Vertical mixing in the upper Antarctic Circumpolar Current

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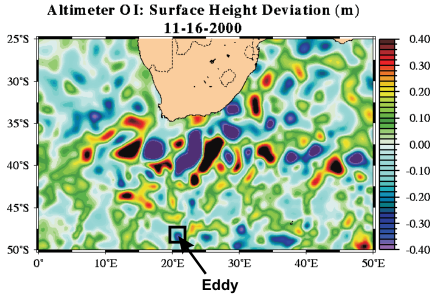

Figure 1. Surface Height Deviation depicted from the *Naval Research Laboratory* showing the “EISENEX-Eddy” at 47°S and 21°E

On the basis of 145 CTD casts which were performed from 6th to 29th of November 2000 we calculated the mixed layer depths (MLD) to analyze the response of the upper layer to the wind field by comparing them to the corresponding time series of the shipborne wind and precipitation measurements (**figures 3a** and **3b**).

The wind record reveals three different strong gales (u > 20.8 ms^{-1}) occurring at the 12th, 21st and the 27th of November. Between the 6th and the 11th of November the MLD is 26 - 45 meters. Due to the next strong gale, which is characterized by maximum wind speeds of 20 to 25 $m\,s^{-1}$, the mixed layer deepens to a depth of 80 meters.

Between the 14th and the 16th of November the wind speeds decrease. During this relaxation time the MLD recedes up to 30 meters. The following two days the wind speed increases linearly. Again, the mixed layer deepens, however, increased precipitation ranging from 9.1 to 19.6 mm d^{-1} occurring between the 16th and the 18th of November, leads to a very shallow and light surface layer in the upper 25 meters.

Due to the second severe gale event at the 21st of November, the station work was temporary suspended. Two days later the mixed layer had deepened to nearly 100 m. The temporal development of the buoyancy frequency reflects a relatively short (several hours) response to the wind stress pattern. However, precipitation events occurring between the 16th and 18th of November also have impact on the stratification.

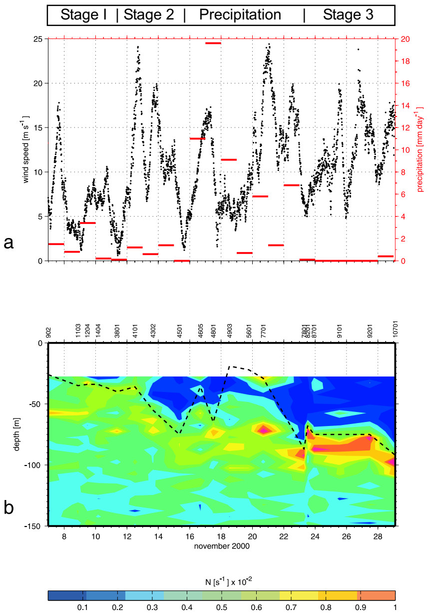

Figure 3. Time series showing (a) wind speed (black) and precipitation (red), (b) Time series of the vertical distribution of the Buoyancy frequency within the eddy; mixed layer depths derived from the difference criterion are indicated by the dashed line.The MLD is defined as that depth at which the calculated in situ density increased by $\delta\sigma_T = 0.02$ from the surface value.

Abstract:

Vertical or diapycnal mixing in the Antarctic Circumpolar Current (ACC) is being recognized as an important process involved in the overturning circulation of the global ocean. We report the results of a mixing study conducted in the upper 180 meters of a mesoscale eddy in the vicinity of the Antarctic Polar Front at 47°S, 21°E. On the basis of conductivity-temperature-depth (CTD) and acoustic doppler current profiler (ADCP) data we deduce the vertical diffusivity K_z from two different parameterizations. Since these parameterizations bear the character of empirical functions, which base on theoretical and idealized assumptions, they were inter alia compared with Cox number and Thorpe scale related diffusivities deduced from microstructure measurements (MSS), which supplied the first direct insights into turbulence of this ocean region.

Values of K_z in the range of 10^{-4}-$10^{-3} m^2 s^{-1}$ appear as a rather robust estimate of vertical diffusivity within the seasonal pycnocline. Values in the mixed layer above are more variable in time and reach $10^{-2} m^2 s^{-1}$ during periods of strong winds. The results confirm a close agreement between the microstructure-based eddy diffusivities and parameterized eddy diffusivities that were calculated after *Pacanowski and Philander* [1981].

Data and Methods:

To investigate the vertical mixing regime of the upper 180 meters of the study area, we deduce the vertical diffusivity K_z from two different parameterizations. Additionally, 85 MSS casts performed at 17 different stations (**figure 2**) provide direct measurements of Thorpe scales and Cox numbers. In combination these data allow a comparison between the parameterized and directly measured turbulence parameters.

To investigate the vertical mixing within the eddy that might be associated with elevated shear and enhanced shear from internal waves, we use the parameterization of *Gregg* [1989].The ADCP velocity components u and v, which are averaged for each station, are used to compute the squared shear S^2 whereas the squared buoyancy frequency N^2 is being calulated from the CTD data.

$$K_G = 5\times10^{-6} m^2 s^{-1} \left\langle \frac{S^4}{N^4} \right\rangle$$

To check these results we use a parameterization of mixing processes by means of coefficients of eddy mixing that are Richardson-number dependent, which was deduced from *Pacanowski and Philander* [1981]

$$K_{PP} = \frac{5\times10^{-3} m^2 s^{-1} + 10^{-4}(1+5Ri)^2}{(1+5Ri)^3} + 10^{-5}$$

From the squared Thorpe scale, the buoyancy frequency N and the mixing efficiency , which is assumed to be 0.2 after *Osborn* [1980], we calculated the vertical Thorpe scale dependent eddy diffusivity

$$K_T = \Gamma \cdot L_T^2 \cdot N$$

For a more direct estimate of the eddy diffusivity K_c from temperature microstructure measurement, we used the Osborn-Cox model [*Osborn and Cox*, 1972], where κ_T is the molecular diffusivity of temperature.

$$K_C = \kappa_T * C$$

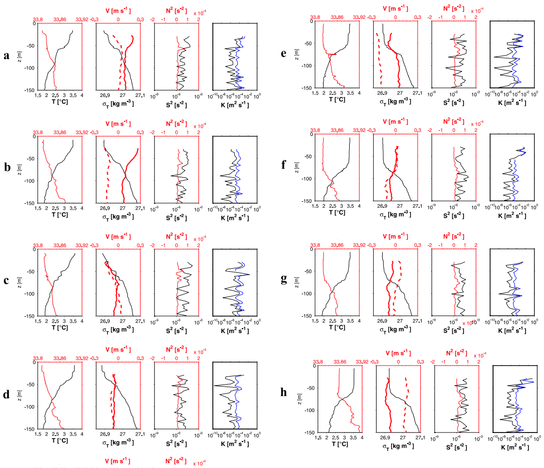
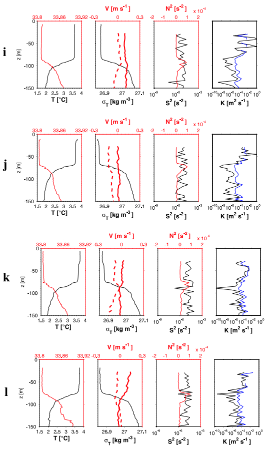

Figure 4. CTD profiles at stations 9 (**a**), 11 (**b**), 12 (**c**),14 (**d**), 43 (**e**), 45 (**f**),46 (**g**), 48 (**h**), 78 (**i**), 82 (**j**), 87 (**k**) and 92 (**l**) each panel shows temperature (black), salinity (red), potential density (black), ADCP u- und v- components (red solid and red dashed), current shear squared (black), buoyancy frequency squared (red), parameterized Eddy diffusivity after *Gregg* (black) and *Pacanowski and Philander* (blue)

References

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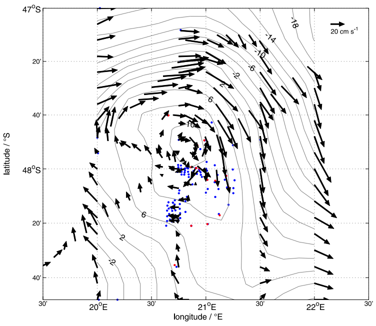

Figure 2. ADCP velocity vectors averaged between 150 and 200 m and 10 km along track and streamfunction [1000 $m^2 s^{-1}$] showing a closed cyclonic circulation centered at 47.85°S, 20.75°E, which extends over roughly 100 to 150 km diameter. Probably detached from a northeast protruding meander, location of CTD (blue circles) and MST stations (red circles)

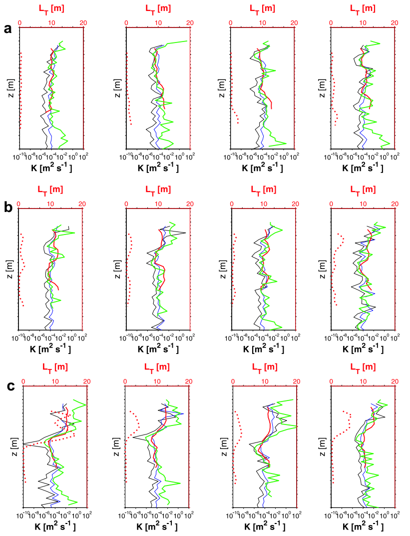

Figure 5. Panel **a** L_T (red dotted line), K_G (black line), K_{PP} (blue line) K_C (green line) and K_T (red line) for stations 9, 11, 14 and 18; panel **b** for stations 43, 45, 46 and 48 and panel **c** for stations 78, 82, 87 and 92

Conclusions

1.Values of K_z in the range of 10^{-4} - $10^{-3} m^2 s^{-1}$ appear as a rather robust estimate of vertical diffusivity within the seasonal pycnocline. Values in the mixed layer above can be much higher, up to $10^{-1} m^2 s^{-1}$, correlated with strong wind-forcing. Although the dependence on wind speed is not surprising, it was not revealed by previous estimates of vertical diffusivity from the Southern Ocean, which relied on tracer diffusion experiments and hence represents an integrated measure over all turbulent events during the observation period.

2.Comparison with independent estimates based on the vertical diffusion of iron gives confidence in our results, especially those obtained from L_T.

3.Comparison between K_T and the parameterizations of *Gregg* [1989] and *Pacanowski and Philander* [1981] indicated the following (**figures 4 and 5**):

During the first stage, when the water column is strongly stratified, the K_{PP} and K_{Th} curves agree well, while K_G differs from them by one to two orders of magnitude. The Thorpe scales are small (1meter) and remain constant in the upper 90m, however, at stations 11 and 14, the Thorpe scales increase linearly and then remain constant. The associated eddy diffusivities agree well with the K_{PP} curves, while K_G differs from them by one to two orders of magnitude. The highest Thorpe scales were observed during the third stage and reach their maximum of 16 meters at station 78 just after the second strong gale. The shape of the K_{PP} and K_T curves agree well, while K_G differs from them by one to four orders of magnitude. The deviation of K_{PP} from the other two estimates was most pronounced in the stably stratified water column and less clear in the mixed layer, where K_{PP} appeared to be rather variable.

4.Interesting to note also is the temporal covariability of L_T with the wind forcing, and that L_T always was observed to be much smaller than the mixed layer depth obtained conventionally by applying a density criterion. This highlights the difference between the mixed layer and the actively mixing layer. Ability to distinguish between the two inter alia is vital to assess the underwater light regime for phytoplankton photosynthesis.