Observations for Climate: Expanding to the deep ocean

Silvia L. Garzoli (NOAA/AOML, Silvia.Garzoli@noaa.gov), Gregory Johnson (NOAA/ /PMEL, Gregory.C.Johnson@noaa.gov),
Rik Wanninkhof (NOAA/AOML, Rik.Wanninkhof@noaa.gov), Bernadette Sloyan (CSIRO/Australia, Bernadette.Sloyan@csiro.au)

Abstract

Half of the ocean volume lies below 2000 m, however most of the components of the present ocean observing system are focused on the upper-ocean, with an emphasis for climate studies on seasonal to interannual time-scales. The deep ocean is known to play a crucial role in many aspects of the climate system on longer time-scales. Furthermore, deep ocean observations are needed for an accurate quantification of the global energy uptake and its variability, as well as to better estimate and understand the different contributions to sea level rise. Better observing and understanding the deep ocean circulation will also provide, among others, information on variability of the deep branches of the meridional overturning circulation. Finally, an expanded deep ocean observing system will improve our quantification and understanding of long-term sequestration and redistribution of climatically relevant compounds such as carbon dioxide. Expanding the ocean observing system towards being truly global, that is, adequately measuring the half of the ocean volume below 2000 m depth, will be challenging. It requires an increased commitment to the design and implementation of technologies to withstand high pressures in remote environments for collecting deep ocean data in an efficient manner. Deep-ocean data that has been acquired, mostly on hydrographic surveys, over the past four decades should be (re-) analyzed with focus on multi-parameter analyses on discerning climate trends in the small signals. The need of expanding the observing system below 2000 m was the focus of a white paper submitted and discussed to the OeanObs09 conference in 2009 (Garzoli *et al.*, 2010). This poster describes recent advances on deep-ocean studies that follow the recommendations of the conference. Some highlights of changes in deep ocean heat and carbon content are shown as well as advances on observing deep ocean circulation. Also presented is what observations might be needed, how these observations could best be obtained, and a draft plan of recommended implementation locations to document deep-ocean changes.

Deep circulation

Long-term velocity observations in the deep ocean are limited, and there are regions in all of the major ocean basins where no observations of deep currents exist. The lower limb of the Meridional Overturning Circulation (MOC), the Deep Western Boundary Current (DWBC), transports long term climate signals throughout the world ocean. Roughly equivalent volumes of dense water sink in the North Atlantic and Antarctic limbs of the MOC and are transported to distant ocean basins. Despite its importance, long-term repeated direct velocity observations of the DWBC in the Atlantic exist only in a few locations, most of them in the North Atlantic. In a recent study based on five years of data at 26.5°N near the Atlantic Ocean western boundary, the structure and variability of the DWBC during 2004-2009 and its relation to the MOC was evaluated (Figure 1, Meinen *et al.*, 2011). The strong DWBC transport variability observed, and the significant variability that still exists in the deep ocean even when integrated across the entire western basin out to the mid-Atlantic ridge, demonstrates clearly that the deep layer is more energetic than previously thought. A recent study reinforced the concept that the basin-scale MOC-salt feedback determines whether the thermohaline circulation is stable or unstable; a much more robust MOC-trend estimate can be made by combining sections in the North and South Atlantic (Drijfhout *et al*., 2011). They further noted that the sign of salt flux at 35°S can be used to determine the stability of the MOC. As part of South Atlantic Meridional Overturning Circulation (SAMOC), (Garzoli *et al.*, 2010) modelling studies and pilots arrays are being conducted to observe the MOC and the boundary currents at nominally 34.5°S. The role of the South Atlantic and inter-ocean exchanges has been recently acknowledged by models and observations (Dong *et al.,* 2010; Garzoli and Matano, 2010). The importance of interocean exchanges to the MOC has been demonstrated through modelling studies (e.g. Biastoch *et al*., 2009). Results of a high resolution ocean general circulation model show that the transport of Indian Ocean waters into the South Atlantic via the Agulhas leakage has increased during the past decades in response to the change in wind forcing (Figure 2). Both model and historic measurements off South America suggest that the additional Indian Ocean waters have begun to invade the North Atlantic, with potential implications for the future evolution of the MOC. Unfortunately, few long-term direct velocity measurements have been made in the deep boundary currents exporting Antarctic Bottom Water (AABW). To this date there are very few long-term records of AABW-carrying currents. Abyssal topography is often sufficiently complex that to properly study and model deep currents requires observations not only at the boundaries, but also along the flanks of mid-ocean ridges and in deep trenches. To better model and understand the deep circulation, and its role in sequestering heat and anthropogenic CO_2, it is clear that more observations in the deep ocean will be required. Climate prediction models that presently exist have serious limitations as they poorly reproduce the circulation in the deep ocean as compared to the limited observations that are available.

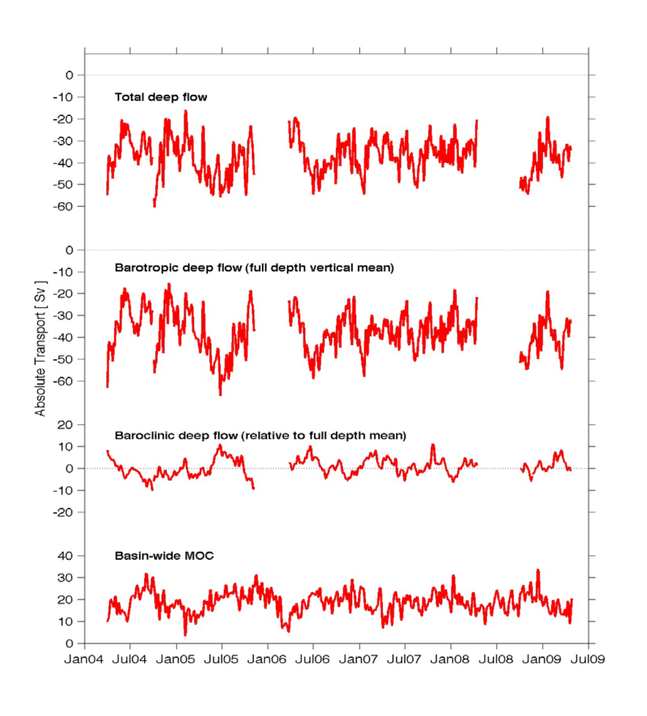

Figure 1: Deep transport in the western basin (800 to 4800 dbrs) integrated from the shelf to the Mid Atlantic Ridge, plotted as the total transport, the barotropic transport (defined based on a full-depth vertical average), and the baroclinic transport (defined as the difference from the full-depth vertical average). Also shown is the basin-wide MOC upper-ocean transport from the basin-wide array. (From Meinen *et al.*, 2011)

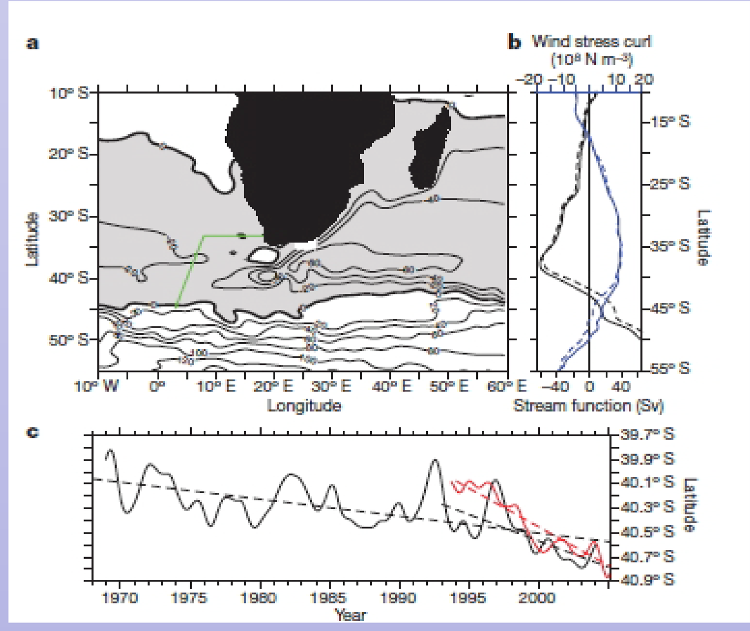

Figure 2: Large-scale circulation changes south of Africa. a, Time-mean (1995–2004) horizontal streamfunction in the Agulhas region (contours marked in Sverdrups) with grey shading denoting anticyclonic circulation. b, Latitudinal dependence of zonal averages of the streamfunction (black) and zonally averaged wind stress curl over the Indian Ocean (blue) for periods 1965–1974 (dashed) and 1995–2004 (solid). c, Latitude of zero sea surface height in (zonal average, black) and a corresponding constant sea surface height line in satellite data (Aviso, red). Dashed lines indicate linear trends over full time range and over the past decade. (From Biastoch *et al*., 2009)

Fresh water balance

Changes in upper ocean salinity have been observed in each of the ocean basins, with an increase in salinity in the subtropical evaporation zones and a decrease at higher latitudes that is consistent with a more vigorous hydrological cycle and increased supply of melt water at high latitudes. Numerous studies have documented a freshening of North Atlantic Deep Water during nearly three decades from the mid-1960s to the mid-1990s, when the North Atlantic Oscillation (NAO) evolved to an extreme positive state . The freshening reversed in the mid-1990s. While measurements are sparse in the Southern Ocean, several recent studies have detected changes in the salinity of Antarctic Bottom Water . The Ross Sea and Adélie Land regions supply about 40% of the total input of AABW . Most of the AABW exported from both sources passes through the Australian Antarctic Basin, making it a good place to monitor changes in properties of the AABW formed in the Indian and Pacific sectors. The deep T-S relationship has changed throughout the basin in recent decades, with a shift toward fresher and lighter bottom water observed in the deepest 1000 m of the water column. The freshening rate is comparable to that observed in the North Atlantic over the same time span, at comparable distances from the source regions. In contrast, in the Weddell Sea the situation is ambiguous, with freshening of bottom water in the west and an increase in the salinity of deep water in the east. The evidence from the North Atlantic and the Southern Ocean suggests that the dense water sinking in both hemispheres is responding to changes in the high latitude freshwater balance, and is rapidly transmitting this climate signal to the deep ocean.

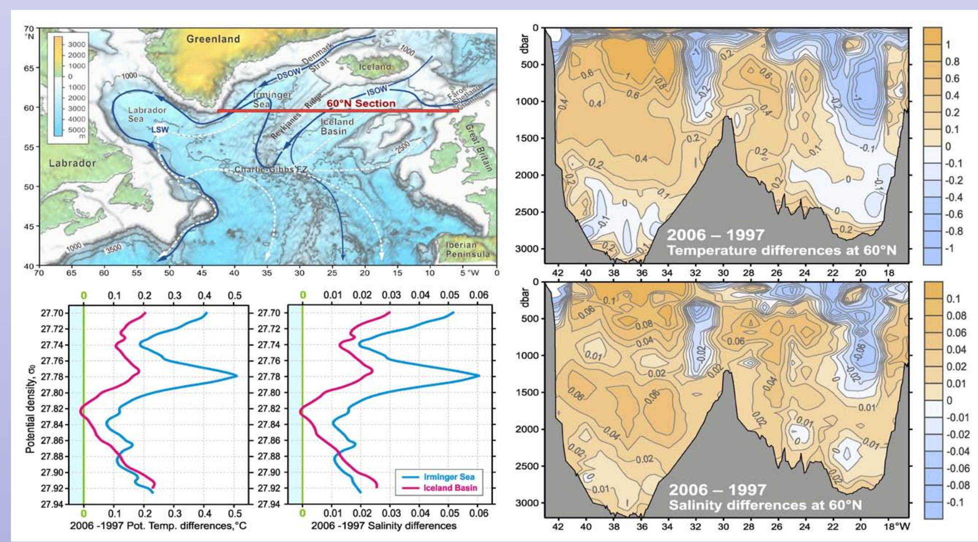

Figure 5*: Upper left:* Location of the 60°N section repeated annually by P. P. Shirshov Institute of Oceanology. ***Right:*** Temperature (°C) and salinity differences between 2006 and 1997. ***Lower left:*** Zonally averaged 2006–1997 potential temperature and salinity differences on isopycnals (σ_0) in the Irminger Sea (30–42°W) and Iceland Basin (16.5–30°W) at the LSW and deeper levels. (Adapted from Sarafanov *et al*., 2007).

Ocean Heat content

Quantification of ocean heat storage and its variability are vital for diagnoses and estimates of global warming and climate change. Observations show that on average the upper ocean has warmed since the mid-1950s. Modeling studies indicate that this warming is consistent with increases in greenhouse gases in the atmosphere. The rate of heat storage in the deep ocean, and hence the net global energy imbalance, remains difficult to estimate owing to the paucity of deep ocean measurements. Repeat hydrographic measurements reveal that waters of Antarctic origin have warmed measurably in the last few decades below 4000-m depth over much of the globe, with this warming reaching as shallow as 1000 m in the Southern Ocean (Figure 3, left side). A comparison of the observed regional deep ocean temperature changes in the Southwest Pacific to those projected from climate models show large differences (Figure 3, right side) suggesting either significant unquantified internal ocean variability or model errors . While these measurements are useful in identifying signals requiring further study, once-a-decade sections cannot distinguish regionally between true decadal variability and variability at shorter time-scales. Expansion of the existing observing system to quantitatively measure the ocean heat content below 2000 m on a more routine basis is critically needed in order to obtain a truly global estimate of ocean heat content and its relationship to climate change.

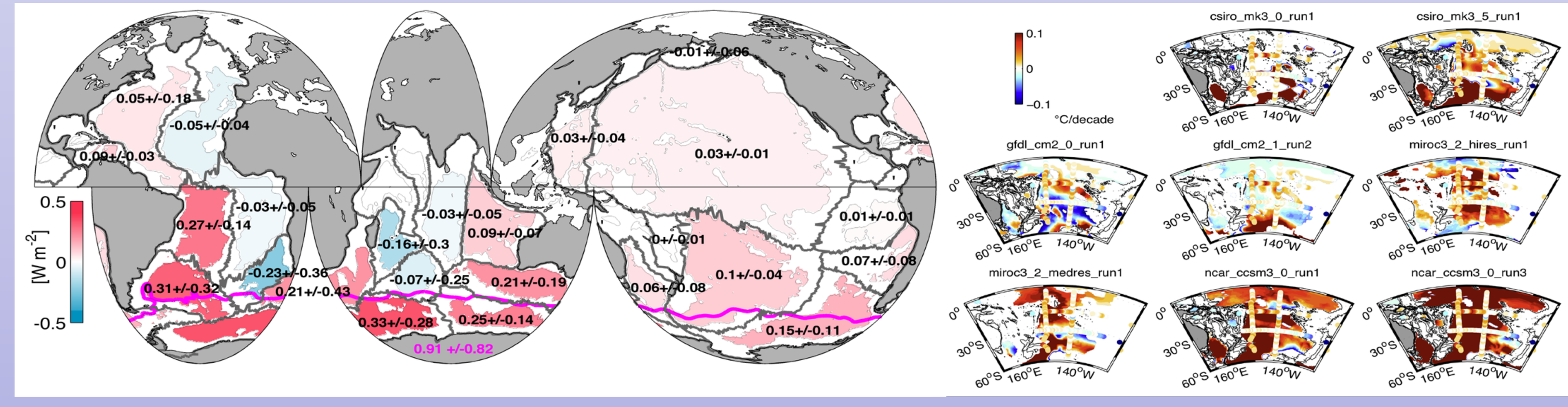

Figure 3: Left side: Mean local heat fluxes through 4000 m implied by abyssal warming below 4000 m from the 1990s to the 2000s within each of 24 sampled deep basins (black numbers and colorbar) with 95% confidence intervals. The local contribution to the heat flux through 1000 m south of the SAF (magenta line) implied by deep Southern Ocean warming from 1000–4000 m is also given (magenta number) with its 95% confidence interval (after Purkey and Johnson, 2010). **Right side:** Depth-averaged rates of change of temperature below 4000 m from the observations (dots) and various climate simulations (shading) for 1980–2000 from CMIP3 (for IPCC AR4). Model control run drift has been removed.

The need for deep ocean carbon observations

The deep ocean (≈> 2000 m) accounts for more than half of the total (natural) oceanic carbon inventory. It exchanges carbon on longer time-scales with the upper ocean, and therefor, once anthropogenic carbon enters the deep ocean it remains there for centuries. Monitoring changes in the deep ocean carbon content is critical as the anthropogenic imprint is starting to penetrate deeper into the ocean (see, Figure 4). The penetration pathways are not a homogeneous diffusive invasion into the deeper waters, but rather are local conduits of rapid penetration and transport primarily at high latitude in areas of deep and intermediate water formation. Observations of transient tracers in the deep ocean indicate that the exchanges with the atmosphere are more rapid than previously thought. Moreover, decadal reoccupations of hydrographic transects in the global ocean show greater variation in biogeochemical parameters at depth, suggesting that natural and/or climate-induced variability has a greater effect on deep waters then previously assumed.

Due to the complexity of separating the small anthropogenic CO_2 imprint from the natural carbon cycle, particularly at depth, monitoring of other indicators of the anthropogenic imprint is desired. The transient tracers are critical in this respect (Figure 4). These include inert man-made compounds released by industrial activities such as a series of halogenated compounds such as chlorofluorocarbons CFC-11, CFC-12, and sulfur hexafluoride, SF_6.

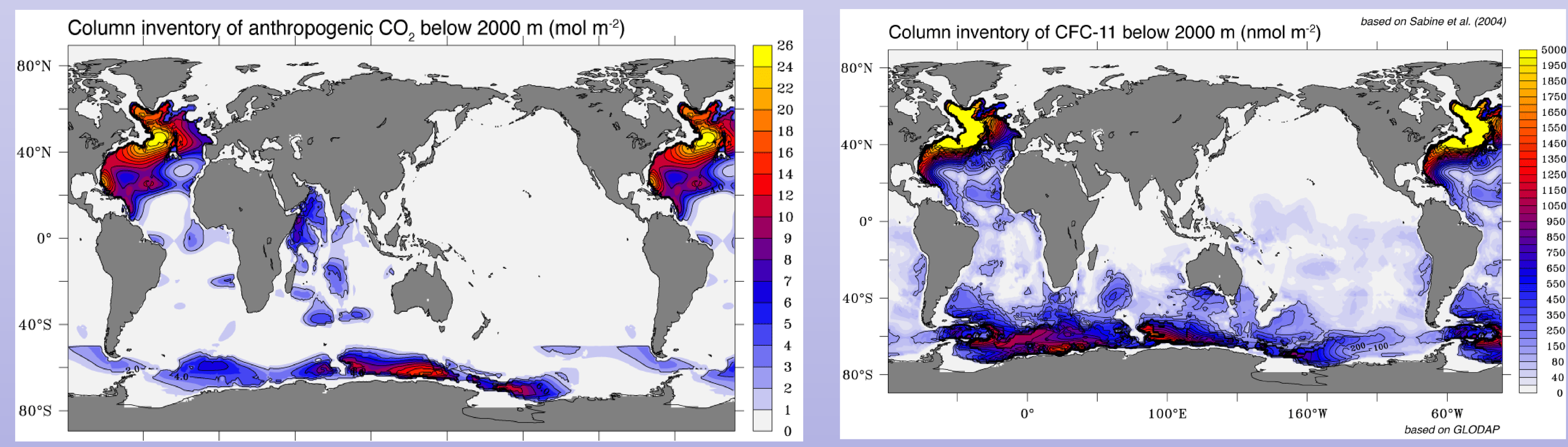

Figure 4. Comparison of the column inventory of anthropogenic CO_2 (mol m^{-2}) from Sabine *et al.* ,2004 (left panel) with the chlorofluorocarbon-11 (CFC-11) inventory from GLODAP (right panel), (Key *et al*., 2004). Courtesy of N. Gruber, ETH Zurich

Recommendations for an Expanded Observing Network

It is imperative to maintain existing observing systems while improving and expanding the deep ocean components of the Global Ocean Observing System.

- It is critical to monitor flow rates and properties of deep water at sites where upper ocean waters are injected into the deep ocean and where these waters are exchanged between sub-basins.
- Ongoing and new observations should have three additional foci: regions where topography significantly alters the deep circulation, choke points where deep water is exchanged between the major ocean basins, and deep strong flows where the major water masses are carried significant distances within basins.
- In addition to initiating and maintaining critical velocity, heat, salt, and carbon systems (deep hydrography cruises) and improving their capability to collect data on climate time-scales, the expansion of the observing system towards the deep ocean will require the development of cost effective new technology.
- For long-term efficient deep velocity and whole water column observations, new data transmission systems should be further developed. Autonomous instruments (e.g. ABIISS, deep ocean moorings that will release data at climate time scale intervals) will considerably reduce the cost of the observing system by reducing the need of ship time operations.
- For deep temperature and fresh water (salinity) observations, an important expansion of the observing system may be the development of deeper-reaching Argo floats as well as the development of new/improved deep ocean T/S moorings.
- Development of new technologies for routine deep ocean observations of carbon is needed (e.g. development of new pH sensors for CO_2 observations and ancillary variables in the deep ocean)

References

Biastoch, A., C. W. Boning, F. U. Schwarzkopf and J. R. E. Lutjeharms. Increase in Agulhas leakage due to poleward shift of Southern Hemisphere westerlies. 2009. *Nature Vol 462|26 November 2009| doi:10.1038/nature08519*
Dong, S., S.L. Garzoli, and M.O. Baringer, 2011: The role of inter-ocean exchanges on decadal variations of the northward heat transport in the South Atlantic. *Journal of Physical Oceanography, 41(8):1498-1511.*
Drijfhout, Sybren S. Susanne L. Weber and Eric van der Swaluw. 2010. The stability of the MOC as diagnosed from model projections for pre-industrial, present and future climates. *Clim Dyn. DOI 10.1007/s00382-010-0930-z*
Garzoli, Silvia L., S. Speich, A. Piola, and E. Campos, 2010: South Atlantic Meridional Overturning Circulation (SAMOC) - Third Workshop, Clivar Exchanges, No. 54.
Garzoli, S.L and R. Matano, 2011: The South Atlantic and the Atlantic Meridional Overturning Circulation. *Deep-Sea Research II*, 58(17-18):1837-1847, doi:10.1016/j.dsr2.2010.10.063.
Garzoli S., O. Boebel, H. Bryden, R.A. Fine, M. Fukasawa, S. Gladysev, G. Johnson, M. Johnson, A. MacDonald, C. Meinen, H. Mercier, A. Orsi, A. Piola, S. Rintoul, S. Speich, M. Visbeck, and R. Wanninkhof, 2010: Progressing towards global sustained deep ocean observations. in Proceedings of the "OceanObs'09: Sustained Ocean Observations and Information for Society" Conference (Vol. 2), Venice, Italy, 21-25 September 2009, Hall, J., Harrison D.E. and Stammer, D., Eds., ESA Publication WPP-306
Key, R. M., A. Kozyr, C. L. Sabine, K. Lee, R. Wanninkhof, J. L. Bullister, R. A. Feely, F. J. Millero, C. Mordy, and T. H. Peng (2004), A global ocean carbon climatology: Results from Global Data Analysis Project (GLODAP), Global Biogeochemical Cycles, 18(4), GB4031, doi:4010.1029/2004GB002247.
Meinen, Christopher M., William E. Johns, Silvia L. Garzoli, Erik van Sebille, Darren Rayner, Torsten Kanzow, and Molly O. Baringer. 2011. Variability of the Deep Western Boundary Current at 26.5°N during 2004-2009, Submitted
Purkey and Johnson, 2010 Warming of global abyssal and deep Southern Ocean waters Between the 1990s and 2000s: Contributions to global heat and sea level rise budgets, in press, doi:10.1175/2010JCLI3682.1
Sabine, C. L., Feely, R. A., Gruber, N., Key, R., Lee, K., Bullister, J. L., Wanninkhof, R., Wong, C. S., Wallace, D. W. R., B.Tilbrook, Millero, F. J., Peng, T.-H., Kozyr, A., Ono, T., and Rios, A. F. (2004), The oceanic sink for anthropogenic CO_2: Science, v. 305, p. 367-371.
Sarafanov *et al*.,(2007). Sarafanov, A., Sokov, A., Demidov, A., and Falina, A., (2007). Warming and salinification of intermediate and deep waters in the Irminger Sea and Iceland Basin in 1997–2006. *Geophysical Research Letters*, 34, L23609, doi:10.1029/2007GL03107