Interannual Variations of the Upper Ocean Mixed Layer in Deep Convection Regions as Revealed by Numerical Experiments With an OGCM

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Variations of the upper ocean mixed layer depth reflect the processes of sea-air interaction and of intrinsic ocean dynamics in a broad range of spatial and time scales. The most vigorous mixing is induced by density convection during the cold season within spatially restricted regions. In modern climatic conditions, the main regions of open ocean deep convection are situated in the Greenland and Labrador Seas (*Marshall and Schott, 1999*). Available, rather sparse, observational data indicate violent interannual variability of convective mixing intensity in such regions (e.g. *Lab Sea Group, 1998*).

Numerical experiments have been performed with an OGCM (*Resnyansky and Zelenko, 1999*) in order to elucidate the mechanisms liable for interannual variations of the upper ocean mixed layer depth (MLD) in deep convection regions. The vertical turbulent mixing in the upper ocean layer induced by wind stirring and by surface buoyancy flux is described in the OGCM using the concept of bulk mixed layer model with potential temperature, salinity, and water density distributions a priori homogeneous in the vertical. The algorithm of convective adjustment was used to parameterize the density convection, which may develop not only in the near-surface layer, but also at any depth. This algorithm ensures the complete elimination of unstable parts of a density profile at each time step. It is similar to that of (*Rahmstorf, 1993*), accepted as a primary option of convective adjustment in last versions of the MOM ocean model.

The computations have been performed using the 6-hourly data on atmospheric forcing, which enable to monitor the variability at time scales from several days to several years.

Figure 1 shows temporal changes of MLD averaged over the Labrador (46º-64ºN, 40º-60ºW) and Greenland (67º-80ºN, 25Wº-20ºE) regions during 1987–2002. The interannual variability reveals itself in changes of the MLD seasonal maximum and in the strength of fluctuations at time scales of 5–10 days. A number of observational evidence can be found for variations of the MLD seasonal maximum (of an order of 1000 m for the Labrador Sea) obtained in the model. Thus, according to (*Lab Sea Group, 1998*), the 1993 winter in the Labrador Sea has been marked by extremely strong convective activity with mixing depths more than 2200 m. However, during subsequent winters, the convection was much weaker, and in the 1995/1996 winter, MLD didn't exceed 1000 m. Such variations (*Lab Sea Group, 1998*) can be related to the North Atlantic Oscillation, the most important signal of interannual variability in the North Atlantic. They are satisfactorily reproduced (Fig. 1) in the numerical experiment. The main model tendencies of interannual variability are also confirmed by some other observations (*Lavender et al., 2002; Pickart et al., 2002; Schott et al., 1993*).

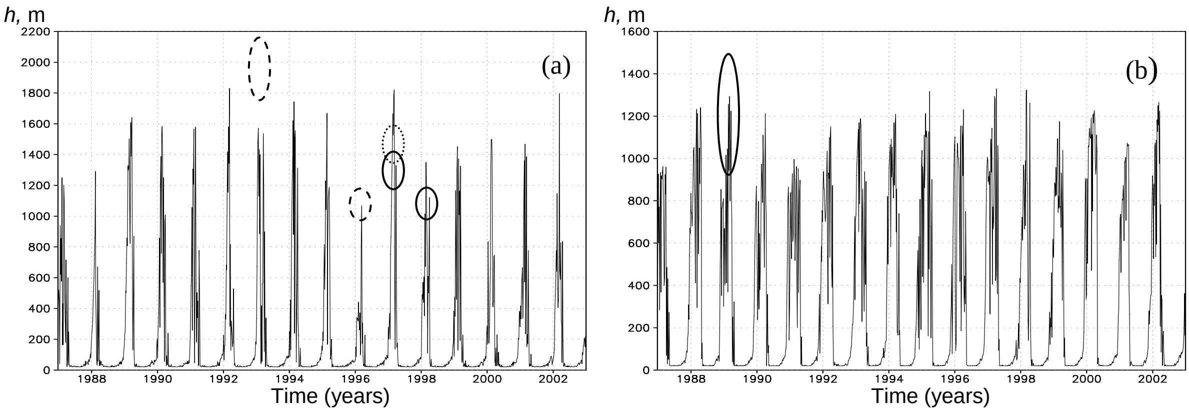

Fig. 1. Temporal changes of computed MLD (h, m) averaged over the Labrador (a) and Greenland (b) regions. Ovals with different edging show the ranges of convective mixing depths according to observational evidences (*Lab Sea Group, 1998* – dashed), (*Lavender et al., 2002* – solid), (*Pickartet al., 2002* – dotted) over the Labrador Sea, and (*Schott et al., 1993* – solid) over the Greenland Sea.

To reveal the role of different factors in variations of MLD (h), we compared the time series of h and the determining factors. Figure 2 shows the interannual changes of mean values of h together with buoyancy flux B_0, vertical component of current velocity curl $rot_z\boldsymbol{u}$, and vertical component of current speed w itself at 500-m depth.

A rather clear interrelation is seen between the changes of h and B_0. An increase (decrease) in buoyancy loss is most often accompanied by an MLD increase (decrease). The absolute maximum of h in 1989 contemporize with $|B_0|$ maximum. However, in some cases, the tendencies in changes of h from one year to another are not consistent with the tendencies in changes of buoyancy flux. For example, buoyancy loss noticeably decreased from 1991 to 1992, whereas MLD didn't change or even slightly increased. The similar situation is found for 1998/1999, 1999/2000, and 2001/2002 winters.

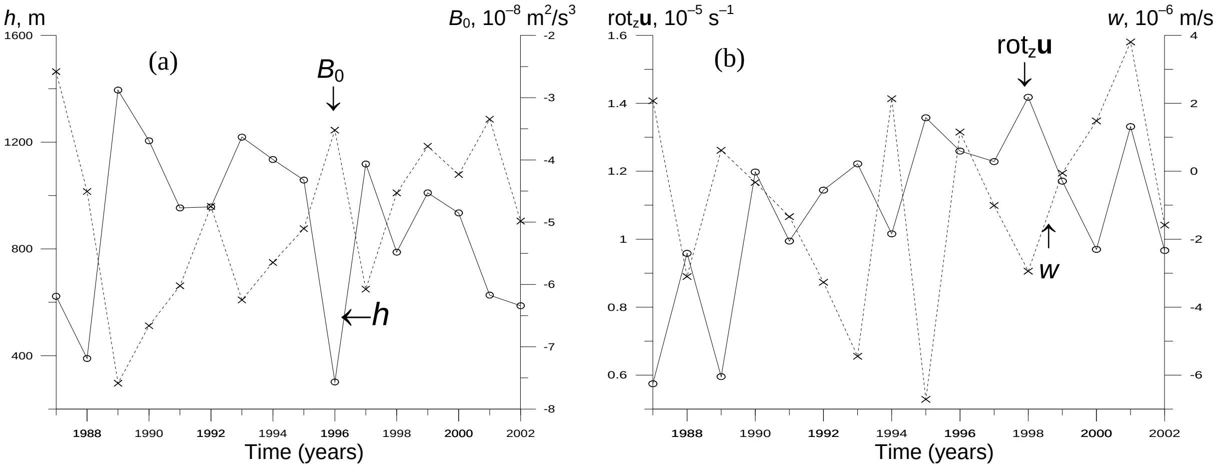

Fig. 2. Interannual variability of model seasonal mean of convective mixing depth and of associated variables in the Labrador region (55º–42ºW, 53º–59ºN). (a) – January–March mean MLD h (left scale, m) and the surface buoyancy flux B_0 (right scale, 10^{-8} m^2/s^3); (b) – December mean dynamical characteristics at 500-m depth: vertical component of ocean current velocity curl $rot_z\boldsymbol{u}$ (left scale, 10^{-5} s^{-1}), and vertical component of current speed itself w (right scale, 10^{-6} m/s). Positive w corresponds to descending motions.

Dynamical factors can cause discrepancies between h and B_0 in these years. As is well known (e.g. *Marshall and Schott*, *1999*), an enhancement of cyclonic circulation in the ocean prior to strong cooling of its surface results in raising of underlying weekly stratified waters nearer to the surface, and this, in turn, fosters the penetration of convective mixing to greater depths. Taking into account this fact allows one to advance in explaining indicated above peculiarities in Fig. 2. Thus, with reference to 1991/1992 it may be seen that enhanced cyclonicity of the circulation in 1992 favored the maintenance of deeper mixing even against the background of weakened surface buoyancy loss. The processes during 2001/2002 winter may be interpreted in a similar way.

The explanation for convective seasons in 1999 and 2000, when deeper mixed layer was observed during weakened buoyancy flux and concurrent decrease of $rot_z\boldsymbol{u}$, can be related to immediate influence of vertical motions. As is seen from Fig. 2b, the vertical velocity w at 500 m depth prior to the beginning of these convective periods was close to zero (in 1999) or positive (in 2000). That is, a large scale sinking took place at this time instead of an ascent, which, presumably, influenced the development of convective processes.

Taking into account the ocean state before the beginning of convective season also enables us to clarify the noticeable differences in mean MLD during different years with approximately identical buoyancy fluxes. Thus, in 1992 and 2002, the mean buoyancy loss from the ocean surface was about -5×10^{-8} m^2/s^3, whereas MLD differed by a factor of one and a half. The difference can be caused by different $rot_z\boldsymbol{u}$ and w before convective seasons during these years.

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