Modelling shallow mixed layers in the north Atlantic.

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Summary

Output from the Met Office's Forecasting Ocean Atmosphere Model (FOAM) and a one-dimensional model initialised using Argo float data show that at 40°N in the northeast Atlantic in winter the mixed layer can shallow from 100m to 10m over a day because of the buoyancy input from rainbands. For this case study errors in the moisture flux were almost as important as those in the heat and momentum fluxes for forecasting the mixed layer.

A second case study in spring showed that the moisture flux was less important in this season, but the vertical resolution was important. This was because a model with a 10m vertical resolution must mix properties over 10m even when the applied wind stress is too small to achieve this, whereas a 2m resolution model only has to mix down to 2m depth. We show that a change from a 10m to a 2m vertical resolution can increase the forecast SST in spring by 1°K.

To solve this resolution problem without the need for many extra levels, a variable-depth sublayer was added to the top level of a 10m resolution model to accomodate the non-penetrating buoyancy flux. The sublayer's mixed layer depths and SSTs were close to the results of a 2m resolution model.

1 Introduction

Rain falling on the ocean surface both cools and freshens it. The freshening can have a greater effect on near-surface buoyancy than the cooling. Rain water is typically 5^oC cooler than ocean water (Anderson *et al.*,1998) and its salinity is zero. When 70 mm day^{-1} of rain water (h) falls on an ocean at 10^oC and 35 *psu* for one day the reduction in density of a layer of depth H(50m) due to the rain water's temperature is given by $\delta\sigma = -\alpha\delta T \times h/H = 6 \times 10^{-6} kg\ m^{-3}$. Similarly the decrease in density due to the rain water's salinity is $\delta\sigma = -\beta\delta S \times h/H = 2 \times 10^{-4} kg\ m^{-3}$. The reduction of ocean density due to the zero salinity of the rain is 30 times the increase in ocean density because of the rain's lower temperature. Therefore, rainfall increases surface buoyancy and inhibits turbulence.

An example of this was discussed by Price (1979) who observed in the Gulf of Mexico that the buoyancy input by 48mm of rain over 2 hours stabilised a 7m mixed layer (ML) against vertical mixing by $10 ms^{-1}$ winds. Similar examples from the Sargasso Sea (30^oN) are discussed in Federov and Ginsburg (1988). The more permanent shallow MLs observed in the tropical Pacific are due to the buoyancy input of the heavy rainfall there (Sprintall and McFadden, 1994).

In section 2 of this paper we present results from an ocean model that imply that rainfall can cause transient shallow mixed layers even in winter in the northeast Atlantic at 40-50^oN where one might expect convection to deepen the mixed layer, and in section 3 we verify the model's forecast using the new Argo float data. In section 4 we use Argo data and a one-dimensional model to confirm the shallowing is due to the buoyancy input from the rain, demonstrate the importance of this effect in winter, but show that vertical resolution becomes more important in spring.

In section 5 we show how a GCM's near-surface vertical resolution could be inexpensively improved by adding a sublayer within its top layer. This method is tested within a one-dimensional 10m resolution model and produced ML depths and sea surface temperatures (SSTs) close to those of a 2m resolution model.

2 Shallow mixed layers in FOAM output

The Met Office's Forecasting Ocean Atmosphere Model (FOAM) system is based on an ocean model descended from the Bryan-Cox code (Bryan, 1979 and Cox, 1984). FOAM uses a Kraus and Turner (1967) mixing scheme for tracers and a neutral Large scheme (Large *et al.*, 1994) for momentum. The effects of shear driven mixing are parameterised using the scheme of Pacanowski and Philander (1981) and a simple convective adjustment scheme is included. The vertical resolution near the surface is 10m decreasing to 600m at the sea bed. In the version of FOAM used here the horizontal grid spacing was 1^o. For a more detailed description of the system see Gordon *et al.*, (2000).

Every day FOAM produces five-day forecasts of 3-d ocean temperature, salinity and velocity fields using the air-sea heat, moisture and momentum fluxes output by the Met Office's operational numerical weather prediction (NWP) model (see Cullen, 1993).

FOAM assimilates observations using an analysis correction scheme described by Bell *et al.* (2000). It ingests roughly 400 temperature profile observations per day taken using XBTs, CTDs, moored buoys and Argo floats. Several hundred ship SSTs and several thousand satellite (AVHRR) SST reports are also assimilated per day within the mixed layer.

Figure 1a shows the three-day mean air-sea moisture flux output by the Met Office's NWP system between the 17th and 19th of December 1999. There is a band of net rainfall (dark shading) between 25^{o}N,35^{o}W and 45^{o}N,30^{o}W with a moisture flux of up to 0.8 g m^{-2} s^{-1} (or 70 mm day^{-1}) which was associated with a slow-moving cold front (Weather, 2000).

Figure 1b shows the daily-mean mixed layer (ML) depth output by FOAM at the end of this period. The ML under the rainband has shallowed from the 100-150m depth one would expect, given the strong convection at this time of year, to only 10-20m depth (the dark band). As demonstrated in sections 3 and 4.1 this shallowing has occured because the addition of freshwater to the ocean surface stabilises the water column against vertical mixing. Similar spatial correlations between the moisture flux and ML depth can be seen every few days in the FOAM output in winter. As far as we know the shallow layers previously documented (eg: Price, 1979, Federov and Ginsburg ,1988) were in the heating season and at lower latitudes.

3 Verification using Argo float data

The rain-induced shallow mixed layers predicted by FOAM on the 20th December 1999 (Fig 1b), can also be seen in newly-available Argo data. Argo (1999) is an internationally coordinated series of projects to establish a global array of autonomous profiling floats. The floats cruise at 1.5km depth for 10-15 days, then rise to the surface collecting a profile of temperature. These data are eventually received at the Met Office over the GTS. As of September 2001 there were 458 floats in place, of which 82 collect salinity profiles as well.

Figure 2 shows the temperature (solid line) and salinity (dashed line) profiles collected by an Argo float at 44°W, 37°N (marked as 'F' on Fig. 1a) two days after the rainfall event shown in Fig 1a (on December 21st). The float is several hundred kilometres west of the rainband shown in Fig 1a, but the ML is less than 20m according to the salinity profile (dashed line) and a fresh surface layer can be seen. The rainfall required to produce the freshening is δ_w, where

$$\delta_w = \frac{\triangle S h_w}{S_1 \times 10^{-3}}(mm) \tag{1}$$

The depth of the surface fresh layer h_w was 15m, the surface salinity anomaly $\triangle$S was 0.03 and the ambient salinity S_1 was 35.88. Therefore $\delta_w = 12mm$. The rainband had a three day mean rainfall rate of 70 mm day^{-1} and the front was fairly static so could have provided this freshwater.

4 Simulations using a one-dimensional model

To confirm that the shallowing was due to the moisture flux we simulated it using a one dimensional (1-d) model. We used a Kraus and Turner (1967) model, as used for tracers in FOAM. The wind mixing factor was 1.25 and the penetrative convection factor was 0.15. The vertical diffusion coefficient below the mixed layer was taken to be $2 \times 10^{-5} m^2 s^{-1}$ following Ledwell *et al.* (1993). The vertical resolutions tried were 2 and 10m (the latter as used in FOAM) and the time step was one day. The model was initialised using the Argo data.

4.1 Case study in December 1999

This run simulates the mixed layer shallowing forecast by FOAM on 20th December 1999 and shown in Fig. 1b. The 1-d model was initialised on the 10th December 1999 using temperature and salinity profiles from an Argo float located at 44°W,37°N (see F in Figure 1a).

The model was driven using air-sea heat, moisture and momentum fluxes from the Met Office NWP (Numerical Weather Predicted) system (see Figure 3a) and the ECMWF (European Centre for Medium-Range Weather Forecasting) model (Fig. 3b) for a location (36°N,36°W, shown by the P in Fig. 1a) where the mixed layer shallowed significantly according to FOAM (Fig. 1b). Note that the Met Office moisture fluxes show a large amount of rainfall (dotted line) occured (as also seen in Fig. 1a) whereas the ECMWF rainfall (dotted) was relatively small. The heat fluxes (dashed line) and wind strength (solid line) were similar.

Figure 4a shows the mixed layer depth forecast by the 1-d model using Met office fluxes for the ten days after the 10th December, 1999 (solid line). The ML depth was defined where the density was 0.125 kg m^{-3} greater than at the surface. After day 348 the mixed layer shallowed from 95 to 20m following the rain, as shown also by the FOAM output (Fig. 1b). When the model was run using the ECMWF moisture fluxes (dashed line) or with no moisture flux (dotted line) the mixed layer did not shallow at all. This shows that the shallowing was caused by the buoyancy input by the rainfall.

Figure 4b shows the mixed layer depth forecasts obtained when various inputs to the model were alterred by the size of their likely uncertainty. The control experiment is shown by the solid line. The dashed line shows the forecast when the sea-air heat flux was increased by its systematic error of 30 W m^{-2} (see Isemer *et al.* (1989). The dotted line shows the results when the ECMWF wind stress was used. The longer-dashed line shows the results when Levitus data were used for the initial conditions. In this last case, the mixed layer still shallowed under the rainband. These results are summarised in the sensitivity study in section 4.3.

4.2 Case study in May-June 1999

A second experiment was performed to determine whether rainfall is similarly important in spring. The 1-d model was initialised using an Argo float at 50^oW,35^oN on 10th May 1999 and run for 30 days till the 11th June. The Met Office fluxes are shown in Figure 5a as a time series. Shown are the wind friction velocity (solid line), the net heat flux (dashed line) and the moisture flux (dotted line). During this period four fronts passed over the float (denoted on Fig. 5 by A,B,C and D). Each front caused a decrease in the air-sea heat flux, as clouds attenuated the shortwave radiative flux and stronger winds increased the ocean's latent heat loss. Each front was also accompanied by an increase in the wind friction velocity, and, especially for A, C and D, an abrupt increase in the rainfall rate. For comparison Figure 5b shows the ECMWF fluxes. The same four fronts can be seen.

Figure 6a shows the predicted (lines) and observed ML depth derived from the Argo float profiles (the large crosses) when available once every 10 days. The model reproduced the shallowing of the ML after day 140 quite well.

In order to quantify the importance of rainfall to the ML depth the model was run using Met Office (solid line) and ECMWF (dotted) moisture fluxes. In this spring case the rainfall alterred the final ML depth by only 5m.

In Figure 6b the control experiment with Met Office fluxes is shown by the solid line. The dashed and dotted lines show the forecasts when the sea-air heat flux and wind stresses were changed as described in section 4.1.

The longer-dashed line shows the results when the model was initialised with the Levitus climatology instead of the Argo data. The ML depth was initially 20m shallower, as the Levitus profile was more stratified than the Argo profile. This may have occured because 1) the Argo data was unusually unstratified for the season, 2) vertical smoothing of the data stratifies the Levitus ML and 3) hydrographic data has a fair-weather bias as ships avoid storms and so climatological MLs are too shallow. As the ML deepened to 70m (days 130-137), the initial Levitus profile was erased, and when the ML shallowed again (days 138-140) the upper 70m was restratified as the ML warmed during its retreat towards the surface. The rate of shallowing and warming depends on the air-sea fluxes and not the initial profile, now erased, so the stratification set up was similar in both the Levitus- and float-initialised cases. As a result the long-dashed line follows the solid line in

Fig 6b closely after the first few days. This shows that errors in initial conditions may have little lasting effect on ML depth forecasts in cases where the ML deepens, then shallows again.

4.3 Sensitivity Study

RMS MLD DIFFERENCE FROM CONTROL RUN

Change to model	Winter (m)	Spring (m)
MO-ECMWF moisture flux	35	4
MO-ECMWF heat flux	32	8
MO-ECMWF wind stress	54	8
Argo-Levitus initialisation	42	4
2-10m vertical resolution	20	6

Table 1: Columns 2 and 3 show respectively the time-averaged rms difference to the forecast MLD of the experiments shown in Figures 4b and 6b following the changes described in column 1 (MO = Met Office

Table 1 summarises the results from Figures 4b (column 2) and 6b (column 3), showing the rms difference from the control run caused by the change described in the left hand column. For the winter run errors in the moisture flux fields have as much effect on the forecast ML depth as errors in the other forcing fields or the initial conditions. This is interesting because more attention is usually given to validating the heat or momentum fluxes. The vertical resolution has a smaller effect because the ML depth in winter is much larger than the vertical resolution.

In the spring case errors in the moisture flux are less important as the water column is relatively stratified already. The heat and momentum fluxes and vertical resolution are more crucial, the latter because the ML in spring (Fig. 6b) is shallow, and the 10m resolution is often too coarse to resolve it. Although the largest errors are due to the heat and momentum fluxes, we focus now on the vertical resolution as it is almost as important, and is easier to improve than the fluxes.

5 Improving near-surface vertical resolution

5.1 The impact of vertical resolution

Figure 7a shows the ML depth forecast by a 2m vertical resolution model (dotted line) and a 10m resolution model (solid line) as used in FOAM or the Hadley Center's climate models (for example: HadCM3, which uses the same code as FOAM). When the winds were light (days 140-150 and 153-157) the 2m model predicted ML depths much less than 10m whereas the top layer of the 10m resolution model was always fully mixed. FOAM and HadCM3 may similarly overestimate the ML depth during spring and summer.

Figure 7b shows the SST forecast obtained using the two resolutions. In calm conditions (low wind stress) the 2m resolution model (dotted line) forecast SSTs 1°C higher then the 10m model (solid line) because the non-penetrating air-sea heat fluxes warmed a shallower surface layer.

This implies that FOAM and HadCM3 may underestimate summer SSTs by $O(1K)$ because of their low vertical resolution. For HadCM3 this has implications for sea-air coupling. Assuming that the strength of this coupling is 35 $Wm^{-2}K^{-1}$ (Oberhuber, 1988) the HadCM3 heat fluxes may be wrong by 35 Wm^{-2}, which is much greater than the 4 Wm^{-2} change due to greenhouse gas forcing (Houghton *et al.*, 1990). Therefore we should aim to improve the near-surface vertical resolution in these models.

5.2 Introducing a sublayer method

In ocean models the non-penetrating buoyancy fluxes (all the fluxes apart from the penetrating shortwave component) are added uniformly to the top model layer whether or not the wind energy is strong enough to mix the non-penetrating buoyancy input over this depth. To add these fluxes more realistically without the expense of using a much higher vertical resolution, we add a sub-layer of depth h within the top layer to accomodate the non-penetrating buoyancy flux until such time as it *can* be mixed over the whole top layer.

Figure 8 is a schematic showing the density profile as the sub-layer deepens from a depth h_i to h_f and changes its density from ρ_i to ρ_f over a time step. The depth Z is the base of the top model layer. To calculate h_f we first assume conservation of buoyancy:

$$\rho_f h_f = \rho_i h_i + B \tag{2}$$

where B is the sum of the air-sea buoyancy flux over the time step. We also assume conservation of energy

$$K = P_f - P_i \tag{3}$$

where K is the input wind mixing energy available for mixing, and P_i and P_f are the initial and final potential energies of the model's top layer. We define $P = -g\int_0^Z \rho z dz$, so that

$$K = P_f - P_i = g\frac{(\rho_f h_f)h_f}{2} - g\frac{\rho_i {h_i}^2}{2} \tag{4}$$

Replacing the $\rho_f h_f$ in the first term using (2), and rearranging for h_f

$$h_f = \frac{2K + g\rho_i {h_i}^2}{g(\rho_i h_i + B)} \tag{5}$$

The first time the sublayer is needed, we assume the non-penetrating flux is added to a layer of zero thickness at the surface. Therefore, in (5) h_i is zero, and we have

$$h_f = \frac{2K}{gB} \tag{6}$$

When running the 1-d model (6) was used, for every time step without a pre-existing sublayer, to calculate h_f. When h_f was greater than Z a standard mixed layer model was utilised because the wind was strong enough to mix the non- penetrating buoyancy flux over the top model level. However, when h_f was less than Z a sub-layer was added of depth h_f.

Here h_f was limited to be more than 2m because our comparison was with a 2m resolution model, and we wished to avoid very shallow layers in which mixing due to waves and near-surface convection was important. This choice of 2m was not crucial as when a limit of 1m was chosen instead the sublayer SST on day 146 was $0.15K$ higher but unchanged on other days.

Once its depth was found, the sub-layer's temperature and salinity were calculated from the non-penetrating heat and moisture fluxes, and the properties of the top model box were updated using the penetrating flux only. When the sublayer shallowed or was no longer needed, the heat and salt detrained from it was added to the top model box.

For time steps with a pre-existing sublayer (5) was used to find h_f, and h_i and ρ_i were then the previous sub-layer depth and density anomaly.

5.3 Results

Figure 7a shows the ML depth forecast using the 10m vertical resolution model (solid line), the 2m model (dotted line) and a 10m model with a sublayer added (dashed line). This last forecast ML depths close to those of the 2m model without the computational expense of the extra resolution.

Figure 7b shows the SSTs forecast by the original 10m resolution model (solid line) the 2m model (dotted line) and the model with the sublayer (dashed line). The 2m and sublayer models produced similar forecasts.

5.4 Discussion

In using the sublayer we assumed it was too short-lived to be horizontally advected over a grid box. This assumption was valid for the example in Fig. 7 as the sublayers lasted three days at most and advection was likely to be negligible in this region. However, a maximum ocean flow of 1 ms^{-1} in the Gulf Stream would cause a movement of 260 km (more than a grid-box width in FOAM) over three days. Therefore, the sublayer should be used with care when there are strong currents

The sublayer was designed to accomodate the non-penetrating flux only. The penetrating flux was assumed to be fully mixed over the top model box. In reality the penetrating flux causes some stratification in the upper 10m, and so the sublayer depths may be overestimated here.

Conclusions

The Met Office's FOAM model predicts that transient shallow mixed layers 10m deep can form within a day in the northeast Atlantic in winter (where mixed layers are generally deeper than 100m) because of the buoyancy input from rainbands. Argo float data was used to validate one of these forecasts.

Due to the large positive air-sea heat fluxes in spring the mixed layer can be shallower than 10m over periods of a few days. FOAM and HadCM3 and other models with 10m vertical resolutions may underestimate surface anomalies of temperature and salinity as a result. In HadCM3 this is likely to effect air-sea coupling.

The near-surface resolution can be improved cheaply by adding a sublayer to the top layer of a model. Such a scheme was tested in a 10m resolution model and reproduced quite closely the ML depths and SSTs of a 2m model.

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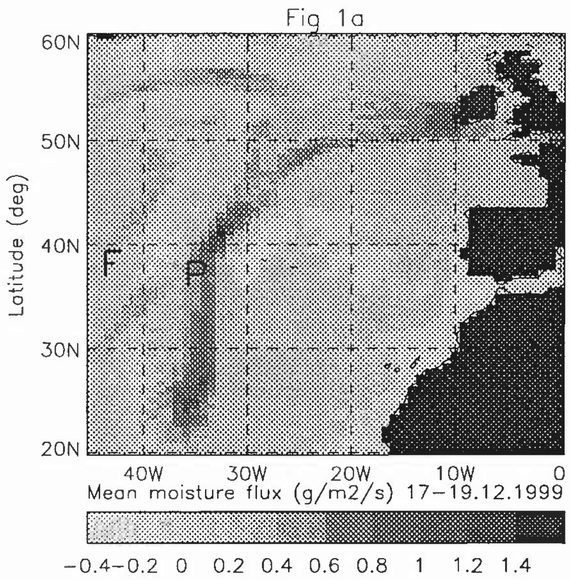
Fig 1. a) Met Office moisture fluxes averaged over 17-19th December, 1999 showing a rainband and b) The ML depth (m) output by FOAM on 19th December showing the ML has shallowed from 100 to 10m under the rainband. The buoyancy input from the rain has suppressed wind-driven mixing.



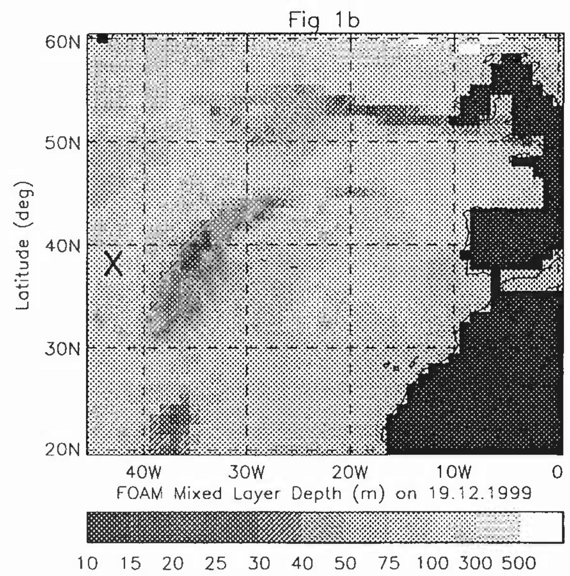


Fig. 2. Temperature (solid line) and salinity (dashed line) profiles from an Argo float at the position marked with an F in Fig 1a (44°W,37°N) on the 20th December, 1999. Note the fresh surface layer, shortly after the passage of the rainband.

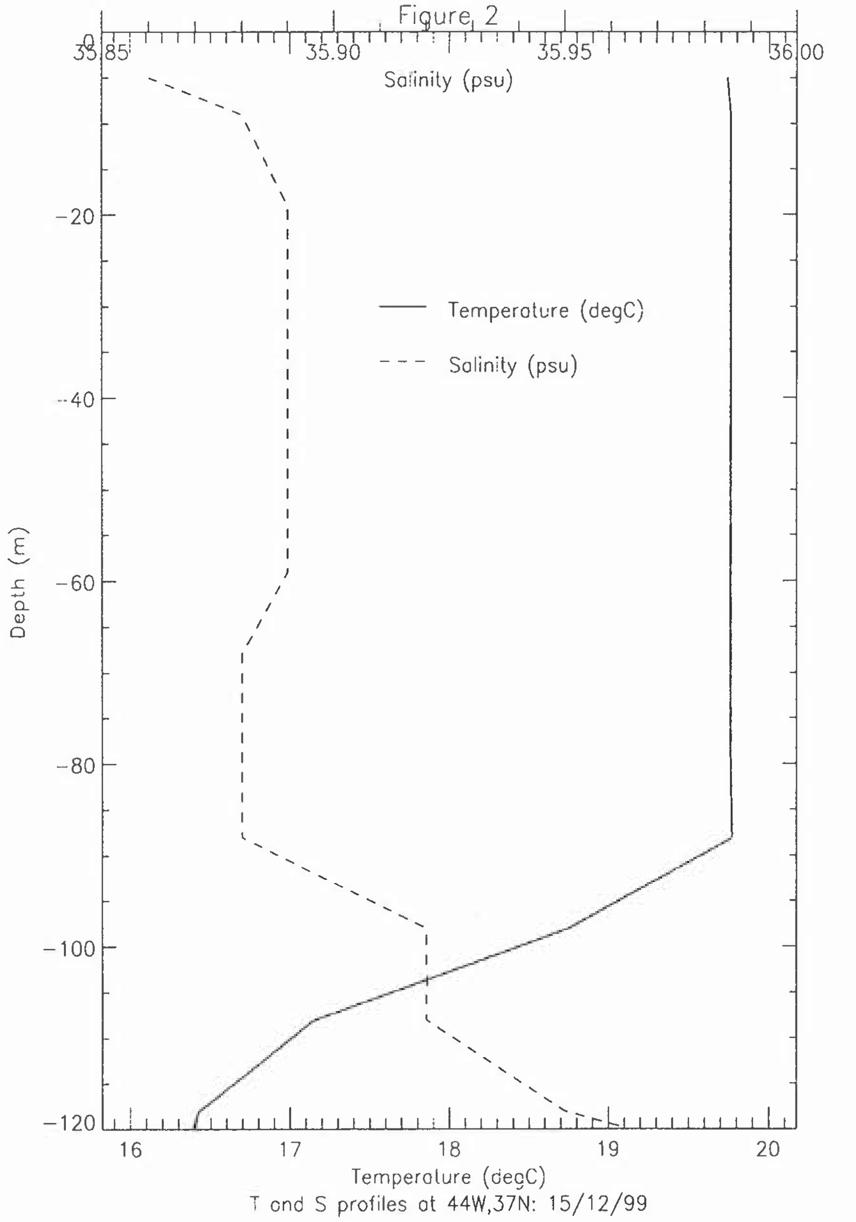
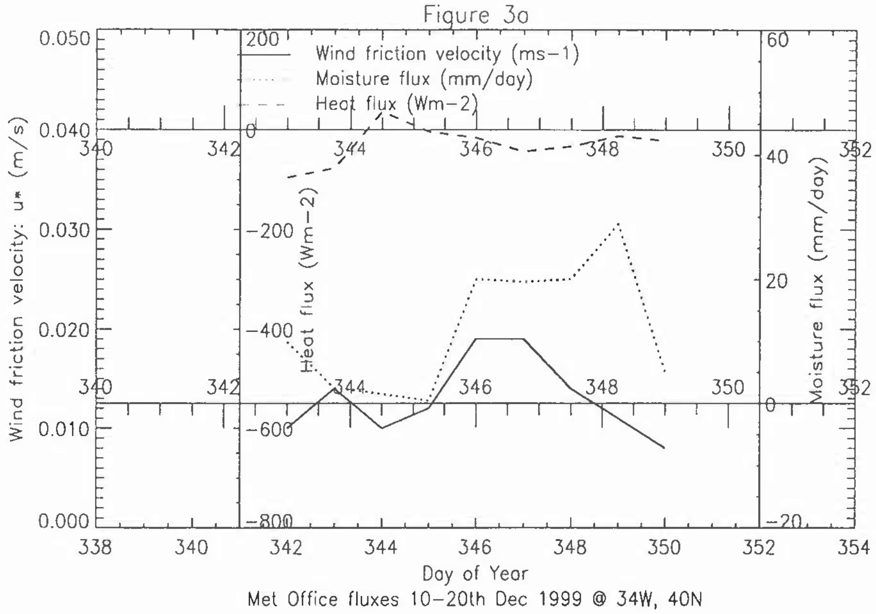


Fig. 3(a-b). Timeseries between 10-20th December 1999 of heat (dashed line), moisture (dotted line) and momentum (solid line) fluxes at 34°W, 40°N from a) the Met Office and b) ECMWF.



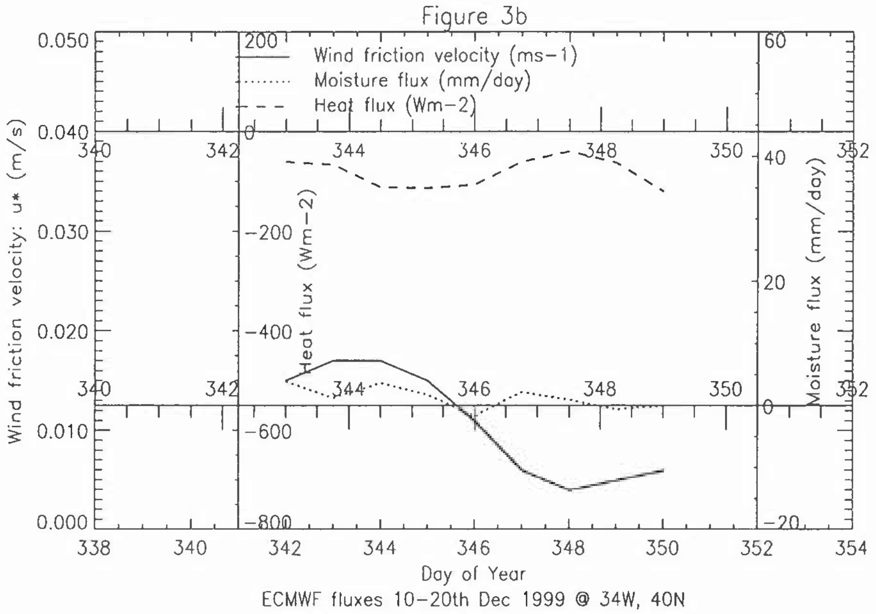
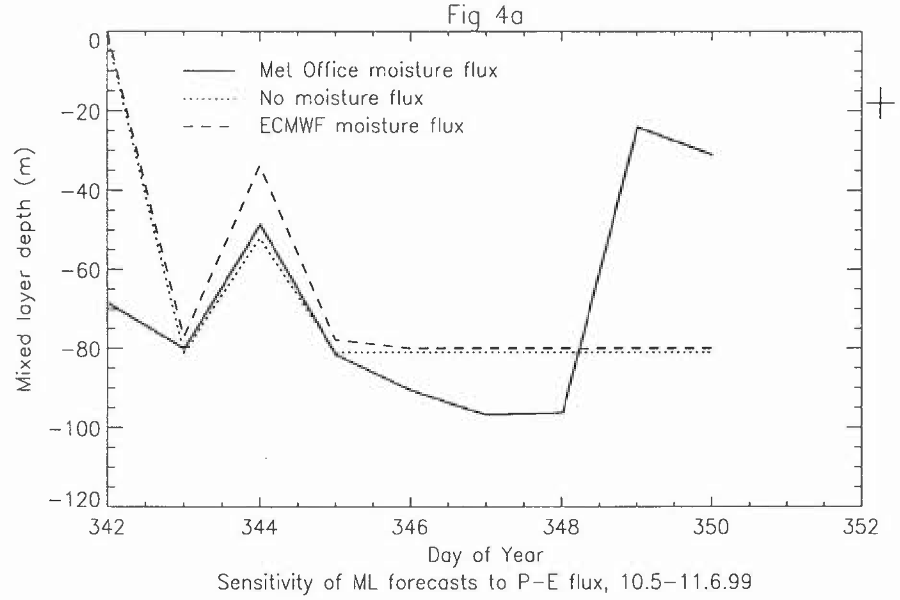


Fig. 4. Timeseries between 10-20th December 1999 of the mixed layer depth output by the 1-d model a) using Met Office (solid line), ECMWF (dashed) and zero (dotted) moisture fluxes, b) the result of altering the other forcing fields, the initial conditions and the model vertical resolution.



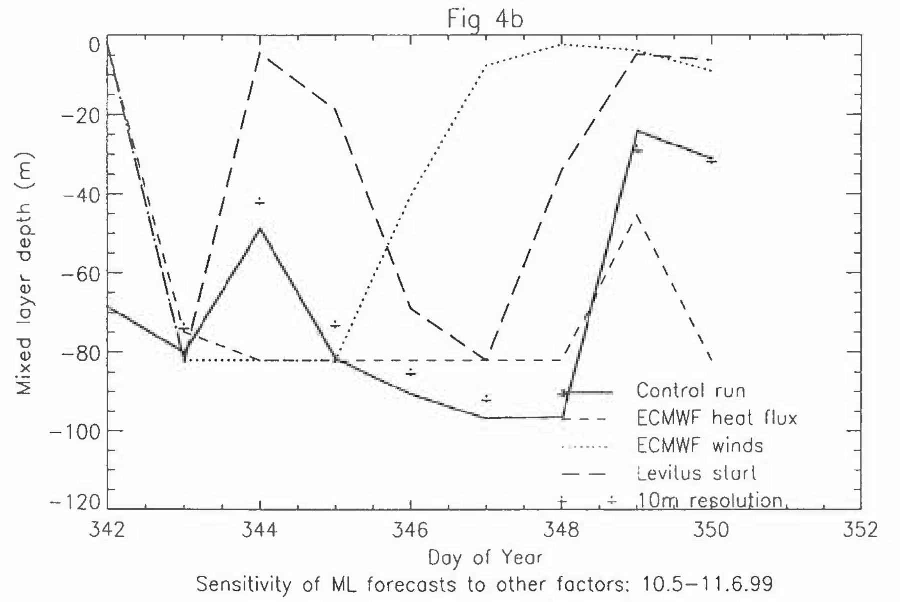
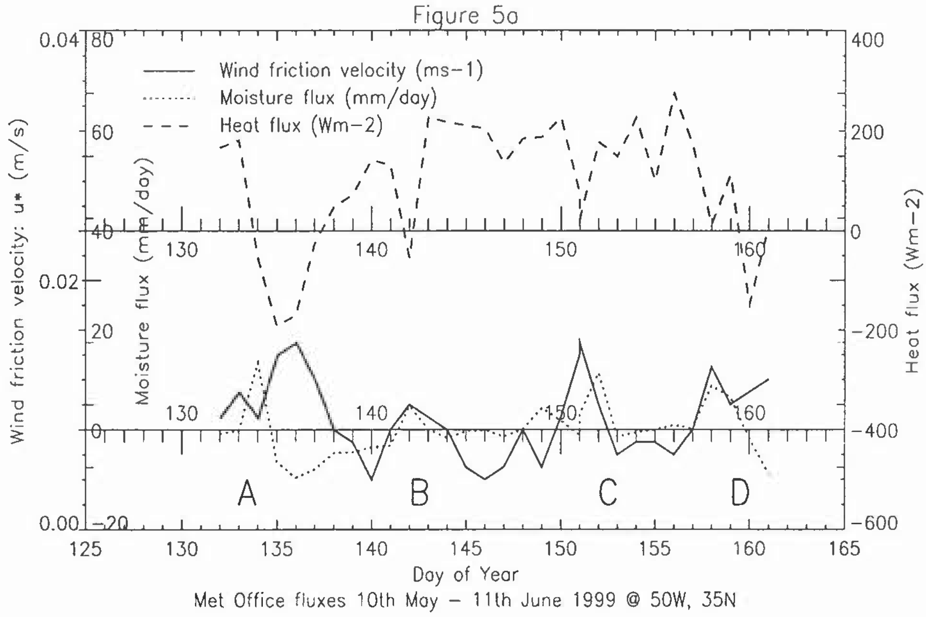


Fig. 5. Timeseries between 10th May and 10th June, 1999 of the heat (dashed line), moisture (dotted) and momentum (solid) air-sea fluxes from a) the Met Office and b) ECMWF at 50°W, 35°N.



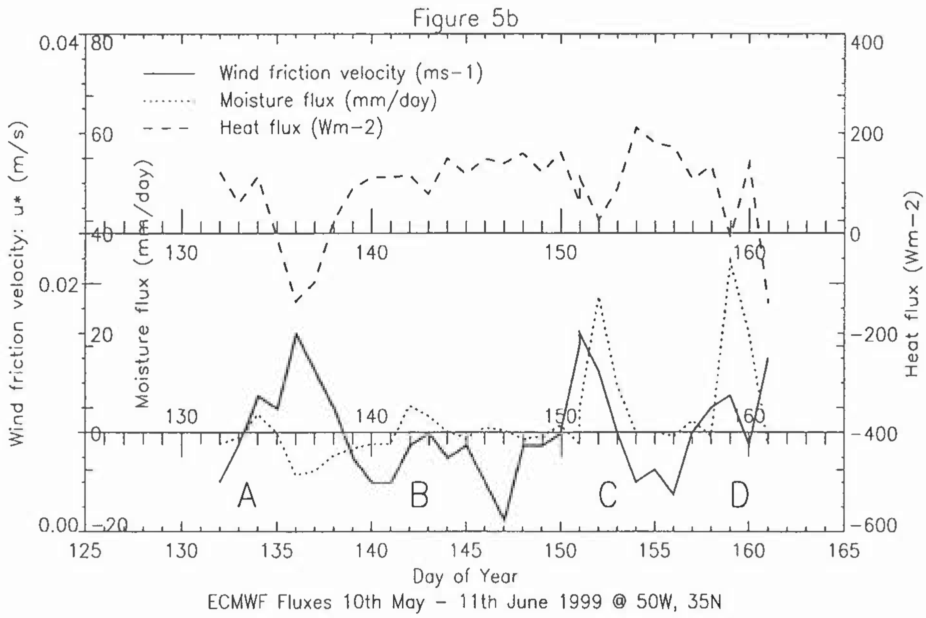
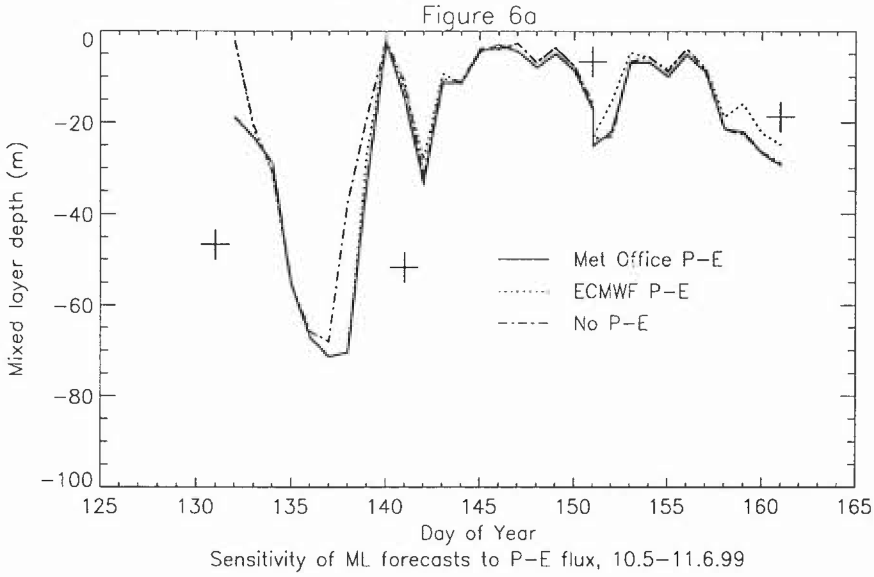


Fig. 6. a) Timeseries of the forecast ML depth from 11th May to 10th June, 1999 using the Met Office (solid line) and ECMWF (dotted line) moisture fluxes. The crosses show the observed ML depth from an Argo float. b) The forecast when the heat flux (dashed line), wind energy (dotted) and initial conditions (long dashed) were varied.



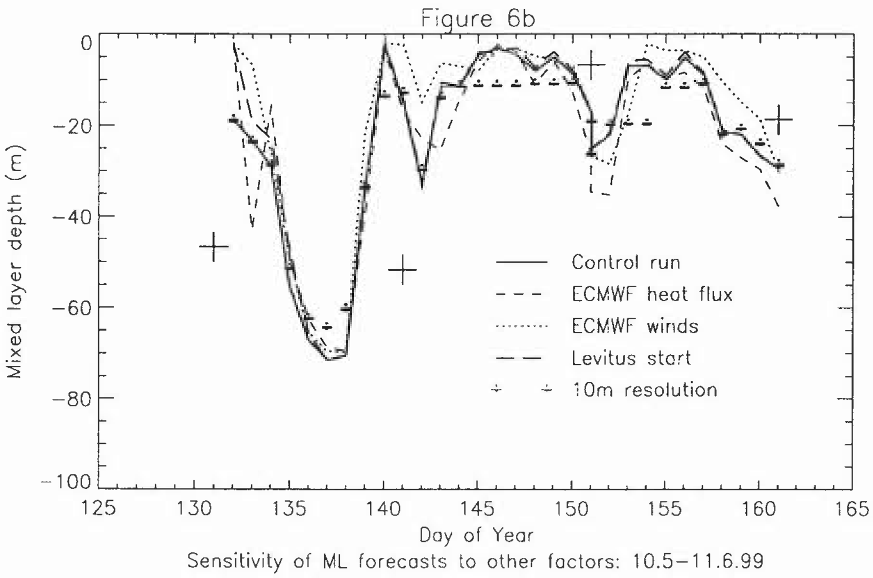
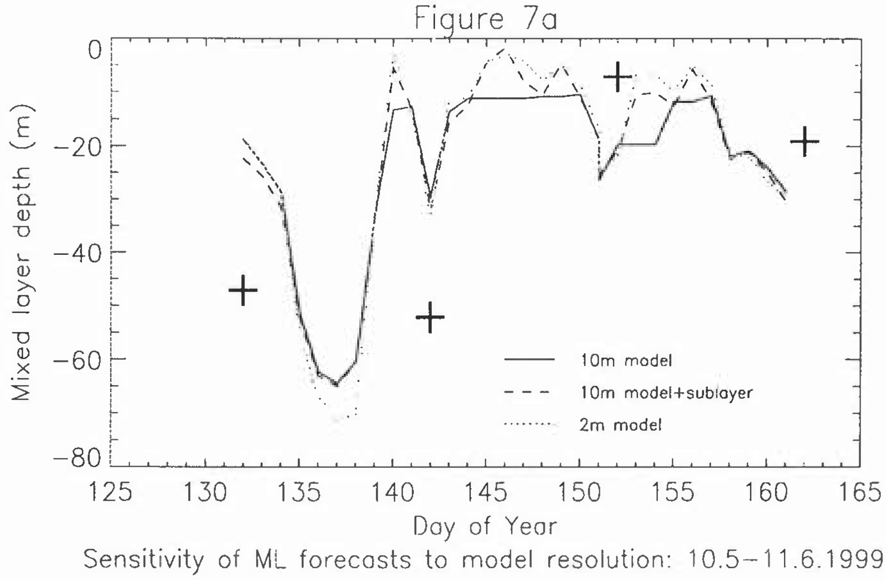


Fig. 7. The forecast ML depth (a) and SST (b) obtained from a 10m resolution model (solid line) a 2m resolution model (dotted) and a 10m resolution model with a sublayer (dashed). The results with the sub-layer and the 2m resolution are similar (the Argo float observations are shown by the crosses).



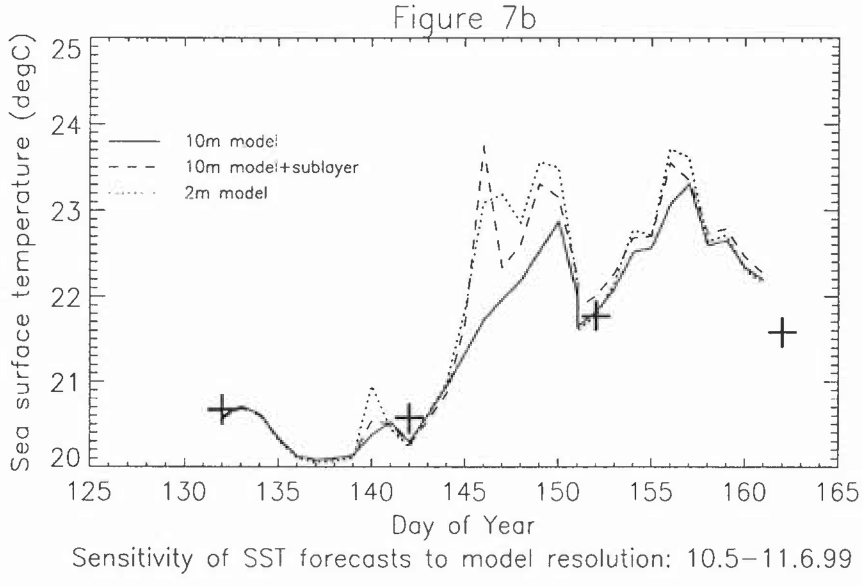


Fig. 8. Schematic showing an initial and final density profile of a sub-layer. The dashed line ($z = Z$) is the bottom of the top model layer.