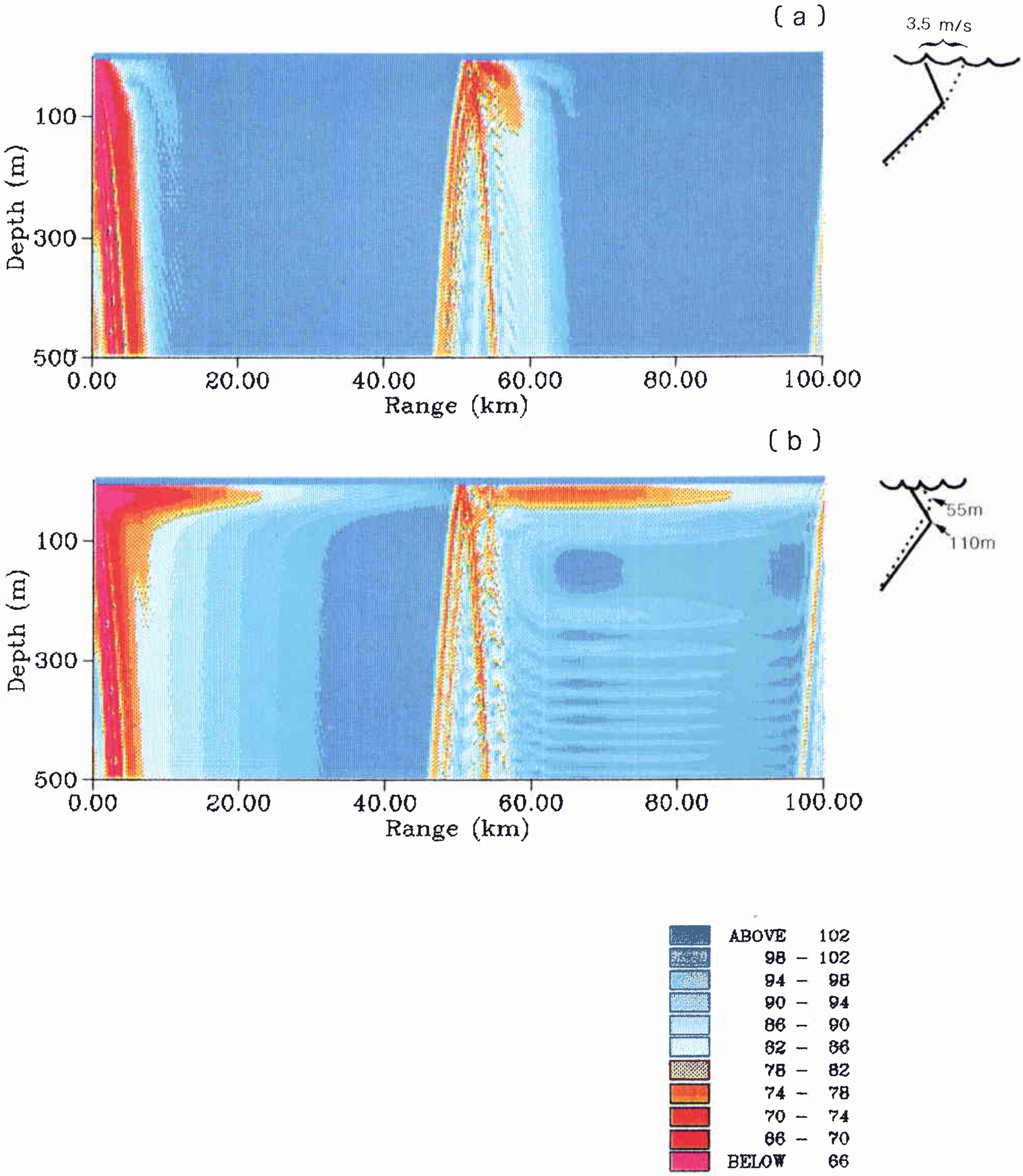

Figure 3 *Transmission loss calculations for (a) profile with mixed-layer gradient changed to* $-0.016 m/s$, *and (b) profile mixed-layer depth changed to 55 m. [The inset indicates schematically the difference between the perturbed profile (dotted) and reference profile (solid).]*

4

Mixed-layer models *vs* data

The results of the sensitivity study will now be considered in more concrete terms by using actual mixed-layer model output. Ground truth for the following simulations comes from XBT measurements made by ocean weather ship *Lima* (57°N, 20°W) in September 1985. The XBT profile measured on September 5 was used to initialize the Niiler mixed-layer model [8, 9]. Forcing terms, such as the local wind and solar flux, were also measured by the weather ship. Of particular interest is the wind stress, which is plotted in Fig. 4 and shows the development of strong winds on approximately September 10 and lasting for several days. The effect of these winds is to provide a substantial deepening of the mixed layer which is clearly manifest in the plots of the experimentally measured sound-speed profile in Fig. 5.

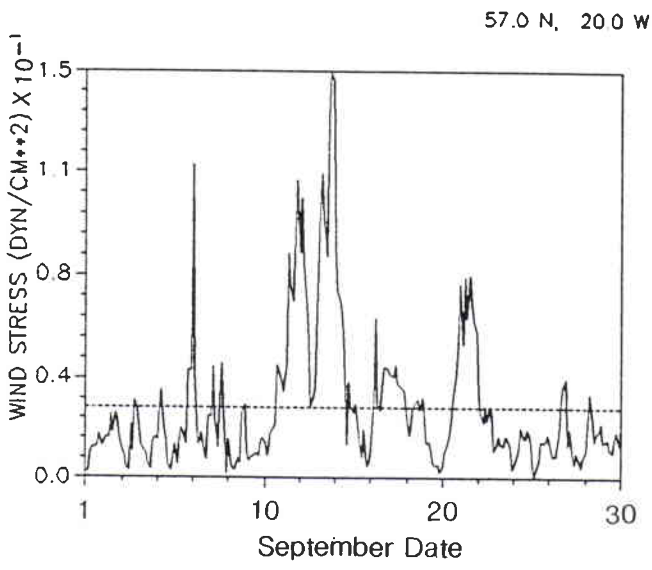

Figure 4 *Wind stress during September 1985.*

As may also be seen in Fig. 5, the Niiler mixed-layer model provides a satisfactory tracking of this event. That is, by a conventional measure of mixed-layer depth, the model does extremely well in tracking the deepening of the mixed layer. However, as was demonstrated in the previous section, the gradient is a much more important parameter. Thus, we can anticipate where a TL calculation based on the MLM will differ greatly from one based on the XBT's. On September 8 we see that both the XBT and Niiler model show an upward refracting mixed layer; however, the gradient

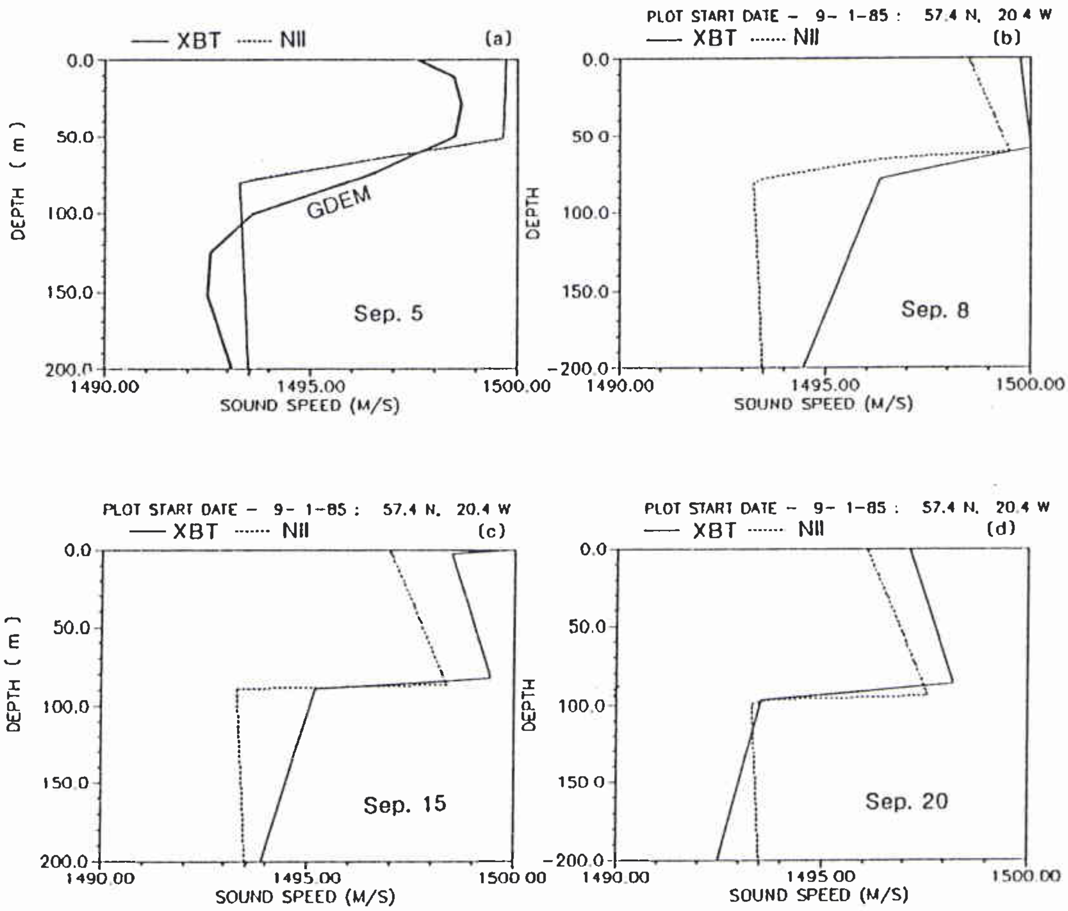

Figure 5 *(a)-(d) Comparison of experimentally measured (solid line) and ML modelled (dashed line) sound-speed profile. In (a) where the XBT and model profiles are identical, the summer GDEM profile (climatology) is also shown.*

in the XBT profile is much weaker. Thus we anticipate poor agreement between the TL predictions. On the other hand, by September 20 the model and data agree both in mixed-layer gradient and depth; however, the profile is offset. Considering our sensitivity study, we may anticipate good agreement in the TL calculation.

These predictions are borne out in the actual transmission loss plots for these days shown in Figs. 6 and 7. In both figures we see from top to bottom the results using the XBT profile, the MLM profile, and the climatological profile. The climatology is taken from the GDEM [13] database, which provides temperature and salinity profiles on a seasonal basis from which the SSP was calculated. (The climatological

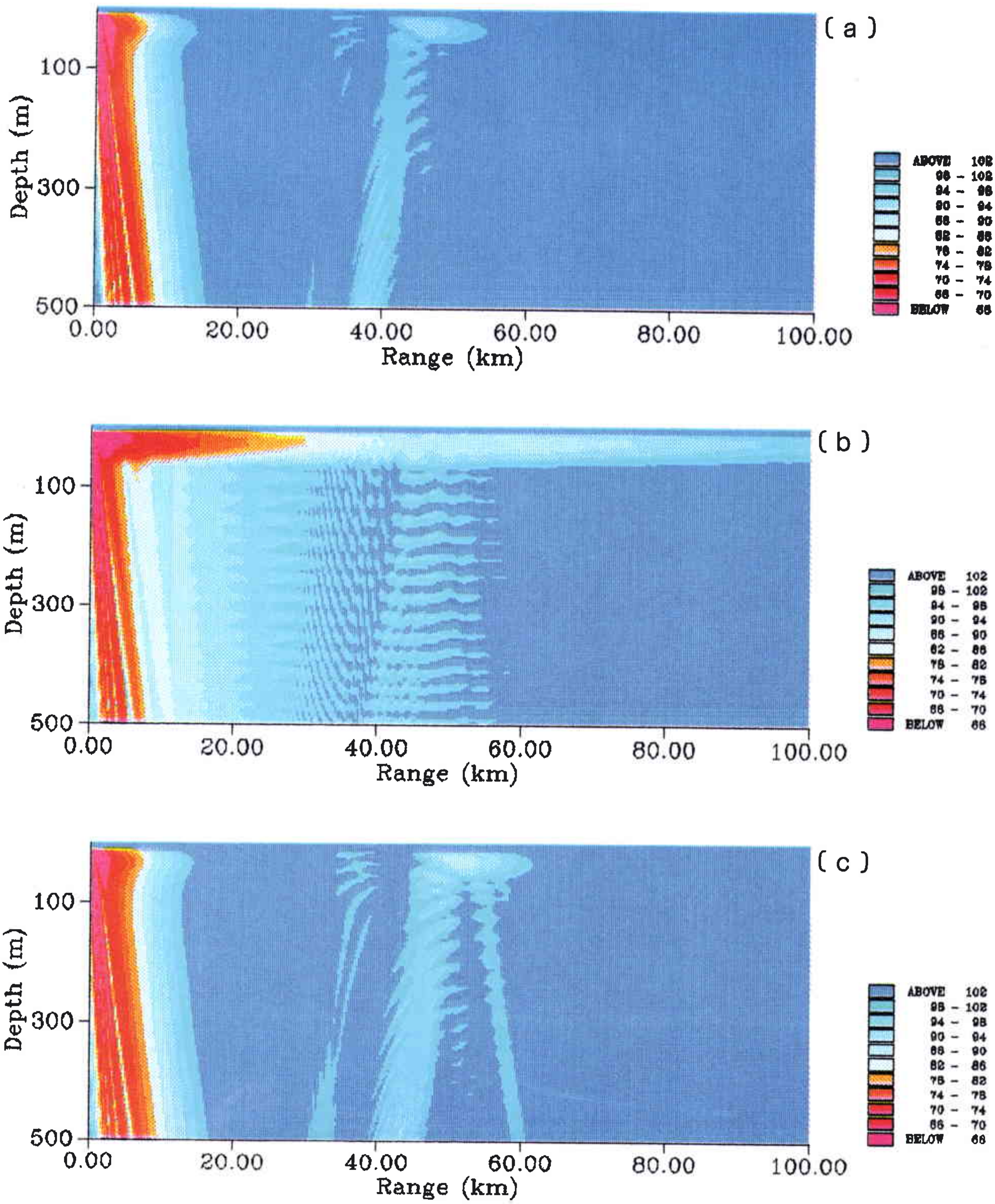

Figure 6 *Transmission loss calculations on September 8 using (a) experimental measurements, (b) ML model, and (c) climatology to derive the sound-speed profile.*

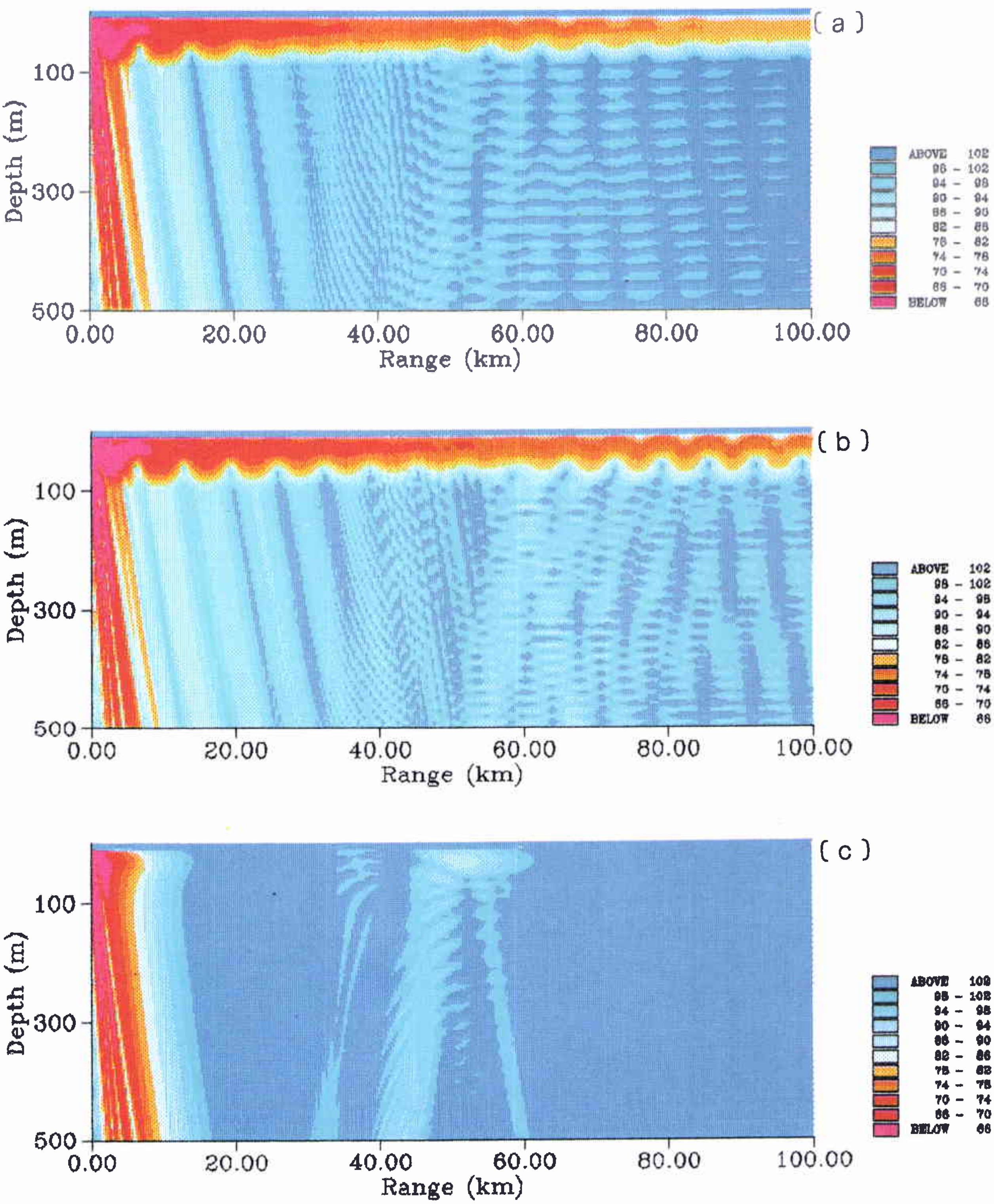

Figure 7 *Transmission loss calculations on September 20 using (a) experimental measurements, (b) ML model, and (c) climatology to derive the sound-speed profile.*

SSP is also plotted in Fig. 5a.) The data from the weather ship is included in the database, which implies this is a favorable location for climatology. A seasonal average, however, cannot hope to provide much accuracy during a storm event. Thus we see that climatology (Fig. 6c) agrees quite well with the XBT results (Fig. 6a) on September 8. In fact, the agreement with the XBT solution is actually better than the MLM because of the incorrect gradient in the latter. However, by September 20 the climatological profile bears little resemblance to the measured profile, while the MLM does quite well.

One cannot conclude from these results whether climatology is in general better or worse than the MLM and indeed this is not our objective. We must also caution that the XBT data are somewhat undersampled in depth, so that the MLM profile may actually be providing a better answer than the XBT profile on September 8. At any rate, several points are illustrated by this comparison. First, mixed-layer depth is an inadequate criterion for judging the performance of a mixed-layer model. Secondly, changes in mixed layers can have an important effect on transmission loss even in the mid-frequency band.

5
Model comparison

Previous mixed-layer studies have shown that appreciable differences arise in the predicted SST (sea-surface temperature) and MLD (mixed-layer depth) if different models are used. Most of these experiments have been performed at weather ship sites *Papa* and *November* in the North Pacific [7], where a strong halocline prevents the formation of very deep mixed layers. Here we have tested these models in the northeast Atlantic, in particular the GIN Sea (Greenland–Iceland–Norwegian Sea) where much deeper mixed layers have been observed, with corresponding ducting effects at much lower frequencies.

To include both a cooling/deepening and a warming/shallowing event, we have chosen to simulate the mixed-layer development during May 1964, in the neighbourhood of the weather ship *Mike*. The exact hydrographic location chosen is 62.5°N, 1.0°E, where the predominant water mass characteristics are typically those of the North Atlantic Inflow water, with a gentle decrease of temperature in the seasonal thermocline and a location known for the occurrence of deep mixed layers in the winter.

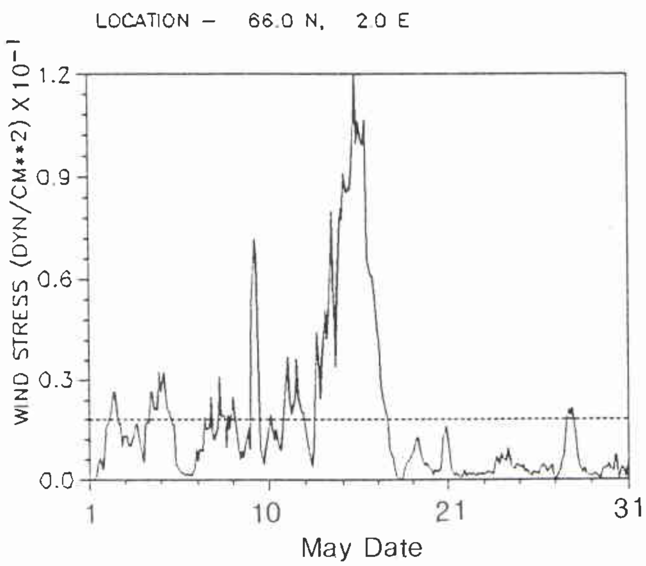

Figure 8 *Wind stress during May of 1964 at weather ship Mike.*

Figure 8 shows the wind forcing in May 1964, dominated by a rather large, somewhat unseasonable but by no means uncommon, storm commencing on May 9 and ending around May 18 or so. The remaining period in May is characterized by rather light winds which allow the seasonal warming to proceed almost uninhibited, providing only enough mixing to transport the heat downward to lower layers, thus preventing the formation of an excessively warm near-surface layer. The particular onset time of the heating was also influenced by the appearance of clear skies and a warmer overlying air mass.

The time history of the mixed-layer development is illustrated in Fig. 9, as obtained by three models: the Mellor–Yamada level 2.5 (a profile type), the Garwood (a bulk type), and the Niiler (another bulk type). The general behaviour of the model-predicted temperature field is the same for all models, but there are important quantitative differences. In all models, the mixed-layer deepening proceeds more or less steadily for the eight days of the storm, until about May 17 or so, and then the mixed layer becomes stationary. On about May 20 a marked surface heating episode commences and continues until the end of the month.

In Fig. 9 the results are presented in order of increasing mixing efficiencies: the Mellor–Yamada level 2.5 (MY2.5) mixing the least and the Niiler mixing the most. The MY2.5 model mixes to a final depth of ~ 75–80 m, the Garwood model to ~ 95–100 m, and the Niiler model to ~ 100–105 m. The total simulation region had a depth of 200 m, but only the top 120 m are presented here in order to further enhance variations within the mixed layer, and to better observe the transition region below it. In these discussions we would rather avoid giving an exact definition of mixed-layer depth (MLD), which can be based on the depth at which various physical quantities drop a certain increment below their surface value (e.g. 0.2°C for temperature), or at which they reach their near-surface maximum (e.g. sound speed, Brunt-Väisäla frequency). At any rate, when multiple well-mixed layers appear, these definitions lead to ambiguities and are not very adequate, as for example during the heating period in the last 10 days of May. We will rather confine ourselves to simple ad hoc definitions and estimates that best describe the results presented in these figures. With this in mind, the contour intervals and shading scales have been selected to best present the regions of strong mixing and the transition region immediately below them, but neglecting the seasonal thermocline.

The depths of the new surface layers due to the late-May heating are again predicted in the same manner, with the MY2.5 model predicting a depth of ~ 20 m, the Garwood model a depth of ~ 30 m, and the Niiler model ~ 40 m. A useful definition of the MLD here is the depth of the isotherm representing the first 0.2°C increase above the temperature of the storm-induced deep mixed layer.

The corresponding acoustic propagation results are illustrated in Fig. 10, for a frequency of 600 Hz and a source depth of 25 m. Figure 10a shows the propagation in the initial environment, taken from spring climatology. There is only a very shallow mixed layer present initially, of ~ 10 m in depth, and there is no evidence of any duct for this frequency. Figures 10b,c show propagation loss in the environment present

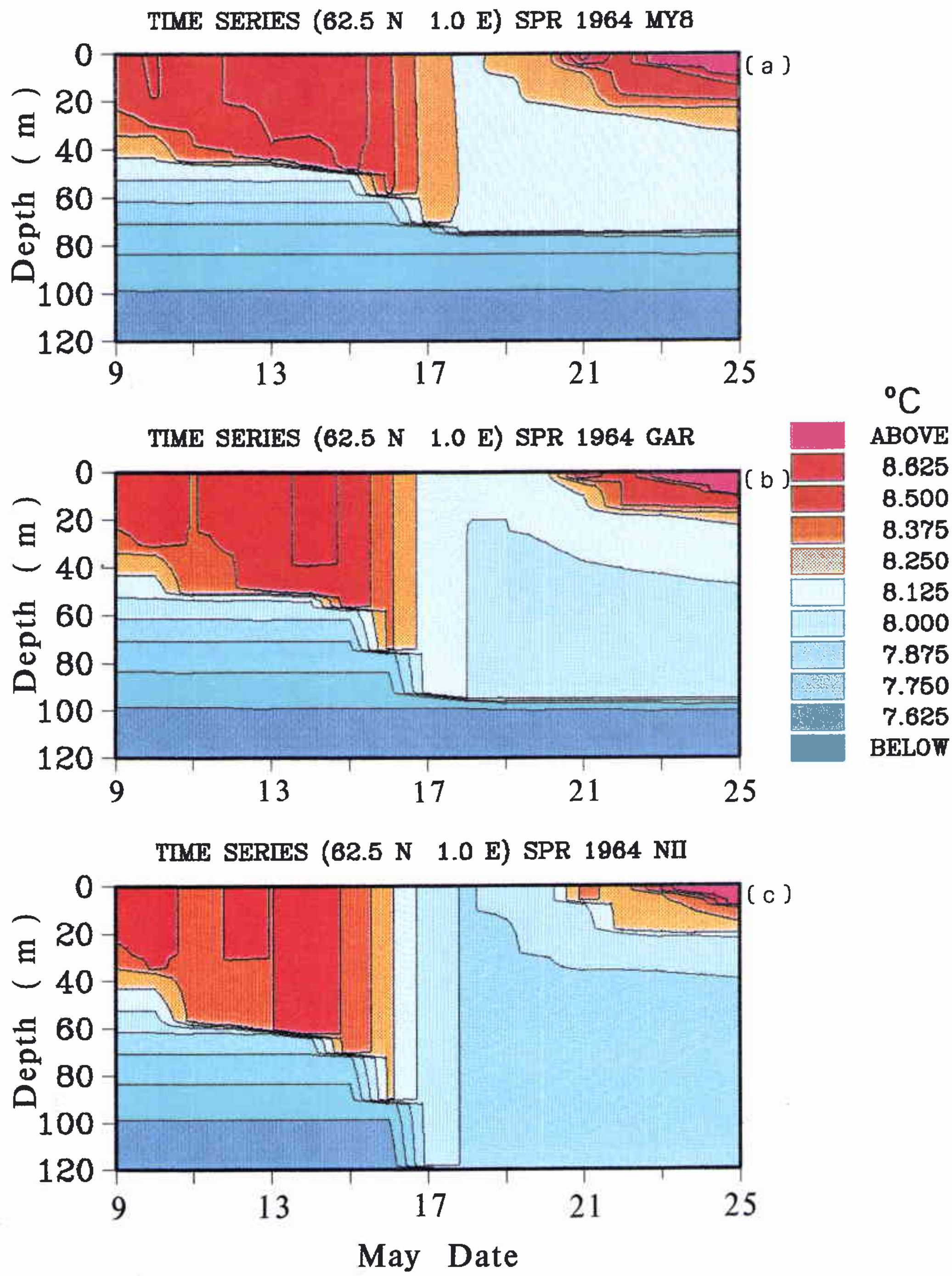

Figure 9 *Evolution of the mixed-layer temperature calculated using (a) Mellor–Yamada level 2.5, (b) Garwood, and (c) Niiler models.*

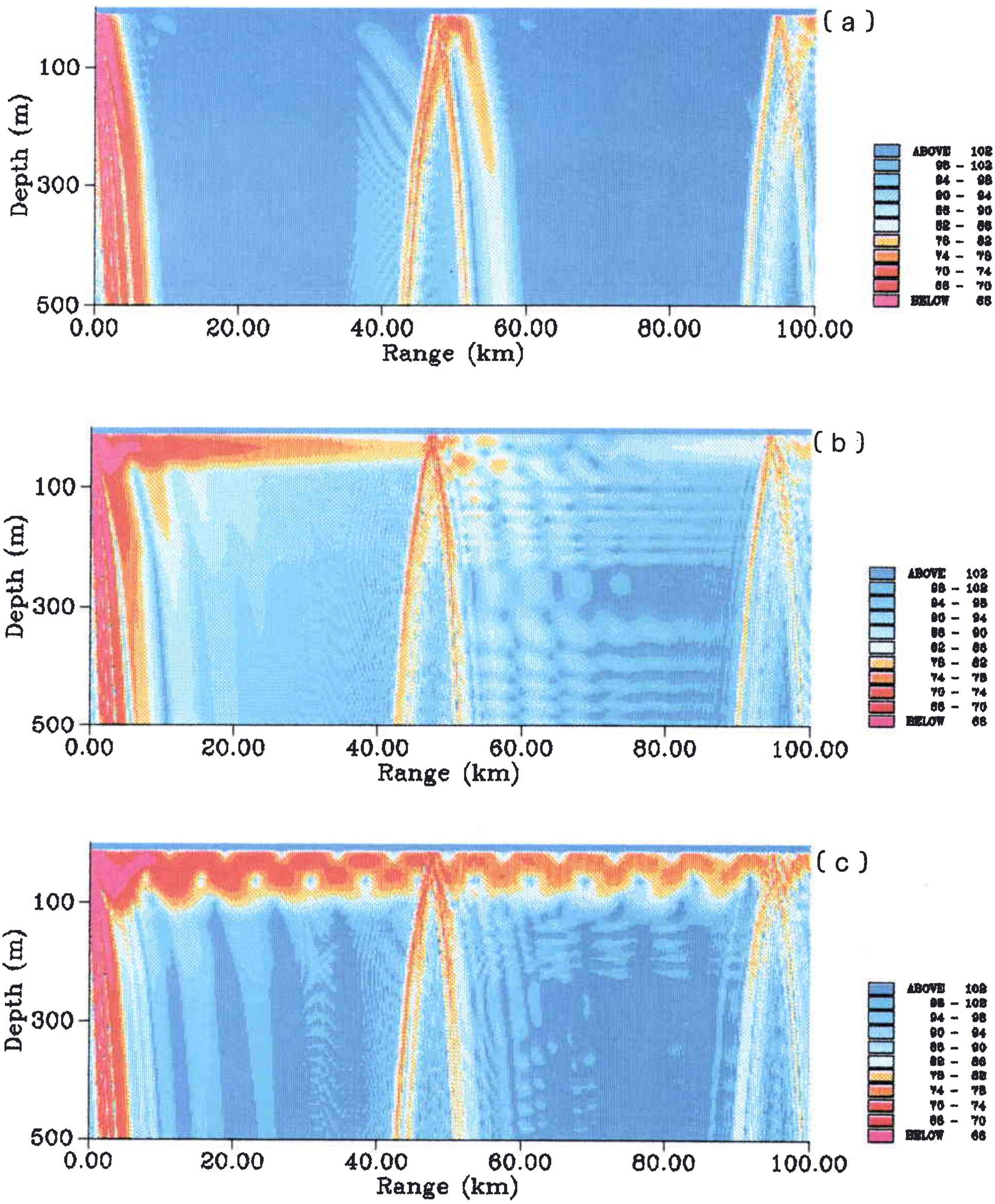

Figure 10 *Transmission loss calculations on May 19 (day 8) using (a) the climatology initial condition, (b) Mellor–Yamada level 2.5 MLM, and (c) Niiler MLM for the mixed-layer profile.*

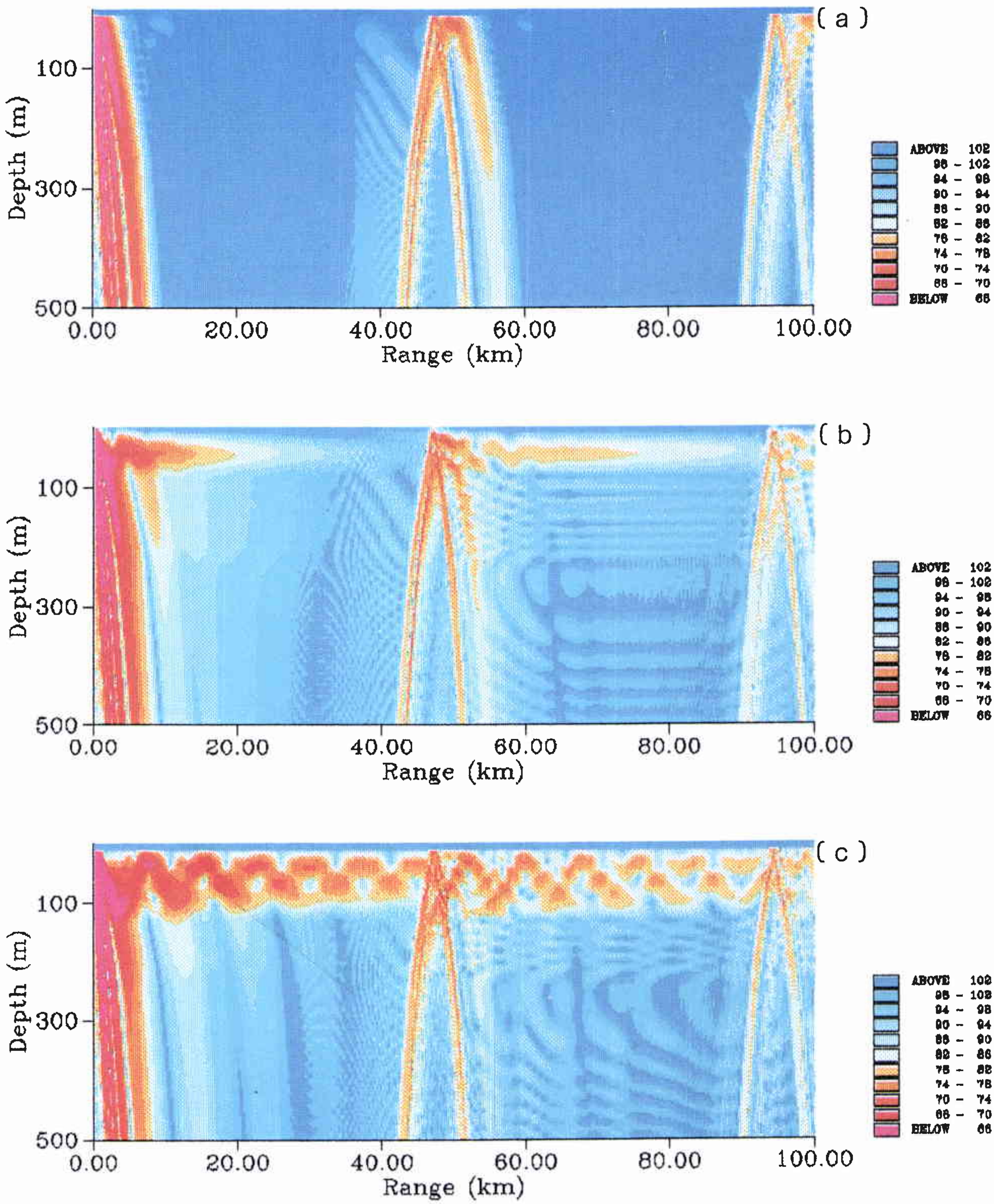

Figure 11 *Transmission loss calculations on May 23 (day 12) using (a) the climatology initial condition, (b) Mellor–Yamada level 2.5 MLM, and (c) Niiler MLM for the mixed-layer profile.*

at the end of the storm, on May 19, the eighth day of the simulation, as predicted by the MY2.5 and the Niiler models, respectively. We see that only a moderate ducting occurs in the MY2.5 environment, but a rather strong duct is present (for 600 Hz) in the Niiler environment. The results of the Garwood model (not shown) fall somewhat in-between.

Figure 11 presents the acoustic propagation results in the environments predicted for May 23, day 12 of the simulations, at the end of the heating period. The conclusions for the simulations of May 19 apply here, too, with significant ducting occurring only in the Niiler environment. In comparison to the previous figure, we observe that the surface heating has induced fairly minor changes in the TL plots. Both models show some increase in TL which is associated with a reduction in surface duct thickness. The differences between the individual models are more important than the differences resulting from the surface heating.

To capture a very deep winter mixing event, with its potential ducting effect on even lower frequencies, we have simulated the mixed-layer behaviour during the large winter storm of February 1960, commencing on February 3. The time history of the wind stress is illustrated in Fig. 12. Even this large storm, obtaining stress peaks of $\sim$ 17 dynes, represents a wind speed of only 60 mph or so, which is not a rare event in the GIN Sea. A statistic of polar lows shows a significant number of such storms having wind speeds in excess of 35 m/s, or ca. 78 mph.

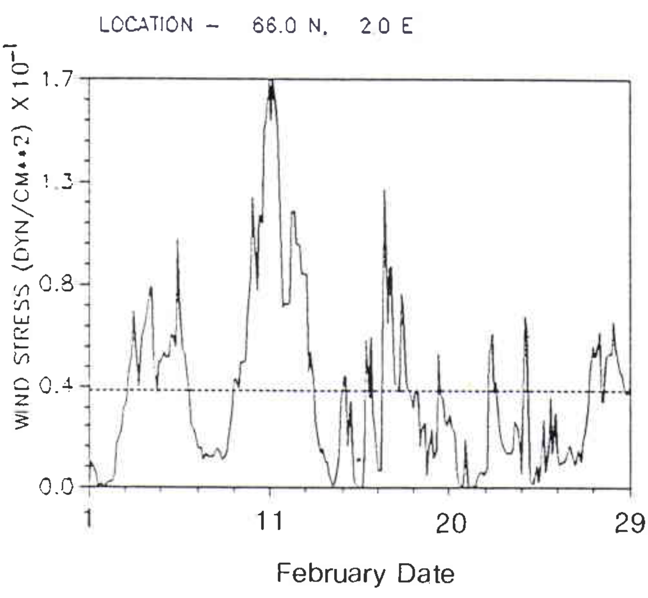

Figure 12 *Wind stress during February of 1960.*

Figure 13 shows the evolution of the mixed layer, commencing on February 3 and ending February 19. Again, the initial state was taken from winter climatology, which shows the typical mixed-layer depth to be 130 m or so. The MLD is predicted to deepen slowly to $\sim$ 225 m by the Garwood model, and somewhat more rapidly to a depth of $\sim$ 275 m by the Niiler model; the MY2.5 model causes very little noticeable deepening.

The corresponding acoustic propagation results are illustrated in Fig. 14. The frequency has been reduced to 200 Hz, yet all three profiles (GDEM, Mellor–Yamada and Niiler) show significant ducting. Taking the GDEM as a plausible winter average, we may say that for this particular location one may expect significant mixed-layer effects for such frequencies during the winter. Placing some faith in the mixed-layer models, we may anticipate that significant surface ducting will occur for frequencies as low as 50 Hz during certain times of the year.

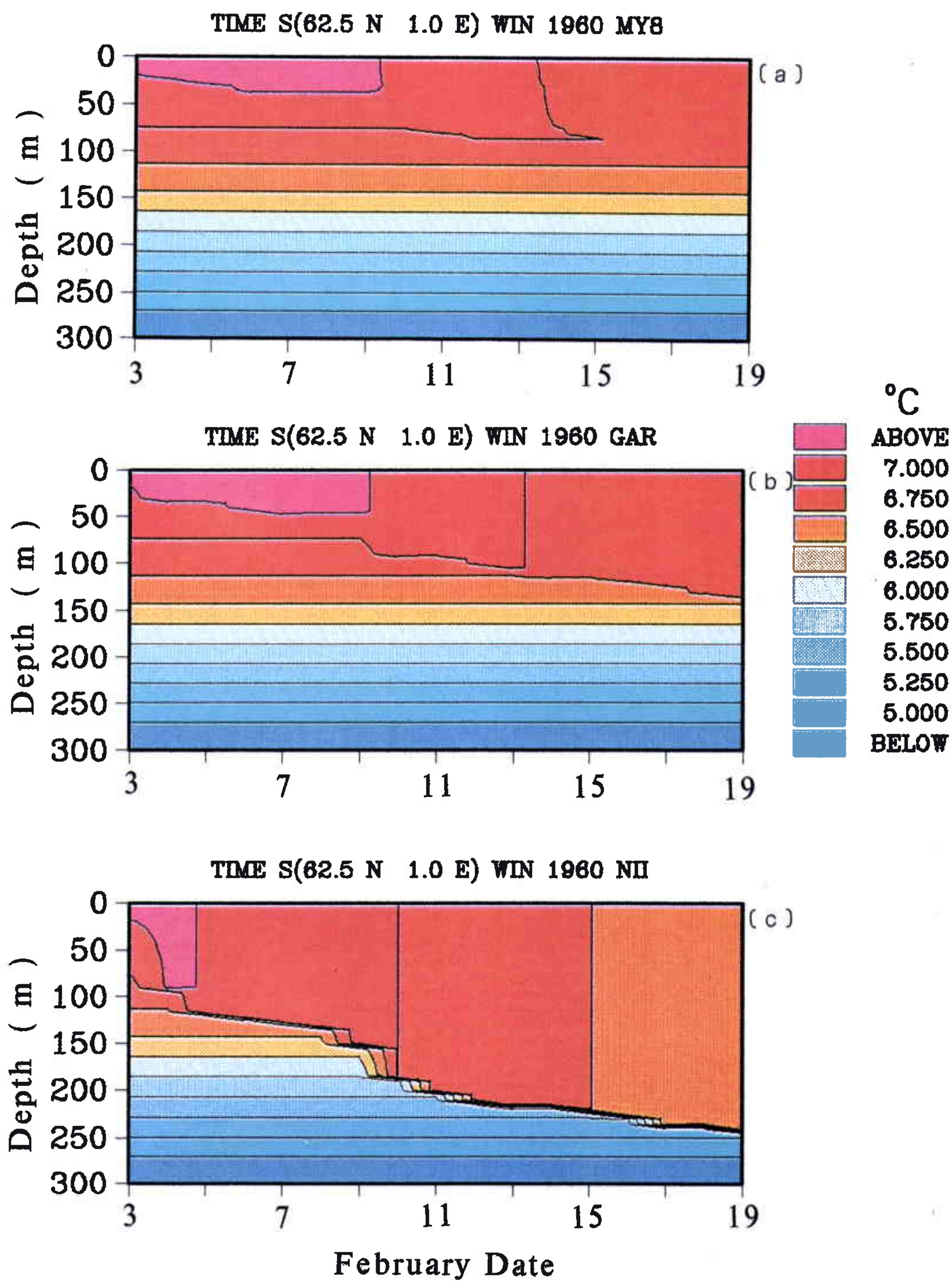

Figure 13 *Evolution of the mixed-layer temperature calculated using (a) Mellor–Yamada level 2.5, (b) Garwood, and (c) Niiler models.*

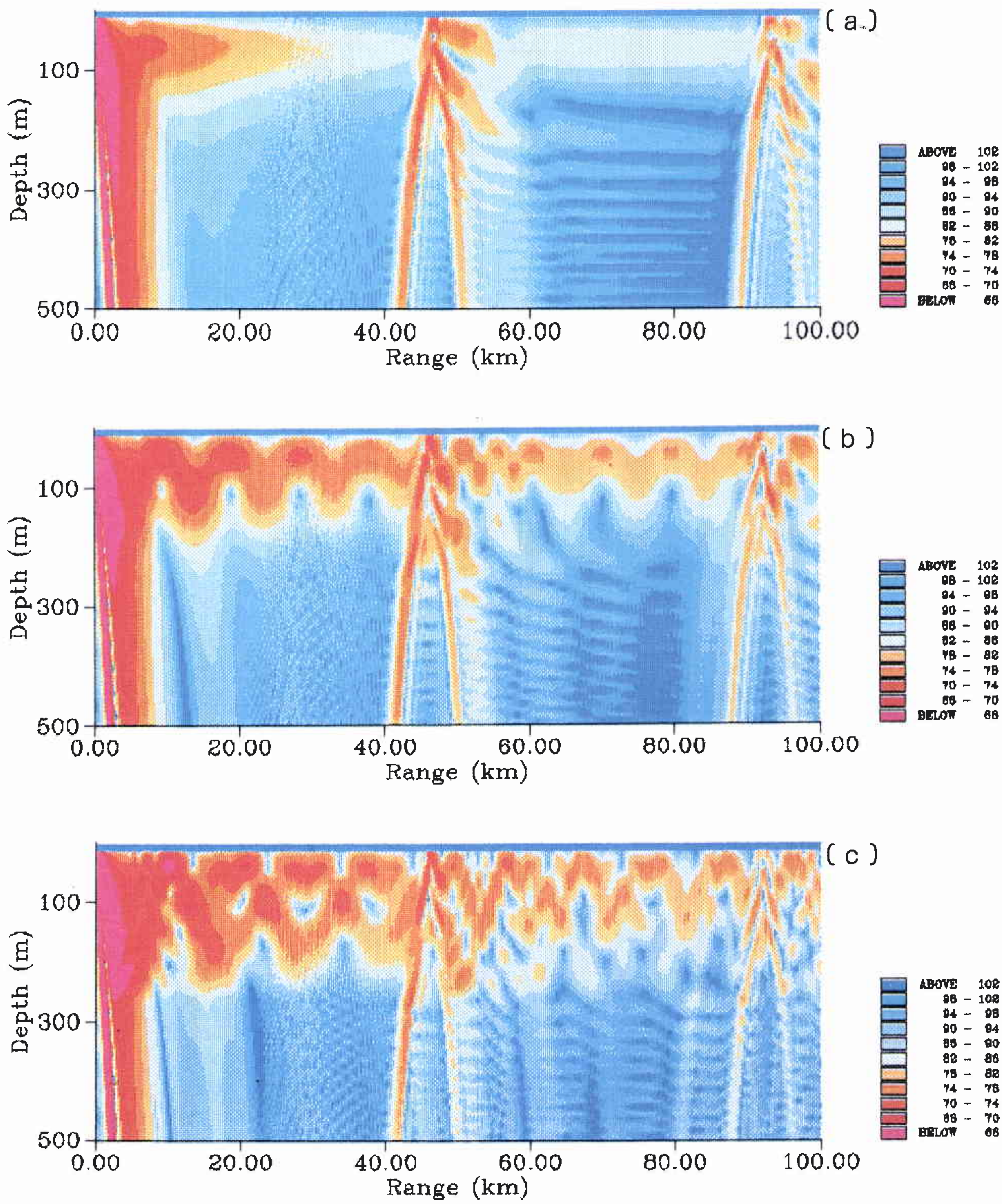

Figure 14 *Transmission loss calculations on February 18 using (a) the climatology initial condition, (b) Mellor-Yamada level 2.5 MLM, and (c) Niiler MLM for the mixed-layer profile.*

6

Summary and Conclusions

We have presented a set of oceanic and acoustic simulation studies for the oceanic surface mixed layers found at high latitudes. The sensitivity study indicates that the near-surface temperature gradient (say in the upper 100 m) is an extremely important parameter, whereas overall mixed-layer temperature is essentially irrelevant. An illustration of these effects has been provided by comparing transmission loss calculations based on profiles from a particular mixed-layer model as well as measured and climatological profiles.

Comparisons of particular mixed-layer models have shown that the different models predict substantial differences in the mixed-layer depth. This, in turn, is found to have a profound influence on predicted acoustic propagation for certain frequency and source/receiver depths. In general, the MY2.5 model creates the shallowest mixed layers, and the Niiler model the deepest ones, with the Garwood model yielding intermediate values.

Finally, we have shown that in the winter significant ducting occurs for frequencies as low as 200 Hz, and in the spring as low as 600 Hz.

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