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Oceanographic Observations in Support of Defining Vulnerable Marine Ecosystems in the NAFO Regulatory Area

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Abstract

An investigation of the oceanographic and lower-trophic-level biology has take place in the region of Orphan Knoll. This study has utilized existing data sets as well as collecting new data using shipboard and moored instrumentation over the period 2008-2010. Physical properties indicate that Orphan Knoll is in a boundary region between outflow from the Labrador Sea (subpolar gyre) and northward flow of the North Atlantic Current (subtropical gyre), with waters of primarily subpolar origin. However, near-bottom current measurements provide evidence for anti-cyclonic (clockwise) circulation around the knoll, and an upper-ocean incursion of more subtropical water from the North Atlantic Current was observed in one of the three study years. Chlorophyll, small phytoplankton and bacteria in the Orphan Basin-Orphan Knoll region show strong spatial and inter-annual variability, reflecting the complex and variable physical dynamics and growth conditions in the region. Overall, there is little evidence for enhanced lower trophic level biology in the water column above the knoll; however, the near-bottom anti-cyclonic circulation could have important implications for the benthic community.

1. Introduction

Waters over the continental slope and rise off Atlantic Canada are in a highly advective regime because of their location in the western boundary (Labrador) current of the North Atlantic's subpolar gyre (Figure 1), and their close proximity to the energetic subtropical Gulf Stream System (GSS). Strong connectivity among the Atlantic Canadian shelf waters is clear, with major implications for how Atlantic Canadian shelf ecosystems will respond to climate change.

However, the degree and nature of connectivity among the waters over the lower slope and rise are less clear in some cases, particularly in areas with complex topography, major frontal systems, and recirculations. There is additional complexity associated with the shelfward meandering of the North Atlantic Current (Gulf Stream extension) north of Flemish Cap and the projection of Flemish Cap and the Tail of the Grand Bank towards the GSS. As a result, there are competing influences of the major current systems favouring connectivity, and topographic obstructions such as seamounts favouring regional isolation or retention and biological endemism. There is very little historical oceanographic data collected on Orphan Knoll and, therefore, new data sets are providing an improved understanding of the degree to which the regional oceanography has the potential to establish conditions favouring the development of a unique marine environment (relative to the surrounding regions) on Orphan Knoll.

NAFO closed areas (NAFO/FC Doc. 06/5) in the subtropical environment (e.g. Newfoundland Seamounts, New England Seamounts) contrast with those in the subpolar gyre (e.g. Orphan Knoll) in several ways including differences in the background flow, which is relatively weak away from the shelf edge in the subpolar gyre compared to that experienced by the seamounts in the western boundary current of the subtropical gyre. Most improtantly, the lower temperature over the seamounts in subpolar waters will likely contribute to slower recovery of ecosystems in these areas. In addition, environmental factors such as increasing ocean acidification will have a higher impact in the colder regions such as those in the subpolar gyre.

2. Methods

Ship-based observations of physical, chemical and lower-trophic level biological oceanographic properties are the primary source of information utilized in this analysis. Annual surveys of the Orphan Knoll region were carried out in the month of May in 2008-10. The 2009 survey was the most comprehensive of the three surveys. The 2008 and 2010 surveys were comprised mostly of physical and biological oceanography measurements with the primary purpose of these missions being to deploy and recover moored instrumentation.

Water samples were collected using a 24-bottle rosette attached to a CTD (SeaBird SBE 911). Nutrients (nitrate, silicate and phosphate) were analyzed colourimetrically using standard chemical methods and a Technicon Autoanalyzer, and chlorophyll was determined on acetone-extracted samples by fluorometry (Mitchell et al. 2002). Nanophytoplankton, picophytoplankton and bacterial abundance was determined by flow cytometry according to methods outlined in Li and Dickie (2001).

In 2010, a lowered acoustic Doppler current profiler (LADCP) system was added to the CTD rosette; this system consisted of a battery pack and two 300 kHz Teledyne RDI Workhorse ADCPs (one upward-looking, one downward-looking) with 6000 m depth rating. The downward-looking ADCP acts as the master while the upward-looking is the slave in the system. The output from the two ADCPs is combined during the data processing to provide a vertical range of approximately 200 m for the system. The data acquired with this system is processed with the Lamont-Doherty Earth Observatory (LDEO) LADCP processing software (available at http://www.ldeo.columbia.edu/cgi-bin/ladcp-cgi-bin/hgwebdir.cgi).

In addition to the shipboard measurements, moored instrumentsings were deployed on Orphan Knoll between May 2008 and July 2010 (Figure 8). While the measurement parameters on the moorings were primarily limited to near-bottom currents, temperature, salinity and dissolved oxygen concentration, these instruments provide measures of variability which are not feasible from ship occupations once a year. Moorings with an Aanderaa RCM11 acoustic current meter (25 m above bottom) and SeaBird SBE37 Microcat conductivity/temperature/depth sensor (50 m above bottom) were deployed at sites OK-A (2200 m), OK-B (1750 m) and OK-C (2200 m) in May 2008 on cruise HUD2008006 and recovered in May 2009 on cruise HUD2009011. The current meters provided samples once per hour and the Microcats recorded every 5 minutes. Moorings were deployed in May 2009 at sites OK-D (2200 m), OK-B (1750 m) and OK-E (2200 m). This set of moorings on the flanks of the knoll was designed similar to the moorings deployed in 2008-09, however, the OK-B mooring at the summit of the knoll included additional instrumentation for the 2009-10 deployment; this mooring included two Aanderaa RCM11 acoustic current meters with Optode dissolved oxygen sensors included at depth of 1300 m and 12 m above bottom (nominally 1738 m). SeaBird SBE37 Microcats deployed on the mooring at 1000 m and 1550 m. The OK-B mooring was recovered in May 2010 on cruise HUD2010009. It was decided that in order to provide measurements of currents during the period of HUD2010029, led by Dr. E. Kenchington, the moorings at OK-D and OK-E would be left in place until July 2010. In addition, another near-bottom mooring was deployed in May 2010 at OK-C with the substitution of an RDI Workhorse 300 kHz acoustic Doppler current profiler to provide a measure of the structure of currents over a range of approximately 100 m above the seabed. In July 2010, mooring recoveries were carried out at OK-C and OK-E, however, the acoustic release at OK-D did not respond to attempts to communicate. An attempt was made to drag for the mooring but this was not successful and this instrumentation was not recovered.

Satellite remote sensing provide large-scale context for sea surface temperature (SST) and surface chlorophyll concentrations in the Orphan Basin-Orphan Knoll region during the period of field surveys in 2008 – 2010. Data were extracted from semi-monthly AVHRR SST and MODIS ocean color satellite imagery: (http://www.mar.dfo-mpo.gc.ca/science/ocean/ias/remotesensing.html).

The Ocean Features Analysis (OFA) chart is a combination of SST and added boundary lines for water masses and eddies which is produced by the Department of National Defence Canada METOC office in Halifax. AVHRR composites for the previous 3 days (or since the previous OFA) are blended with surface temperatures from ships, ARGO data, XBT reports from ships, and buoy data (and sometimes AZMP data). Ship and buoy reports are downloaded from ISDM. METOC carries out quality control on all data and removes outliers. The Ocean WorkStation (OWS) software then uses a kriging technique to blend all the observations together, along with monthly historical climatology (provided by Igor Yashayaev, BIO) to produce a temperature field. Guidance from US Navy models and other SST composite images is used (especially in winter) when satellite coverage is sparse. Once the SST field is derived, the water mass boundary lines are added manually, using guidance based on monthly temperature characteristics.

Results from the French Global Ocean Reanalysis and Simulations (GLORYS) project are analyzed and presented. The GLORYS objective is to produce state-of-the-art eddy-resolving global ocean simulations constrained by oceanic observations by means of data assimilation. The results presented here are from GLORYS1V1 (the first version of the stream 1 reanalysis) covering the Argo float era (2002-2008). The reanalysis system is similar in many respects to the Mercator operational ¼° global ocean analysis/prediction system (Dombrowsky et al. 2009).

3. Results

3.1 Physical Oceanography

3.1.1 CTD & LADCP Survey

A cross-section of potential temperature in Orphan Basin and Orphan Knoll provides some insight into interannual variability in this region (Figure 3). At the depth of the summit on Orphan Knoll, the temperature in 2009 was approximately 0.3°C warmer than the preceding year, but there was little change observed between 2009 and 2010. The upper 500 m of the water column was approximately 1-3°C warmer in 2009 than in 2008 or 2010, however, horizontal variability in this upper layer is significant and the warm water mass appears to be limited to the region of Orphan Knoll and approximately 100 km to the west. This variability is likely related to changes in the location of the front between the subpolar gyre and the North Atlantic Current. The section from line OBB indicates that the upper 200 m is relatively low in salinty during the time of the survey (Figure 4).

Denmark Strait Overflow Water (DSOW) is observed near bottom on both sides of Orphan Knoll in 2009 (delineated approximately by the 2°C isotherm), and the volume of this water mass increased significantly in Orphan Basin in 2010 (Figure 3). This could have implications for the benthic communities in that region.

Full- depth velocity profiles were collected and processed on the 2010 cruise using an LADCP system on the CTD rosette. The near-bottom segments of each profile were computed in three bins (25-75 m, 75-125m and 125-175m above bottom). These results show that the near-bottom currents are intensified along the western boundary of Orphan Basin (Figure 5). Over the region of Orphan Knoll, the current magnitudes are weaker but do indicate that an anti-cyclonic (clockwise) circulation exists near the seabed. This is consistent with moored current meter results from the previous year (Greenan et al., 2010).

3.1.2 Remote Sensing (SST)

Analysis of sea surface temperature features is provided by METOC for the periods coinciding with the field expeditions in 2009 and 2010 (Figure 6) as well as from the BIO Ocean Research and Monitoring Section (ORMS, Figure 7). The SST in the Orphan Knoll region is consistent with near-surface data collected with the shipboard CTD. It is apparent from the SST analysis that temperature in the region was warmer in 2009 due to the incursion of a filament or eddy from a meander of the North Atlantic Current (NAC) in the subtropical gyre. This underscores the fact that Orphan Knoll is influenced both by subpolar waters exiting the Labrador Sea as well as periodic episodes of subtropical waters from NAC meanders.

3.1.3 Moored Current Measurements

As stated above, unlike seamounts in the Northwest Atlantic subtropical gyre which experience strong background flows, Orphan Knoll exists in a region with relatively weaker flow. Measurement of current rate 25 m above bottom (mab) at each of the mooring sites for the period May 2008 – May 2009 indicate (Table 1) that flow on the east flank of the knoll (OK-C) is stronger and more variable than encountered on the west flank (OK-A) or at the summit (OK-B). The 2009-10 deployment at OK-D on the northern flank produced results for rate which were very similar to those observed at OK-A & OK-B.

A progressive vector diagram (Figure 8) demonstrates the flow on the west flank of Orphan Knoll (OK-A) is fairly consistently in the northwest direction travelling approximately 400 km over the period of one year. The flow on the summit (OK-B) is predominantly to the south, however, the direction is more variable than that observed on the west flank and the distance traversed in the period of one year is about 200 km. On the east flank (OK-C), there are two periods of quite consistent flow to the southeast interspersed with other periods in which the flow is more variable and predominantly to the southwest. The flow on the north flank (OK-D) of the knoll is predominantly towards the east but the PVD shows very modest transport. The PVD suggests that there exists an anti-cyclonic (clockwise) flow around the knoll. This is consistent with theory for such topography in the Northern Hemisphere. This flow could either be due to: 1) the formation of a Taylor cap over the knoll which is a result of topographic blocking of the background flow, or 2) the process of tidal rectification which results in a residual flow due to tidal forcing.

The annual mean flow at all mooring sites follows topography with current in the western part of Orphan Basin being substantially larger than observed in the eastern part of the basin and on Orphan Knoll (Figure 9). Interannual variability is small for sites at which multi-year data sets exist. This plot is consistent with the snapshot of currents in the region obtained using the LADCP system on the 2010 cruise (Figure 5).

3.1.4 GLORYS Reanalysis

Processing of the GLORYS reanalysis produced by MERCATOR-Ocean also provides results (

Figure 10) which are consistent with the observations from both the LADCP survey (Figure 5) and from the moored current meter measurements (Figure 9). An anti-cyclonic (clockwise) gyre is seen in the reanalysis which represents the mean velocity field over the period of 2002-2008. The higher magnitude currents along the western boundary of Orphan Basin are seen to extend all along the Newfoundland/Labrador slope and around Flemish Cap. The surface velocity plot shows that the currents in the western Orphan Basin region are also strong southerly flows along the topography. In contrast the surface flow over Orphan Knoll is predominantly to the north.

The reanalysis was also used to study mean bottom temperature in this region (Figure 11). Due to the fact the Orphan Knoll extends more than 1000 m above the surrounding seafloor, it is seen on this map to exist as a relatively isolated entity in terms of its bottom temperature. The surface temperature demonstrates that this is a region which is influenced by both the subpolar and subtropical gyres.

3.2 Biological Oceanography

3.2.1 Phytoplankton (including remote sensing of chl)

The highest vertically-integrated (0-100 m) chlorophyll concentrations in 2008 and 2009 were observed on the SW boundary of Orphan Basin and at the margins of Orphan Knoll; lowest concentrations were seen on the top of the Knoll. Overall, concentrations were similar between these two survey years. The chlorophyll concentration was more evenly distributed across the region in 2010 than it had been in the previous two field seasons with the concentration over the Knoll being slightly higher (Figure 12). The high chlorophyll concentrations observed at the boundary of the Orphan Basin were clearly evident in ocean colour imagery for 2008 and particularly 2009 (Greenan et al, 2010). Ocean colour satellite imagery from the first half of May 2010 (Figure 7) indicates that the eastern half of the Knoll was influenced by a strong surface chlorophyll bloom.

The abundance of nano-phytoplankton was similar in all three survey year 2008-2010. No longitudinal trend was observed in any of the years (Figure 13). Pico-phytoplankton abundance was highest along the margins of the Knoll and concentrations increased west to east. The longitudinal gradient of increasing cell abundance reflects the change from Arctic-influenced waters to Atlantic-influenced waters. In both 2009 and 2010, pico-phytoplankton abundance was lower by ~50% than observed in 2008.

3.2.2 Bacteria

The pattern of bacterial abundance showed highest integrated concentrations on and in proximity to Orphan Knoll in 2008 and 2009, however, in 2010 this trend was not evident. The reason for the difference between 2010 and the previous two field surveys is unknown at this point and requires further investigation. Bacteria concentrations generally increased west to east, as seen in small phytoplankton, and integrated abundance was lower (~30%) in 2009 than seen in 2008 (Figure 12). In the 2008 hydrographic section, a local downward displacement of the isopleths of abundance is apparent at depths greater than 1500m in the waters immediately overlying the seamount (Greenan et al., 2010), suggestive of downwelling in the core of a Taylor column. As a result, bacterial concentration on the seamount summit was elevated over that in surrounding waters at the same depth.

Summary

The Orphan Basin-Orphan Knoll region is biologically rich and complex, and strongly influenced by local processes and advection. In the spring, the lower trophic level dynamics are likely dominated by the seasonal large-scale spring bloom event which would certainly mask any ‘knoll-effect’. Investigations in other periods of the year could provide further insight into the role of this topographic feature in the lower trophic level dynamics.

Overall, we have little evidence at this point that Orphan Knoll enhances the lower trophic level biology in the water column above the knoll; however, near-bottom anti-cyclonic circulation has been observed from a variety of measurement technologies and this could have implications for benthic community of the Knoll.

Acknowledgements

Many staff and associates at BIO have contributed to this program which is funded by the DFO International Governance Strategy (IGS). The field expeditions are supported by skilled and dedicated staff in the Technical Operations Section of the Ocean Sciences Division and the Ocean Monitoring and Research Section in the Ecosystem Research Division. These efforts, together with those of the officers and crew of CCGS Hudson, are gratefully acknowledged. The authors would also like to thank Halifax METOC for providing the surface analyses used in this report and Mercator Ocean (http://www.mercator-ocean.fr/) for providing the reanalysis results.

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Table 1: Current statistics for the Orphan Knoll moorings sites

Site	**Mean Current (m s^{-1})**	**Standard Deviation (m s^{-1})**	**Max Current (m s^{-1})**
OK-A	**0.041**	**0.025**	**0.20**
OK-B	**0.043**	**0.023**	**0.15**
OK-C	**0.085**	**0.047**	**0.32**
OK-D	**0.040**	**0.024**	**0.201**

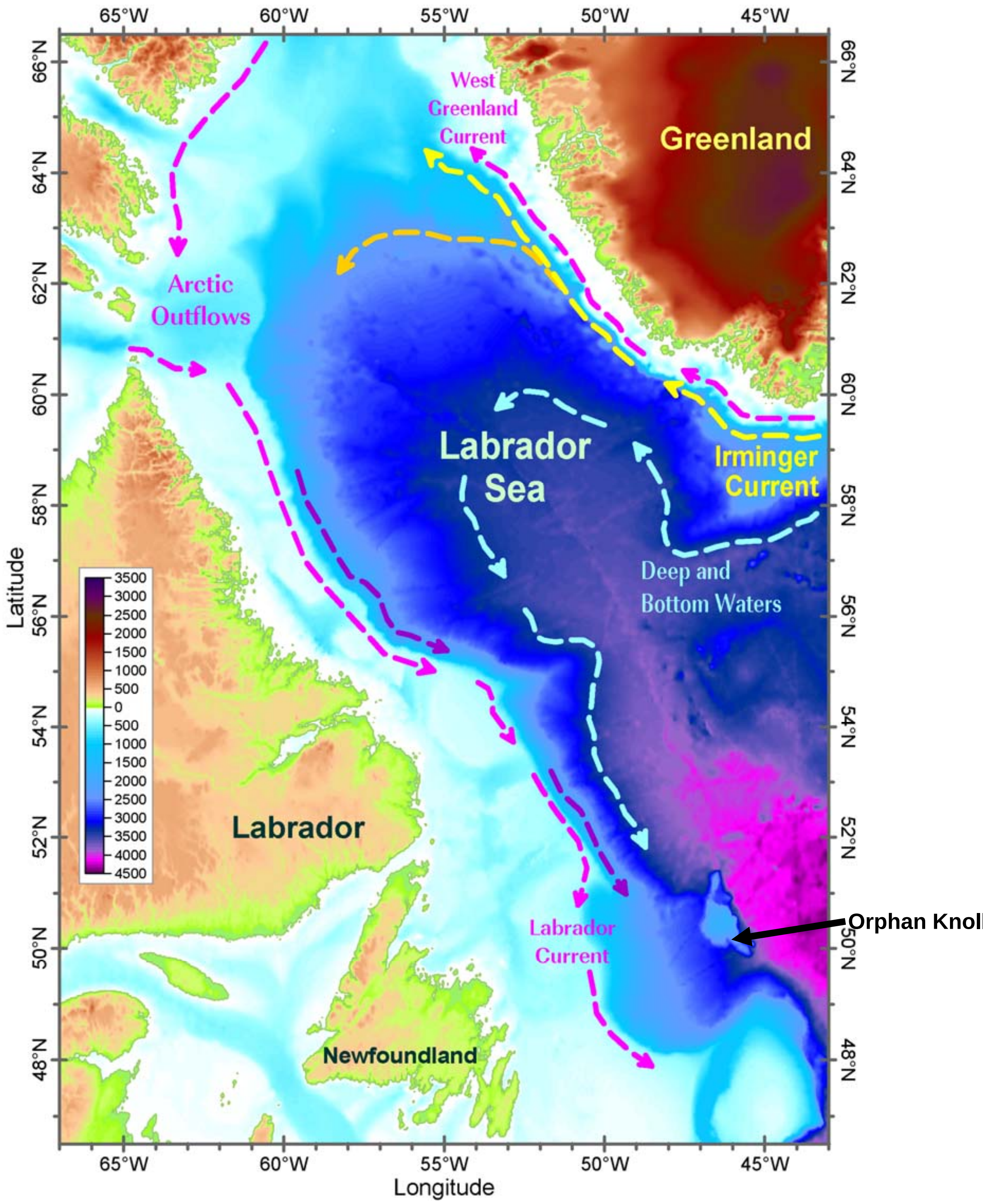


Figure 1: Circulation in the Labrador Sea region consists of upper layer currents along the edge of the Greenland and Labrador continental shelves (magenta lines). Deep and bottom waters (cyan line) enter this region south of Greenland and some of this water encounters Orphan Knoll as it exits the Labrador Sea.

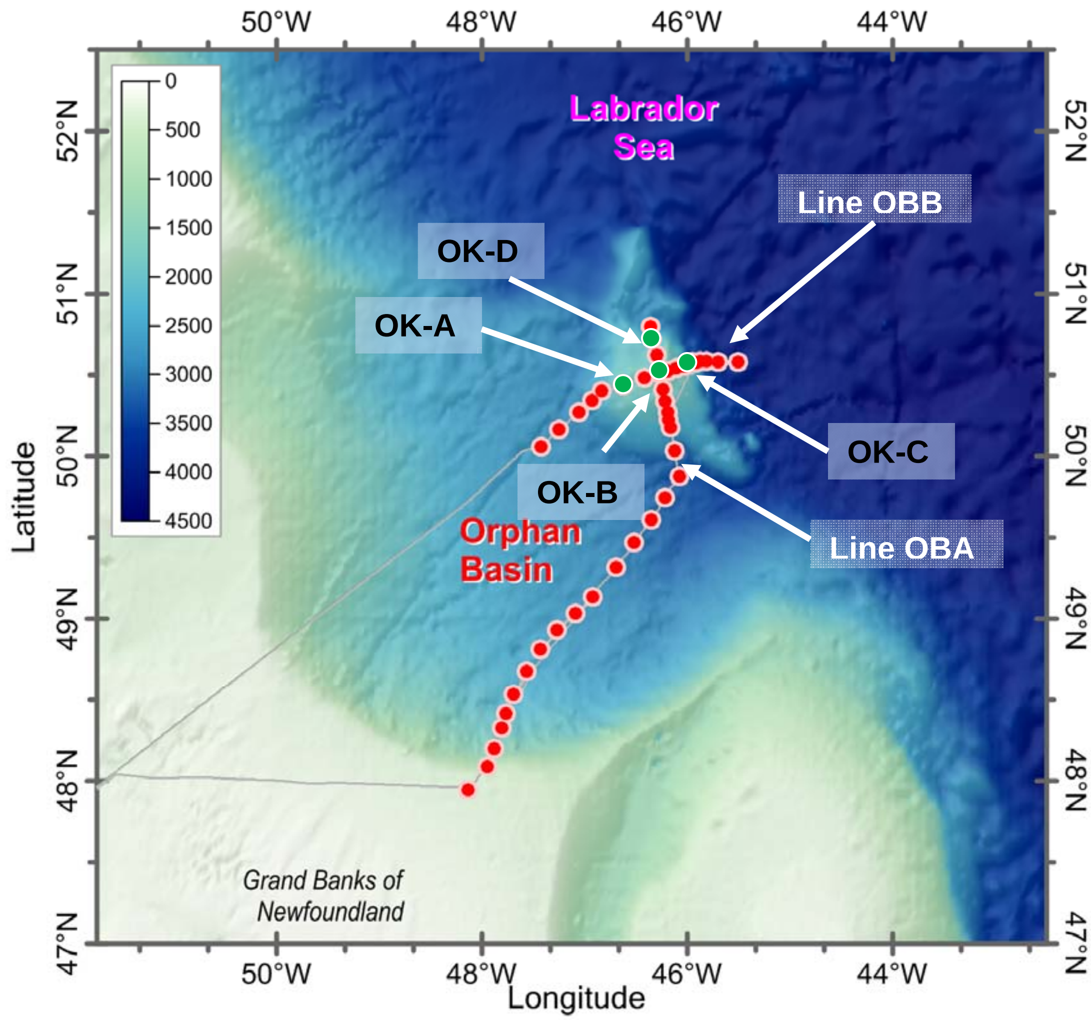


Figure 2: Location of CTD stations (red circles) occupied in May 2010 during a cruise which combined Panel on Energy Research and Development (PERD)-funded research in Orphan Basin with DFO International Governance Strategy (IGS)-funded research on Orphan Knoll. Moorings (green circles) provide year-round measurements of currents, temperature, conductivity and oxygen.

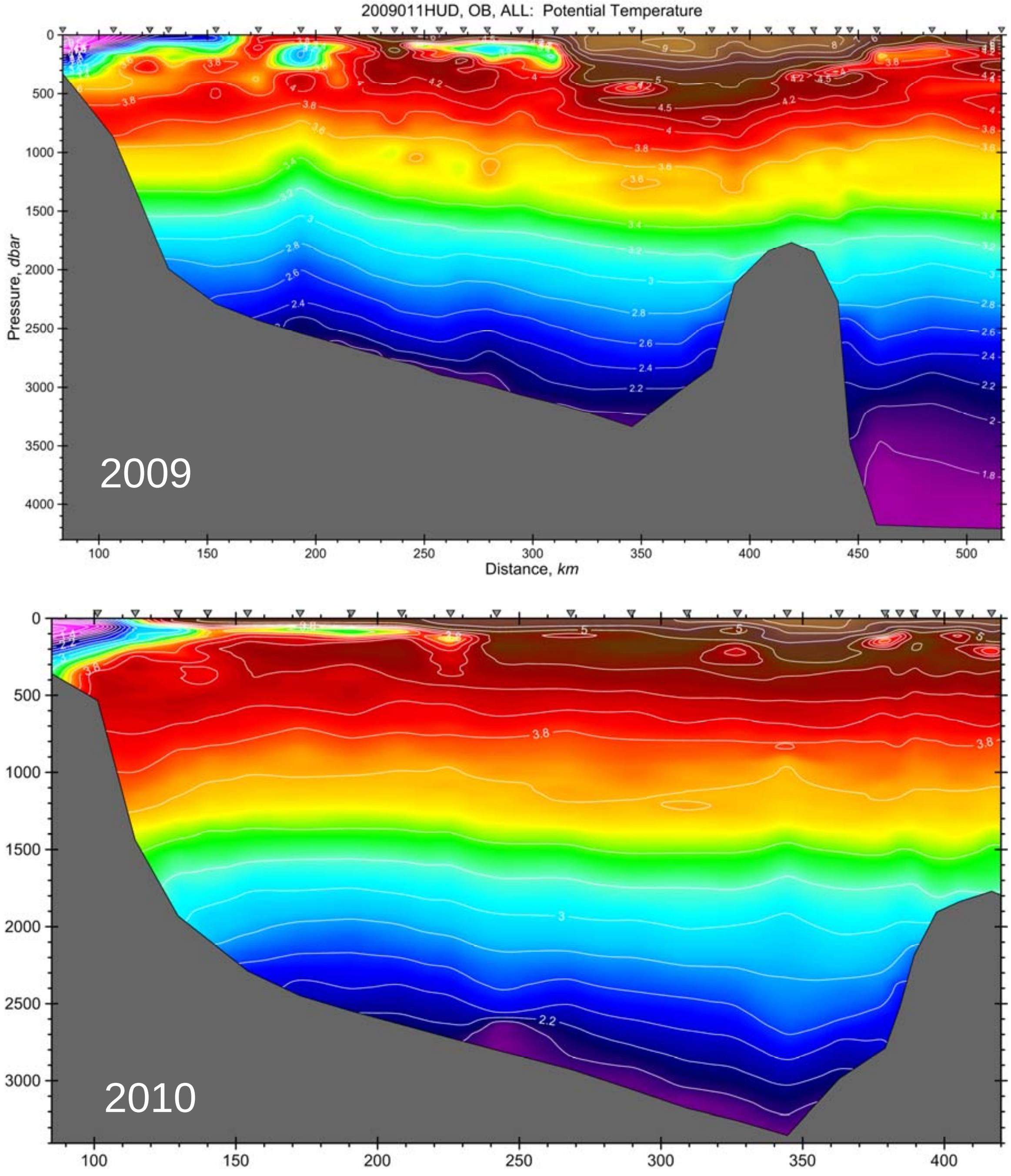


Figure 3: Potential temperature cross-section of Orphan Basin (0-350 km) and Orphan Knoll for 2009 and 2010 for Line OBA (see Figure 2).

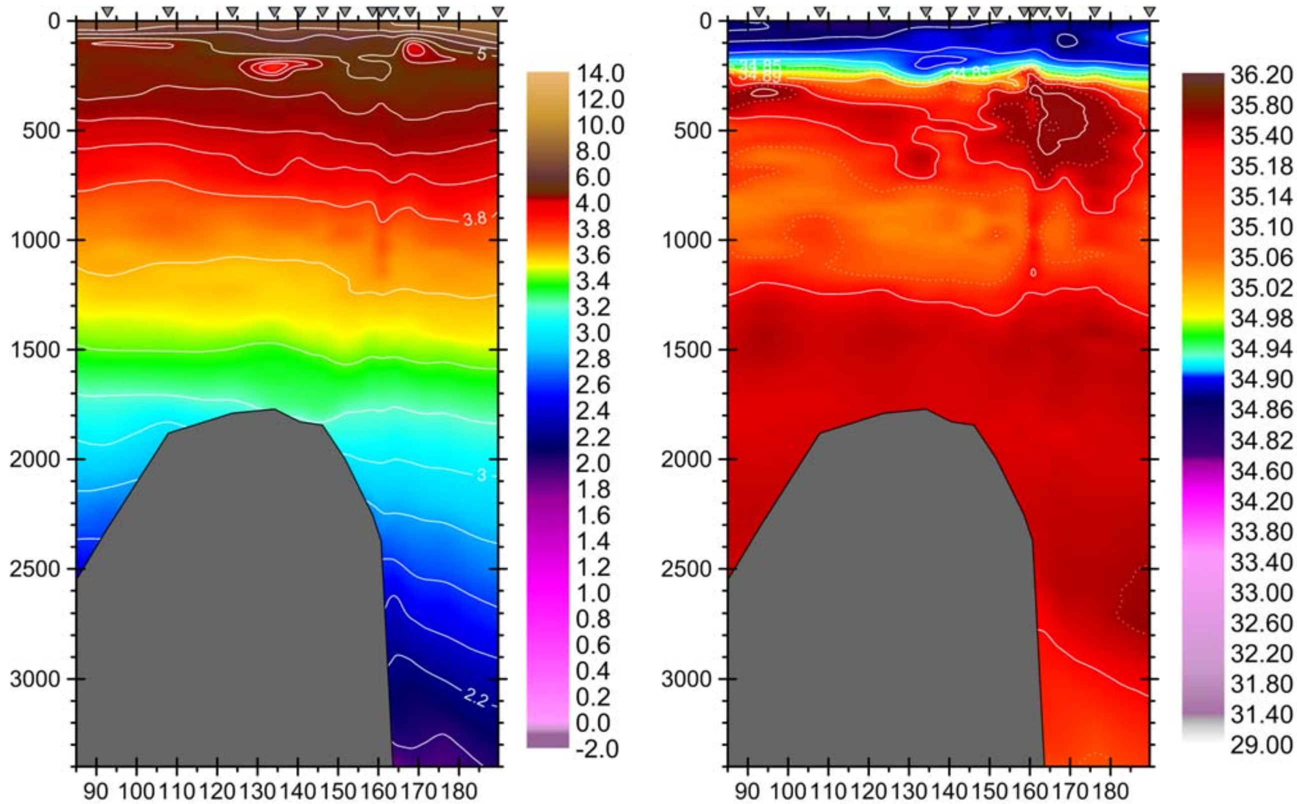


Figure 4: Potential temperature and salinity from the 2010 CTD survey of Orphan Knoll for Line OBB (see Figure 2).

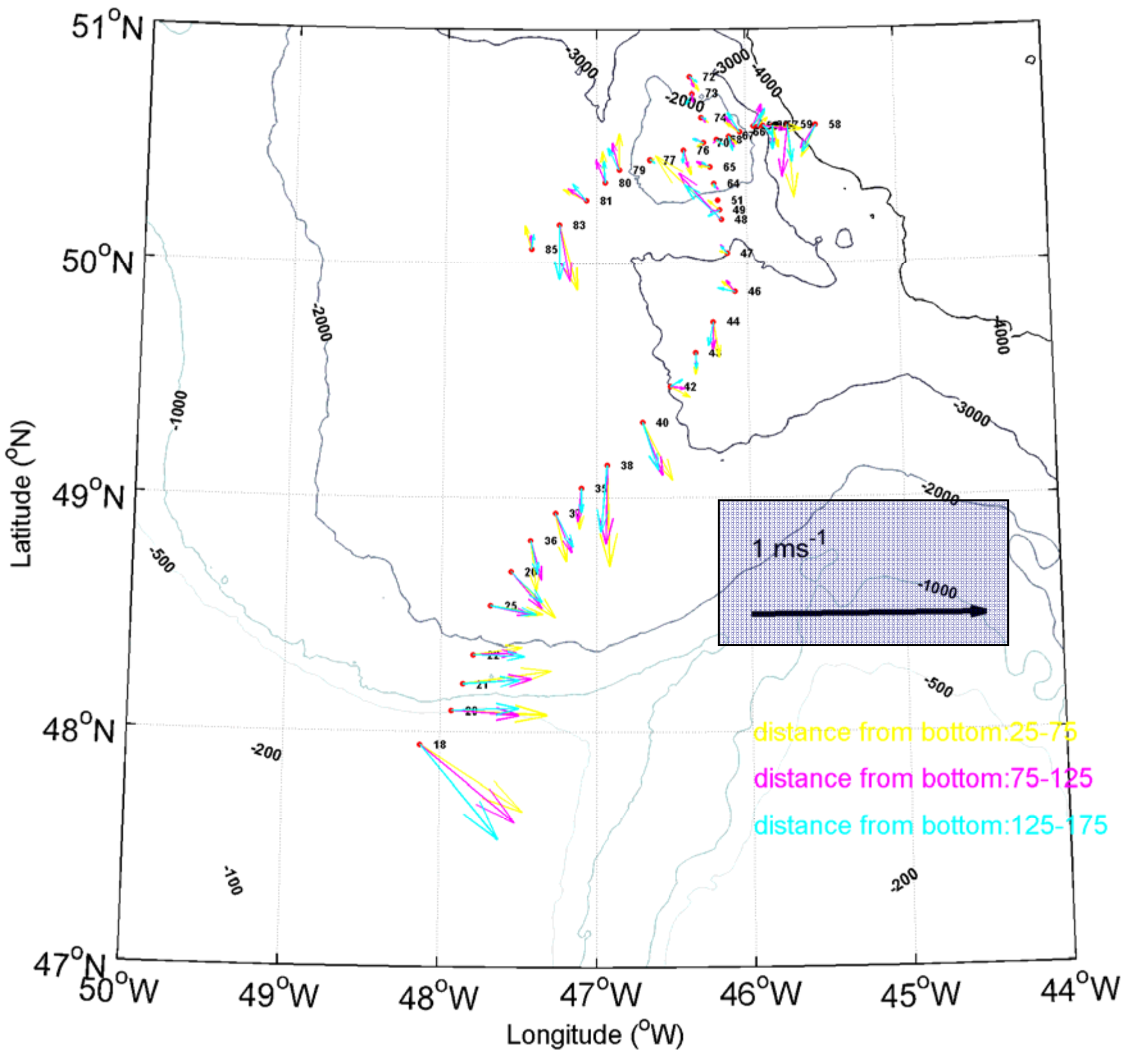


Figure 5: Near-bottom velocities computed from lowered acoustic Doppler current profiles (LADCP) at the CTD stations in Orphan Basin and Knoll. The scaling vector is inset in the figure.

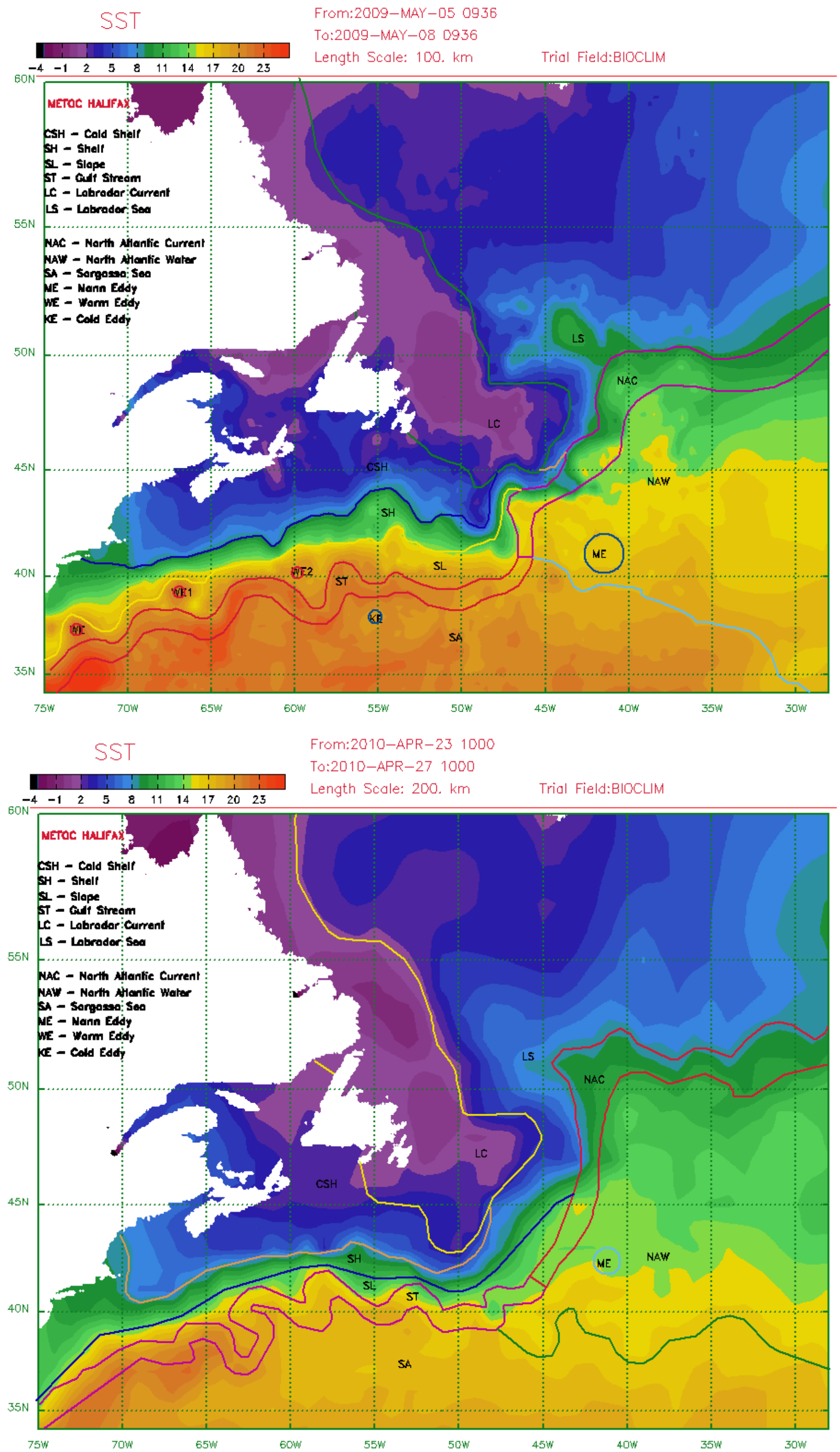
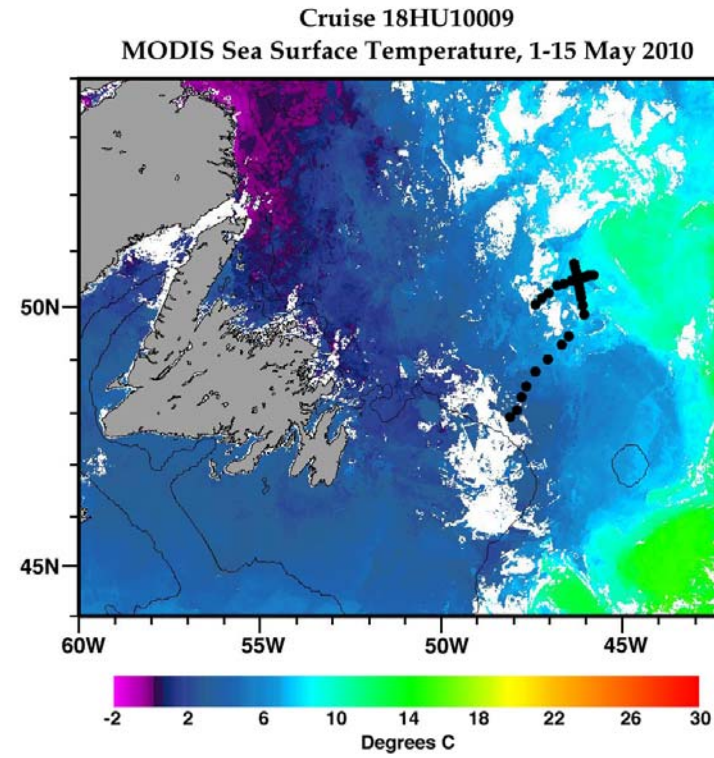


Figure 6: Sea surface temperature analysis for early May 2009 and late April 2010 provided by METOC Halifax.



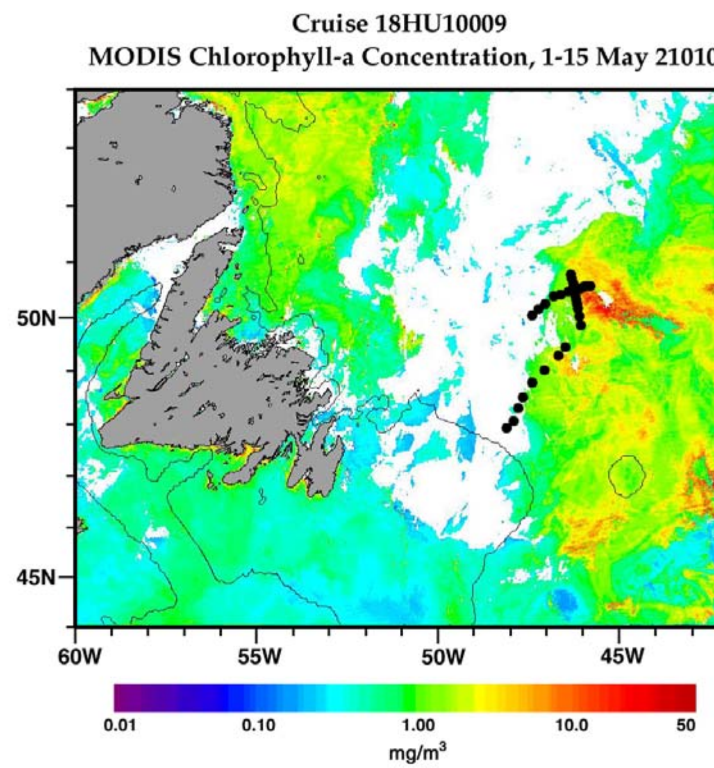


Figure 7: MODIS satellite sea surface temperature (top) and chlorophyll concentration (bottom) composited from images acquired in the first 2 weeks of May 2010. Black dots indicate stations sampled during the 2010 research cruise on CCGS Hudson (HUD2010009).

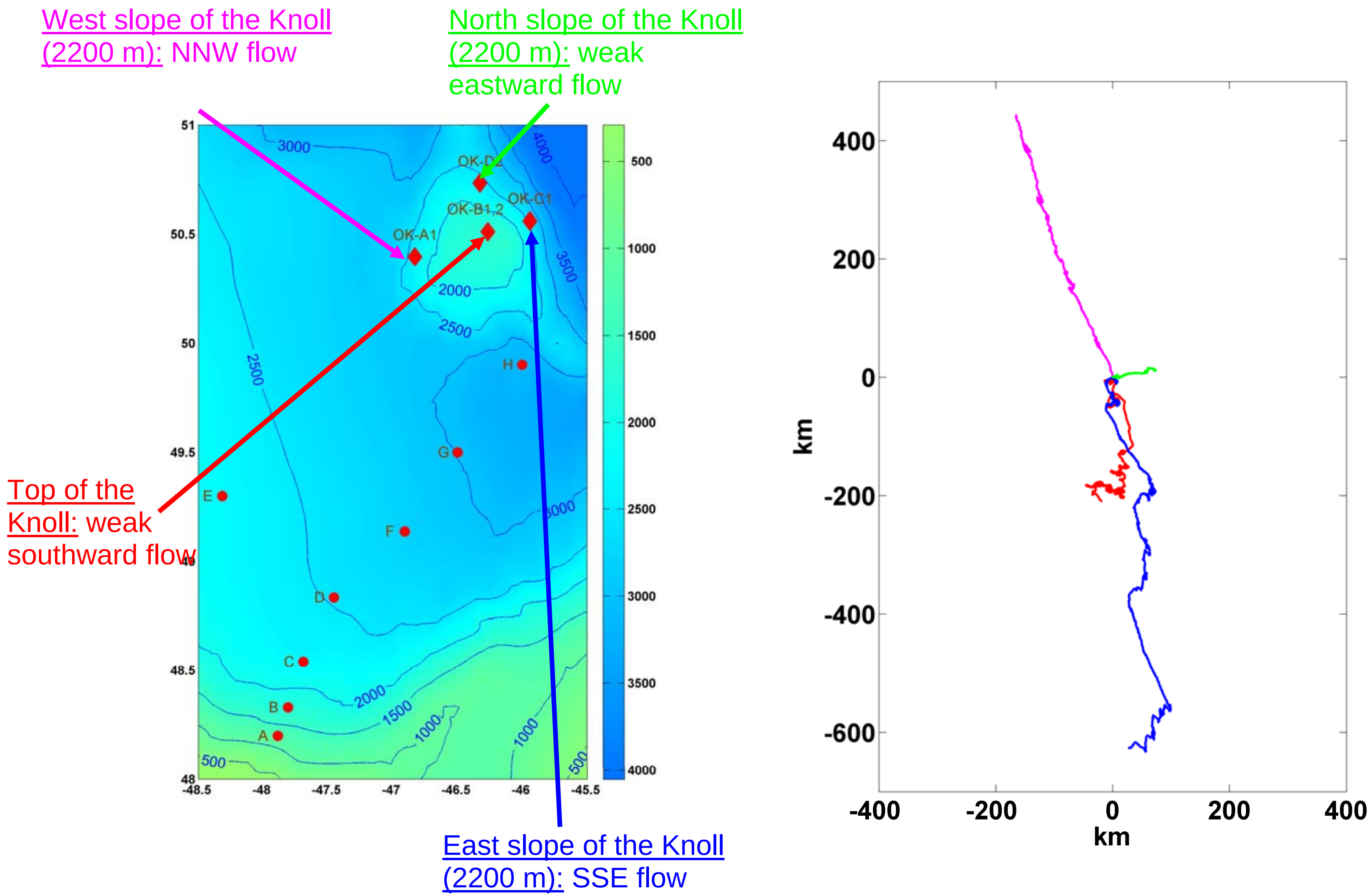


Figure 8: Progressive vector diagram demonstrating consistent flow to the northwest on the western flank of Orphan Knoll (magenta), predominantly southeast flow on the eastern flank (blue), weak easterly flow on the north flank (green) and a weak southerly flow on top of the knoll (red).

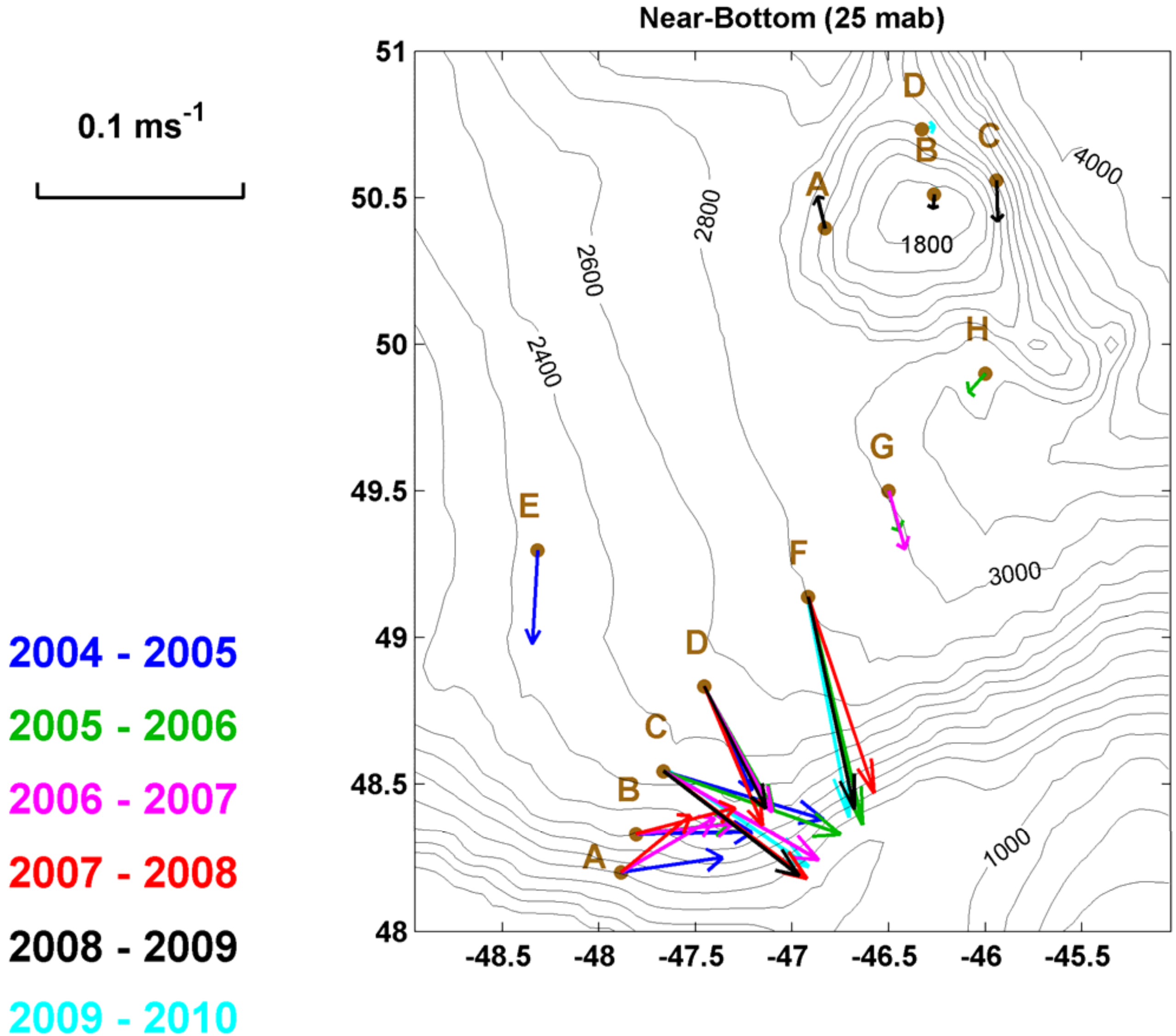


Figure 9: Mean near-bottom currents (25 metres above bottom) in the Orphan Basin and Orphan noll region for the years 2004-10 Color of the arrows corresponds to the legend and the scale length of 0.1 m s-1 is shown.

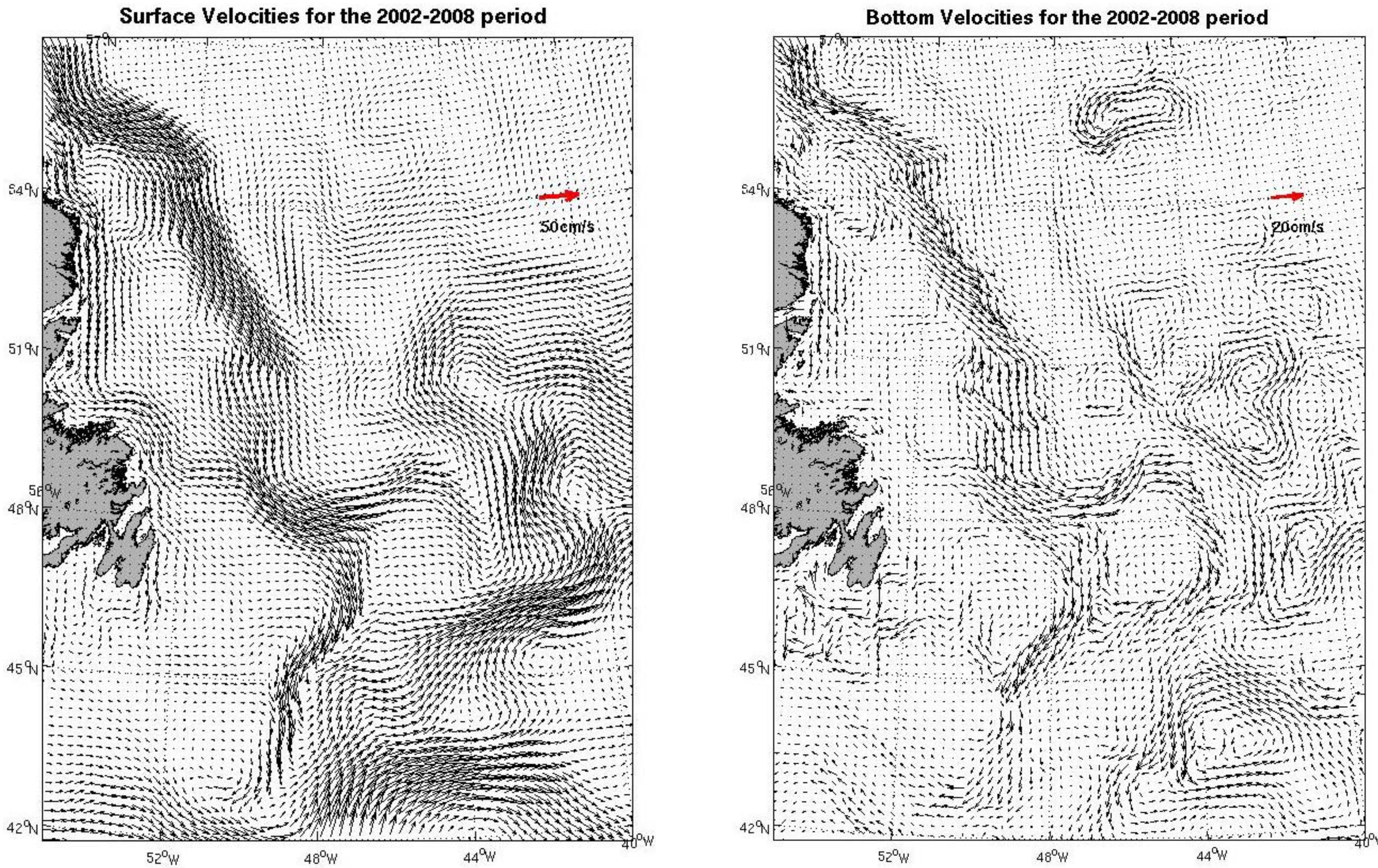


Figure 10: Surface and bottom velocities derived from the GLORYS reanalysis for the period 2002-2008.

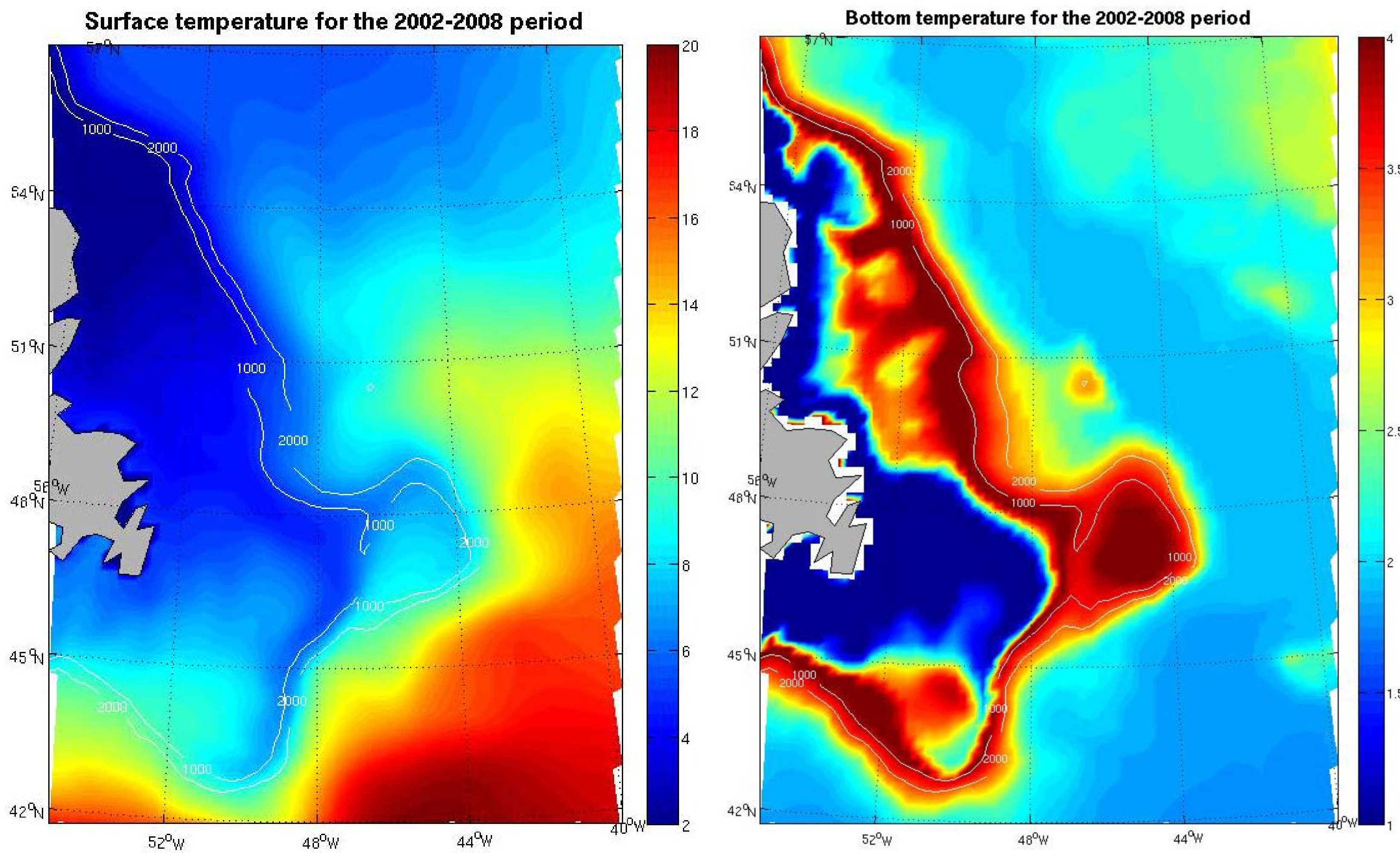


Figure 11: Mean surface and bottom temperature for the period 2002-2008 from the GLORYS reanalysis.

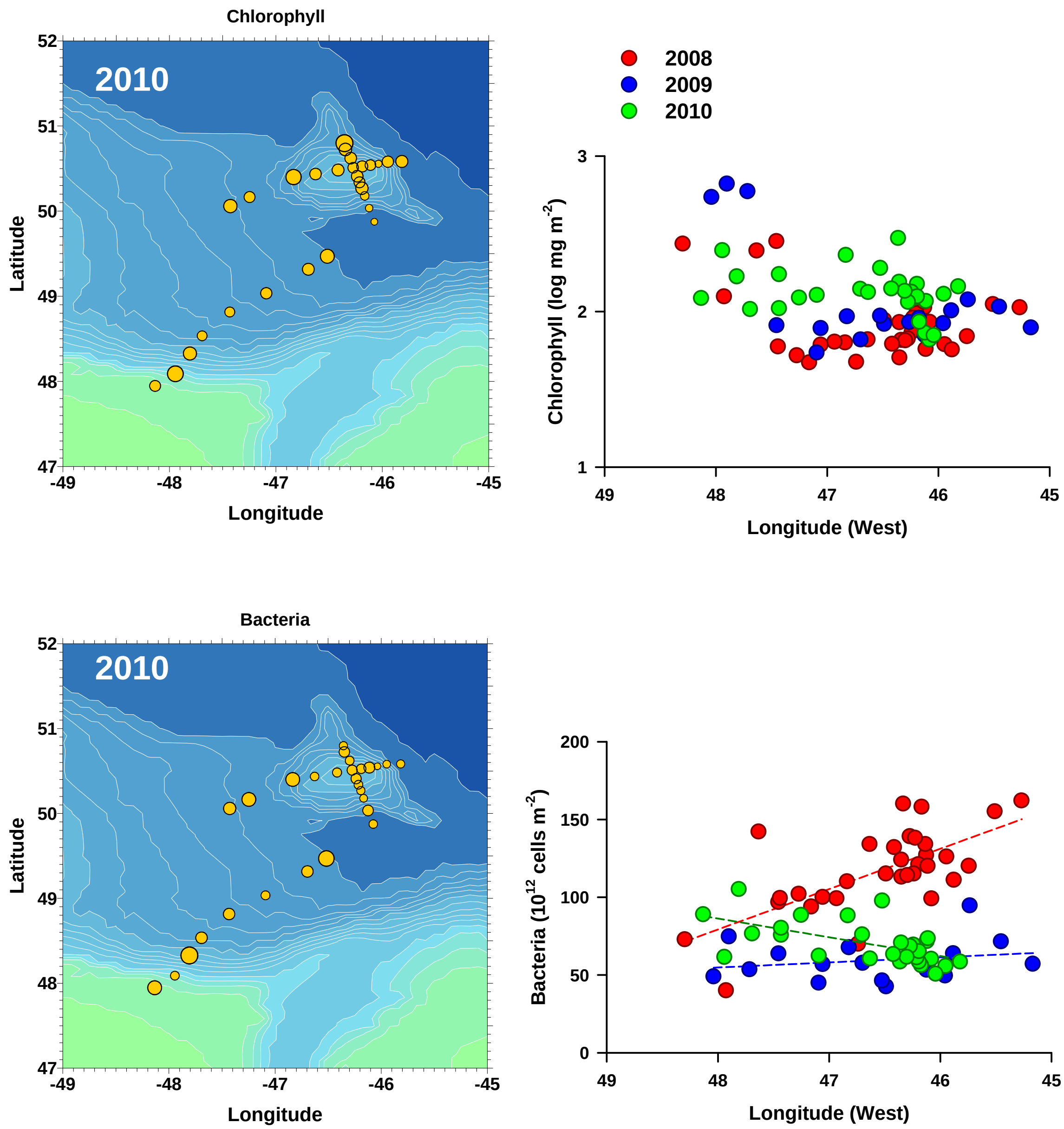


Figure 12: Vertically integrated chlorophyll concentration (mg m^{-2}) and bacterial abundance (cells m^{-2}) for survey stations in Orphan Basin and Orphan Knoll. The size of dots on the maps (left panels) provides a relative measure of concentration in 2010. The longitudinal variation of chlorophyll concentration and bacterial abundance is compared over 3 years (right panels).

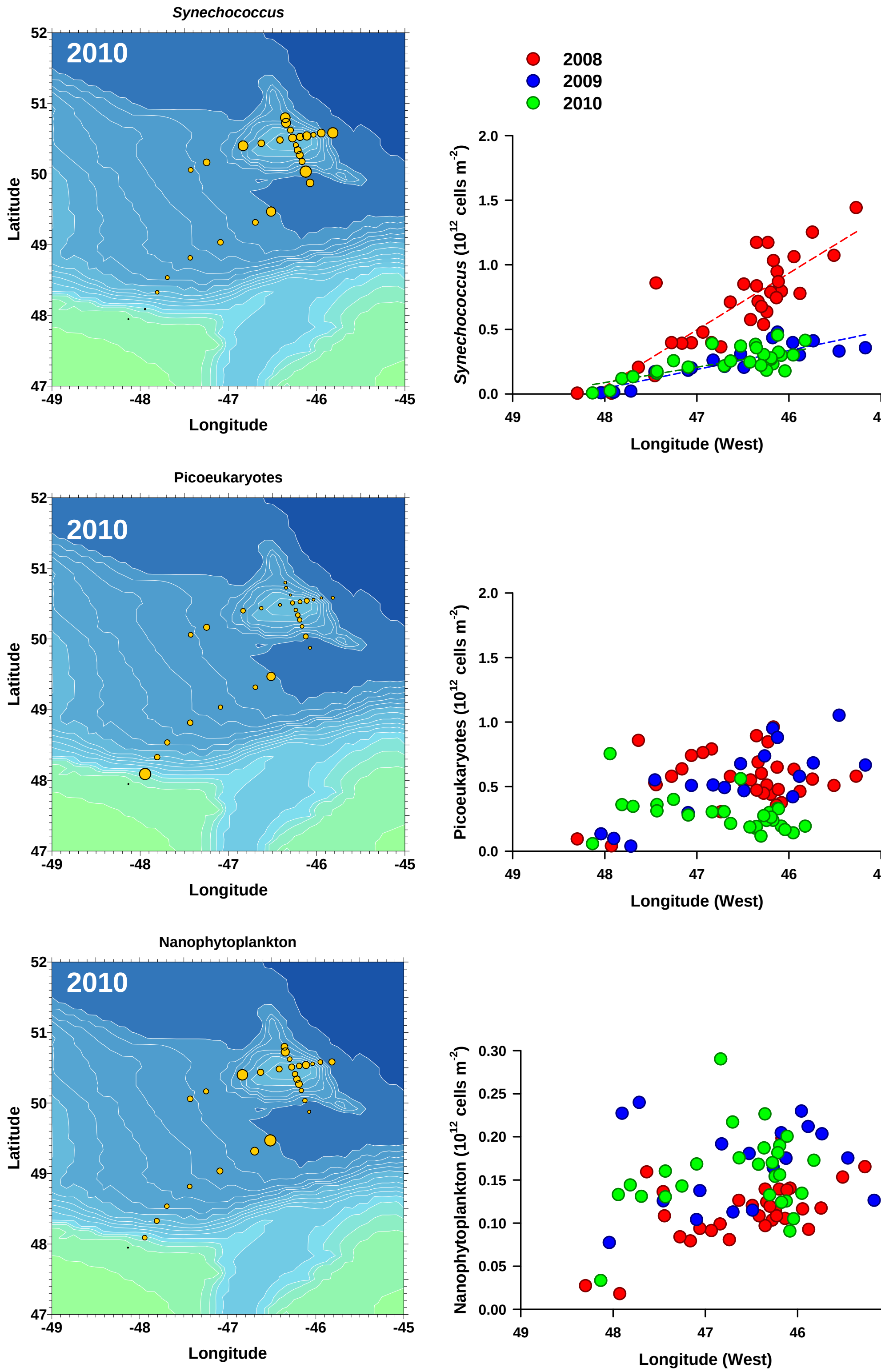


Figure 13: Vertically integrated abundance (mg m^{-2}) of *Synechococcus*, picoeukaryotic phytoplankton, and nanophytoplankton for survey stations in Orphan Basin and Orphan Knoll. The size of dots on the maps (left panels) provides a relative measure of abundance in 2010. The longitudinal variation of cell abundance is compared over 3 years (right panels).