Capabilities of Ocean Mixed Layer Models

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1. Introduction

The capabilities expected in today's state of the art models of the ocean's planetary boundary layer (OBL) are surveyed below. It should be noted that the term mixed layer does not generally apply to the OBL, because of shear and because temperature, salinity and density can be well mixed to different depths. Specific ocean examples are used to demonstrate current capabilities and requirements of modeling various OBL processes responsible both for deepening and mixing, and for stratifying and shoaling. The former processes are more familiar, with the latter more novel and the focus of recent attention. The four chosen examples are Hurricane Response, the Winter Subtropical Gyres, Uptake in the Antarctic Circumpolar Current (ACC) and the Equatorial Diurnal Cycle. The respective time scales are the inertial periods, days to months, years to decades and a day. The underlying processes have horizontal space scales of less than a kilometer, and so are usually sub-grid-scale except for process models such as Large Eddy Simulation (LES).

2. Hurricane Response

Observations in the wakes of northern hemisphere hurricanes show that the ocean response is dominated by an intense cooling (typically more than 2 °C) to the right of the hurricane trajectory. Figure 1, from hurricane Frances in 2004, shows the SST change and wind speed isotachs in the reference frame of the moving hurricane center. Observations and models of wave parameters such as significant wave height indicate that the strongest wave effects should be expected ahead of the center and within 20 km of the path of the hurricane's center (Chen, 2006). The observed pattern of SST response in Fig. 1 is behind the center and

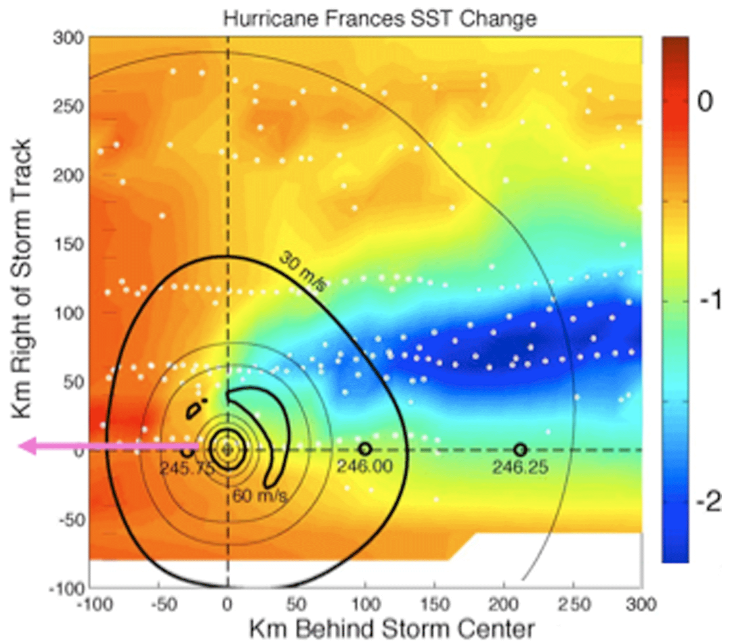

Figure 1: Composite of the wind speed forcing (isotachs contoured at 10 m/s), and sea surface temperature response as observed during hurricane Frances in 2004. The coordinate origin is at the storm center and the storm moves in the negative x-direction (after Chen, 2006).

dominant driver. Instead, the cooling pattern is a classic example of inertial resonance between ocean inertial currents and the wind forcing. In this case the storm's translation speed to the left produces wind vectors that rotate near the inertial period about 60 km to the right of the storm track, where the energy input to the inertial currents given by the integrated dot product of wind stress and surface current is maximum. The narrowness (~75 km) shows that the response is highly tuned. A similar resonant response to the passage of frontal systems has been observed in the open ocean, where the SST has been observed to cool by more than 1°C in only 6 hours (Large et al., 1986). The common mechanism is the entrainment of cold water into a deepening ocean boundary layer, with the energy extracted from the shear between the enormous (1 m/s) near surface inertial currents and the relatively quiescent ocean interior. It is well represented in ocean mixing models whose boundary layer mixing penetrates well into the stratified thermocline (Crawford and Large, 1996).

Following the passage of hurricane Frances, observations suggest that inertial resonant deepening of the well mixed buoyancy layer is followed by re-stratification that is more rapid and more distributed across the OBL than would be expected from surface heating (Chen, 2006). A possible candidate mechanism is an order 1km sub-mesoscale instability (Fox-Kemper et al, 2008). Rather than explore this mechanism in the isolated and small scale of a hurricane, its apparent effects on the large scale are presented in the next section.

3. Winter Subtropical Gyres

Sub-mesoscale re-stratification following winter mixing events appears to have implications in the mean overturning of the Subtropical Gyres. According to Fox-Kemper et al. (2008), the associated streamfunction depends on the mixed-layer depth squared times the horizontal buoyancy gradient, so it is most effective following strong convective or wind mixing over a patch. When parameterized this way in an Ocean General Circulation Model (OGCM), the process tends to stratify the OBL, as shown by the global meridional overturning streamfunction of Figure 2. It brings warmer water poleward nearer the surface and returns colder water equatorward deeper. The net effect of warm water over cold is re-stratification over the whole depth of the mixed layer. In contrast the more familiar and widespread restratification due to surface heating and freshening is confined to be closer to the ocean surface.

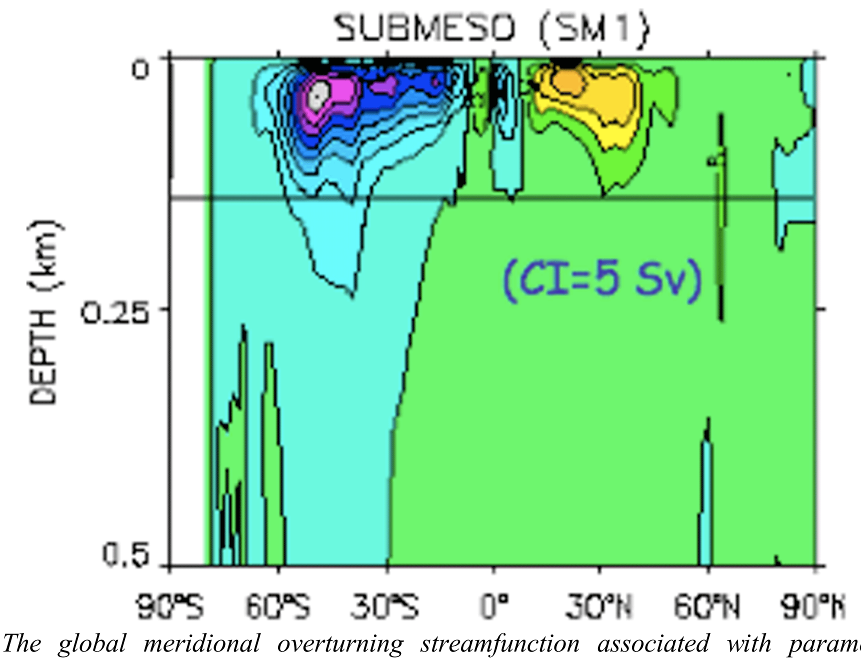

Figure 2: The global meridional overturning streamfunction associated with parameterized sub-mesoscale instability (courtesy G. Danabasoglu, 2008). The grey horizontal line is at about 125 m depth.

Ocean models of the Subtropical Gyres should also be able to represent the following geophysical fluid dynamics problem; namely, that of a fluid whose density depends on two constituents, with the stabilizing profile of one (temperature) greater than the destabilizing profile of the other (salt). This is a common situation over large regions of the ocean's Subtropical Gyres, where strong net evaporation supports a salty near surface ocean and there is subduction underneath of fresher water formed farther poleward. The modeling challenge is the convection resulting in the late fall and winter when surface cooling reduces the stabilizing effects of temperature and increases the surface salinity, until the latter dominates.

Simple models of penetrative convection suggest the formation of highly density compensated layers at the base of the OBL by the end of winter (Yeager and Large, 2007). In some instances the upper ocean can become well mixed in density far deeper than in either temperature or salt. The development of such a structure is useful for model validation, because it is seen in Temperature-Salinity diagrams from both ship observations and from the more globally distributed profiles from the ARGO array. In Figure 3 this behavior is illustrated in OGCM solutions and in matching analyses of the ARGO float profiles. The metric is the summer to winter increase in a bulk Turner angle, Tu_b, a measure of density compensation and double diffusion. Salt fingering becomes active in mixing over the approximate range $75° < Tu_b < 90°$ (green), even though the density profile is statically stable for $-90° < Tu_b < 90°$ (everywhere). In regions of the subtropical gyres where the salinity is destabilizing, the signature of penetrative convection is a summer (top NH) to winter (top SH) increase in Tu_b (yellow to green). It is evident in both ARGO data (left) and the OGCM (right), in all ocean subtropical gyres.

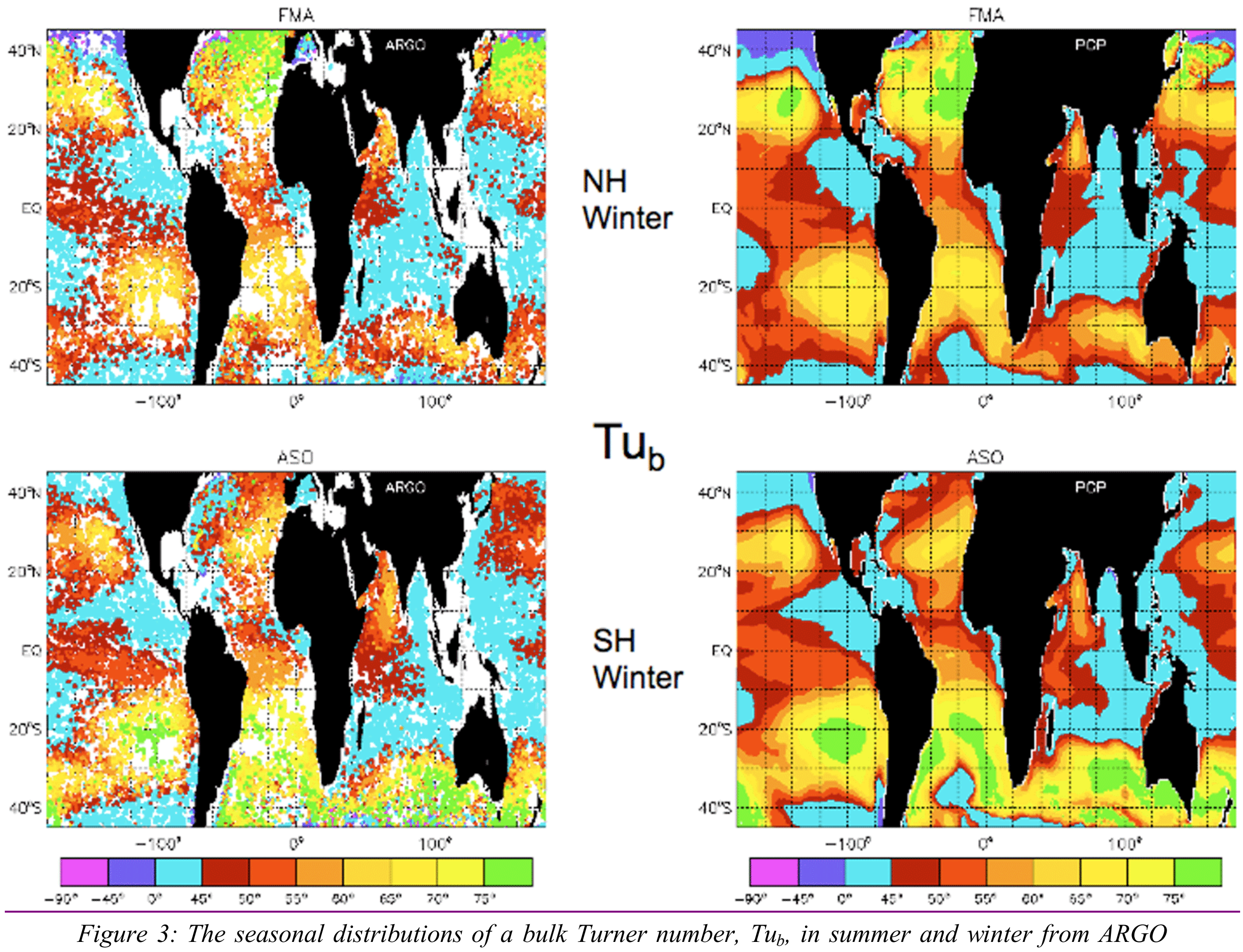

Figure 3: The seasonal distributions of a bulk Turner number, Tu_b, in summer and winter from ARGO observations (left panels) and OGCM simulations (right panels) (from Yeager and Large, 2007). Tu_b between 45° and 90° indicates that stable ocean stratification is due to temperature with salinity destabilizing.

4. Uptake in the Antarctic Circumpolar Current

The particular OCCM solution shown in Figure 4 has a a large deficit of CFC-11 in subducted Antarctic Intermediate Water (AAIW) that is inferred to descend from about 100 m at 60°S to about 700m at 45°S. This deficit is much reduced by improved parameterizations of mesoscale eddy effects, sub-mesoscale instability (as above) and interior diffusivity (bottom left panel). Although the deficit can be nearly eliminated with the addition of parameterized surface wave driven Langmuir circulation in the OBL of the Antarctic Circumpolar Current (ACC), this addition generates much larger biases in the temperature and salinity at higher latitudes in this model. Therefore, a compromise implementation that increases CFC-11 in the AAIW without adversely effecting temperature and salinity is preferred (bottom right panel). The Langmuir parameterization (Fox-Kemper, personal communication 2008) can deepen the boundary layer, and when it does it increases the mixing coefficients throughout the layer. However, in the compromise this process is confined to the ACC region between 50° and 60°S, where the winds and waves are more likely to be equilibrated (Belcher, this volume), so that the Stokes velocity should be more reliably determined from the wind stress magnitude. This restriction could be lifted if a wave model were run in parallel to give the Stokes information directly.

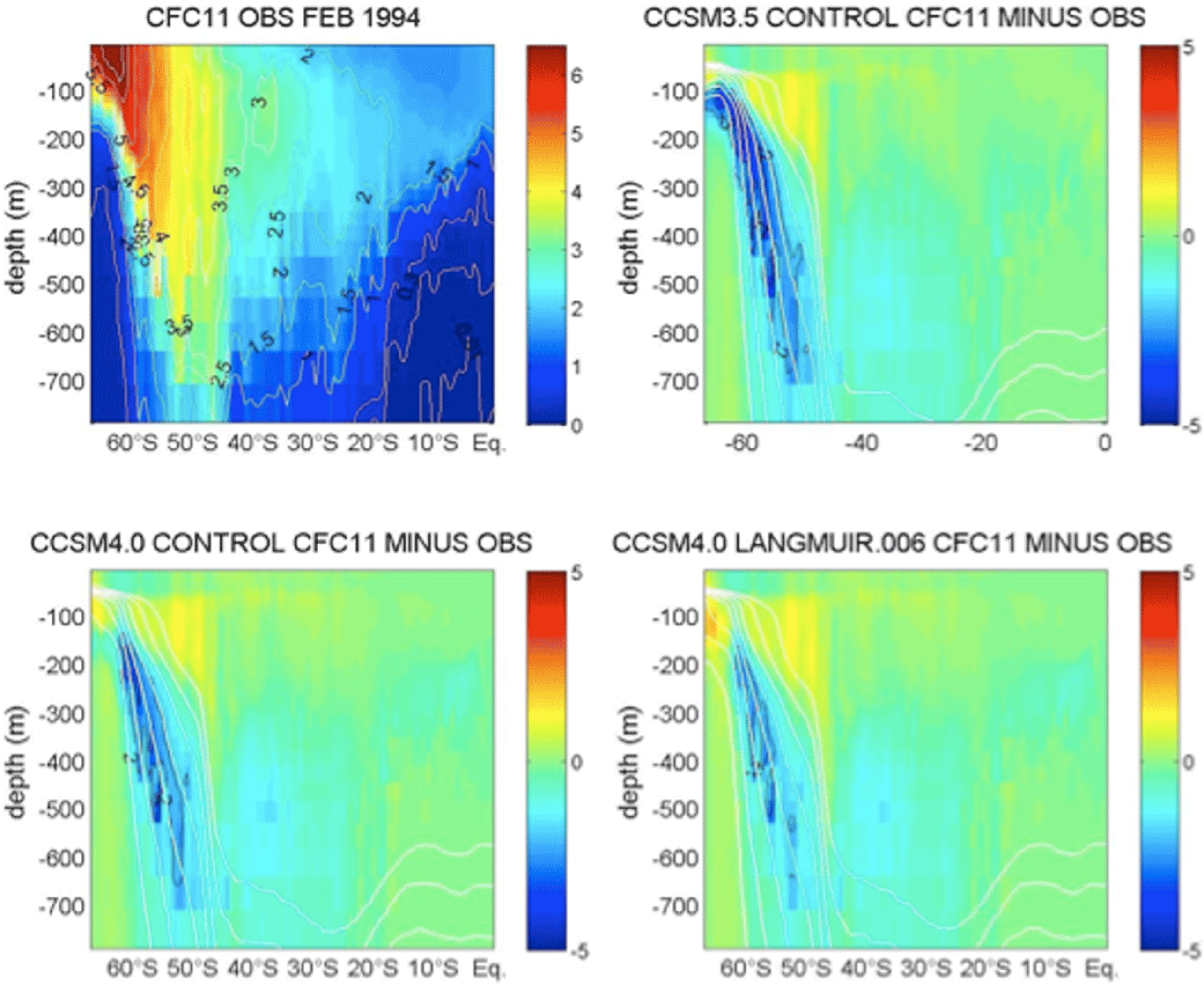

Figure 4: Southern hemisphere meridional section along 170° E of observed CFC-11 in February 1994 (upper left). Differences from these observations in OGCM model solutions prior to (upper right) and following (bottom left) improvements to sub-grid-scale eddy and diffusion parameterizations, and with the further addition (bottom right) of a parameterization of the effects of wave driven Langmuir circulation in the ACC region (courtesy S. Peacock, 2008).

5. Equatorial Diurnal Cycle

The final example, the Equatorial Diurnal Cycle, takes advantage of the unique geophysical laboratory provided by the equatorial oceans, where the vertical Coriolis term goes to zero, lateral boundaries go from top to bottom, solar heating dominates during the day and convection occurs every night. The first two of these features plus a mean zonal wind produce a strong (100 cm/s eastward) Equatorial Undercurrent (EUC) in both the Pacific and Atlantic. The wind produces an order 20 cm/s westward current near the surface, so that the shear t the EUC core at about 100 – 200m depth becomes an interior forcing of the equatorial OBL. The combination of all the features can be modeled to reproduce the observed deep cycle of turbulence, as well as the diurnal cycles of temperature, velocities and mixed layer depth, which rectify into the mean (Wang et al., 1998). The ability to represent such signals is a challenging validation of OBL modeling. Figure 5 shows examples of OGCM diurnal cycles from Danabasoglu et al. (2006). Similar signal strengths over the upper of 10 cm/s in the zonal current and 0.2 degrees in temperature and 20 m in mixed later depth are observed and should be reproduced in models of the Equatorial Ocean. When coupled with an atmospheric model, the small, order 0.1° C, rectified diurnal cycle of surface temperature is amplified to a mean 1° C signal through positive feedbacks with the atmosphere (Danabasoglu et al., 2006).

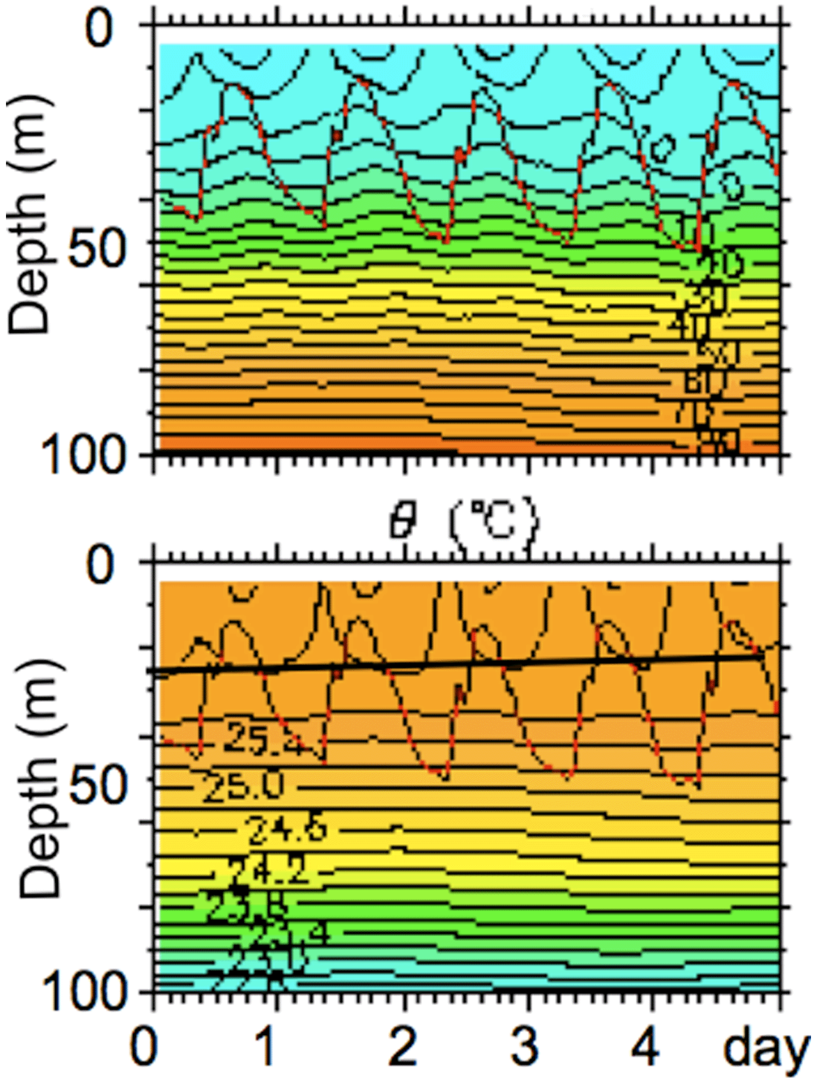

Figure 5: Five day time series of the diurnal cycle of zonal velocity (top panel) and of potential temperature (bottom panel) in the upper equatorial ocean at about 140°W as simulated by an OGCM (adapted from Danabasoglu et al., 2006).

Figure 6 shows the modeled upper ocean heat fluxes corresponding to the diurnal cycles of Fig. 5. Diurnal cycles in heat flux are seen most clearly below the shallowest (daytime) mixed layer depth (10m) and there is a systematic change in phase with maxima occurring later as the depth increases. The mechanism in the model is simply the downward propagation of turbulence generated with the onset of OBL convection at sunset when the surface forcing becomes increasingly a cooling process. The most clear signal in Fig. 6 of deep cycle turbulence (Lien et al., 1995) is seen at about 80m depth where the maximum flux occurs at about 6 am after propagating downwards at the diffusive time scale. The minimum occurs about 12 hours later.

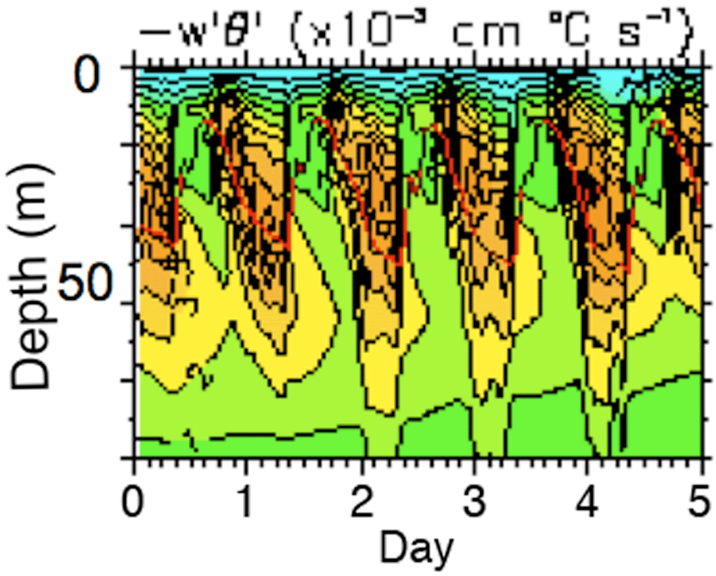

Figure 6 : As in Figure 5, except showing the OGCM modeled kinematic heat flux contoured at intervals of 1 x 10^{-3} °C cm/s, with positive values (green to orange colors) indicating upwards heat flux and negative (blue) colors downward heat flux .

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