Oceanographic and Sound Velocity Fields for the ESME Workbench

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Abstract

We describe the effort to provide three-dimensional global thermohaline and sound velocity fields using a variety of approaches for use in the ESME (Effects of Sound in the Marine Environment) Workbench suite of programs. The primary fields used are from the Modular Ocean Data Assimilation System (MODAS), developed by D. Fox. The system provides global thermohaline and sound velocity fields on a daily basis using environmental inputs from the U. S. Navy as well as remote sensing of sea surface temperature and sea surface height. In order to examine the MODAS fields, we also used data from the Southern California Bight collected by the California Cooperative Fisheries Investigations (CalCOFI) as well as high-resolution hydrographic data collected over the continental shelf south of New England as part of the Shelfbreak PRIMER Experiment. MODAS performs well for features such as large scale boundary currents and eddies but is more limited in resolving features such as shelfbreak and coastal fronts which have small spatial and temporal correlation scales. Due to the considerable computational needs of other ESME modules and its use as a planning tool, we present a pragmatic approach for future applications.

1. Introduction

The ESME (Effects of Sound in the Marine Environment) team of scientists and engineers was presented with the considerable challenge of designing a risk assessment module for use by planners to reduce the possible effects of Naval operations on marine mammals in different regions. The module inherently involved the collection and usage of water column and ocean bottom properties, the use of acoustic propagation models to determine acoustic energy levels within the ocean, and the geographical distribution and hearing of marine mammals within a selected region. We will describe the efforts to collect and furnish the three-dimensional thermohaline and sound velocity fields for use in the ESME Workbench suite of programs.

Three important constraints shaped our development of the "Water Column" module. First, other modules required a significant amount of computational expense, limiting the amount of computation which could be performed within this module. As will be explained later, this precluded the running of large hydrodynamic models concurrent with the other module calculations. Second, the coverage was required to be global, since Naval operations occur over the entire globe in both shallow and deep water. Third, since the ESME Workbench was primarily intended as a risk assessment tool to guide the future planning of Naval operations, it was not possible to use atmospheric forecast fields for forcing an ocean model. The elapsed time between running the Workbench and the planned operation (order six months) is beyond the limits of predictability for both the ocean and atmosphere. These requirements led us to consider global environmental products presently used by the operational Navy.

We will briefly describe the thermohaline and sound velocity fields that we use, consisting of Naval Research Laboratory Modular Ocean Data Assimilation System (MODAS) and historical hydrographic fields. This appears in Section 2 along with a description of test cases from the Southern California Bight and the Middle Atlantic Bight. In Section 3, we examine MODAS fields from the Southern California Bight and compare them with the mean and daily fields from the California Cooperative Fisheries Investigations (CalCOFI) data. This is essentially a deep water case. A shallow water case is considered in Section 4—the Middle Atlantic Bight—where we compare the MODAS fields with individual synoptic sections collected during the Shelfbreak PRIMER experiment as well as a recent climatology of the shelfbreak front. Limitations of the present approach are discussed in Section 5, along with suggestions for future directions. Finally, conclusions appear in Section 6.

2. Methodology and Test Cases

2.1 Methodology

In order to calculate three-dimensional sound speed fields, it is necessary to obtain reasonable temperature and salinity fields. Thermohaline fields vary on a broad range of space and time scales, so that no single model or assimilated field can resolve all the variability. However, MODAS provides a blend between existing climatologies and assimilated in situ data. MODAS utilizes the Naval Oceanographic Office Master Oceanographic Observation Data Set (MOODS) database, which contains a large number of classified sound velocity profiles which are not accessible to academic oceanographers. In addition, satellite-collected surface temperature and height fields and bathythermograph temperature profiles from around the world can be assimilated to improve the climatology data.

As discussed earlier, the massive computational needs of other ESME modules precluded our direct use of time-dependent numerical models for ocean temperature and salinity fields. Because of the large time lag between expected use of the ESME Workbench and actual fleet operations, our approach was to identify one day out of the seasonal cycle (February 1 and August 1 for winter and summer, respectively) and use individual days over five separate previous years, so that some aspects of inter-annual variability could be addressed. For the comparison with CalCOFI data, we also considered cases at various stages of the El Nino/Southern Oscillation cycle because of the long time period of this data set. We will now briefly describe the geographical setting of the two test cases, the method for producing MODAS fields, and the other data sets used for comparison.

2.2 Test Cases

We consider two ESME test regions—the Southern California Bight (SCB) and the Middle Atlantic Bight (MAB)—in our analysis. The SCB test region (Figure 1) stretches from Point Conception to San Diego, and is bounded by 32-34.5 N and 121-117 W. The California coast is dominated by the eastern boundary current system known as the California Current System (CCS) (Hickey, 1998). The CCS includes the equatorward flowing California Current, the poleward-flowing (in winter) Davidson Current, and the poleward-flowing California Undercurrent. The CCS is subject to strong wind forcing and thus considerable upwelling/downwelling. The SCB is a unique portion of the CCS; the oceanography is complicated by weaker wind forcing, narrower shelves (< 10 km), and a number of deep offshore basins (depth > 500m). The region's complex bathymetry reduces the along-shelf scale, amplitude, and seasonal variation of the wind-driven signals. The annual cycle of T/S variation in the deep water (depth > 1500m) CCS has been well established by the CalCOFI project, but there are many smaller scale shallow water processes in the SCB that have yet to be understood (Oey et. al., 2004). The CCS is also impacted by interannual El Nino/Southern Oscillation (ENSO) forcing, which can cause temperature anomalies on the order of 2-4°C in water depths 50-200m.

The MAB (Figure 2) is part of a large scale coastal current extending from the Labrador shelf down to Cape Hatteras (Loder et al., 1998). Mean currents are typically to the southwest, with inflows from the Gulf of Maine and Georges Bank contributing to inter-annual variability (Mountain, 2003). We have focused on the region bounded by 39-41 N and 70-72 W, which is the continental shelf south of southern New England. An important feature over the outer shelf is the shelfbreak front, a sharp transition in both temperature (up to 12 °C over 20 km) and salinity which occurs near the shelfbreak (Linder and Gawarkiewicz, 1998). In winter, mixing from storms homogenizes the shelf water, so that stratification over the shelf is weak or non-existent. As insolation increases in spring, the seasonal thermocline (and pycnocline) begins to develop. The cold shelf waters that are bounded by the shelfbreak front and the seasonal thermocline during this time of year are known as the "cold pool". As the thermocline deepens through the summer, the slope of the frontal isopycnals decreases. Autumn, like spring, is a transition season—synoptic sections from this time tend to resemble either a "summer" regime or a "winter" regime depending on storm activity. As is the case with many mid-latitude shelves, the changes in shelf stratification through the seasons are large and the dominant physical processes change during the seasons with the changing stratification.

The two study areas reflect two different cases in acoustic propagation. The SCB is a deep water case in which ray-tracing propagation models such as BELLHOP are effective, while the MAB is a shallow water environment necessitating the use of modal technique code such as KRAKEN. Both types of codes are implemented in the ESME Workbench (Siderius and Porter, this issue), and the two test cases reflect the two major techniques for calculating acoustic propagation. We note that sub-bottom characteristics have been provided in a separate module (Potty and Miller, this issue) for these two regions.

2.3 Modular Ocean Data Assimilation System (MODAS)

The Naval Research Laboratory MODAS (Fox et. al., 2001) is a computer program for estimating global three dimensional temperature and salinity (T/S). The program, primarily used by the U. S. Navy, consists of both static and dynamic climatology modes. In static mode, MODAS yields mean bimonthly T/S fields. Data in the upper 1500 m of the water column comes from the MOODS Data Set (Teague et al. 1990), and data below that comes from *The World Ocean Atlas 1994* (Levitus 1982, Levitus and Boyer 1994, Levitus et al. 1994). In dynamic mode, MODAS merges *in situ* measurements such as bathythermograph traces, satellite altimetry, and sea surface temperature data with the static field via optimum interpolation. The assimilation of data in dynamic mode improves on the static climatology by more accurately depicting mesoscale ocean features such as fronts and eddies. MODAS spatial resolution varies from 1.0 degree in the deep ocean to 1/8th of a degree near the coast.

2.4 Other data sources

In addition to the MODAS data fields, we have analyzed several other data sources for the two study regions. The different data sets allow us to evaluate the strengths and weaknesses of the MODAS fields for the deep and shallow water cases.

In the SCB test region (Figure 1), we analyzed repeat hydrographic sections from the CalCOFI dataset (Lynn et. al., 1982) and National Data Buoy Center (NDBC) surface buoy data. The CalCOFI project was initiated in 1949 to study the collapse of the sardine fishery. Hydrographic stations have been occupied from 1950 to the present along cross-shelf transects. The abundance of data allows the temperature and salinity to be computed for any day at any station using a polynomial and a set of harmonic coefficients. We use the sea surface temperature data from a buoy in the SCB to identify daily and annual cycles in the temperature signal for comparison with the surface temperatures from the CalCOFI fields.

In the New England MAB (Figure 2), we have used both high resolution *in situ* data from a recent field project and as well as a recent climatology of the shelfbreak front. The Shelfbreak PRIMER Experiment (Gawarkiewicz et al., 2003) consisted of a set of cruises with SeaSoar (a towed, undulating CTD) sampling. Numerous cross-shelf SeaSoar sections were obtained during 1996 (spring and summer) and early 1997 (winter; (Gawarkiewicz et al., 2001; Gawarkiewicz et al., 2003). Details of the processing of these data are described in the two cited papers. The SeaSoar sections were located near 71°W, with cross-shelf transects sampled between the 90 m and 500 m isobaths. Typical profiles were generally spaced 1 km apart in the cross-shelf direction. In addition, we have used a two-dimensional climatology (Linder and Gawarkiewicz, 1998) of the shelfbreak region. The climatology averages 90 years of hydrographic data from the area south of

Nantucket Shoals (the box delineated by 69-72 W, 39-41 N). The resulting bi-monthly mean cross-shelf T/S fields describe the seasonal evolution of the shelfbreak front. Geostrophic velocity calculations are also used to identify both the location and strength of the associated jet.

3. Comparison of Fields in the Southern California Bight

3.1 MODAS and CalCOFI mean fields

To examine the gross features which might impact sound propagation from the deep waters to the shelf, we have extracted two-dimensional cross-shelf sections from dynamic MODAS and CalCOFI harmonic fields from the southwest to northeast corners of the SCB study area. The CalCOFI section is the longest SCB section (number 90), and the MODAS section is an extract from the three-dimensional MODAS data. The sections are nearly coincident (data point locations are shown in Figure 1). The MODAS data comes from dynamic runs in midwinter (January 15, 2001) and midsummer (July 15, 2000). The CalCOFI fields were computed from harmonics (mean data) for the same days. Figure 3 shows the comparison of winter MODAS and CalCOFI data, while Figure 4 shows the summer.

In winter, the MODAS and CalCOFI fields show excellent agreement in both horizontal and vertical gradients. In summer, the fields agree well below 100m depth, but in the surface layer the CalCOFI field has a slightly lower (5-10 ms^{-1}) average sound speed. We have examined several different winter and summer fields, both synoptic CalCOFI sections and dynamic MODAS runs, and found similar excellent agreement.

3.2 National Data Buoy Center Surface Buoy Data

We have analyzed data from buoy numbers 46025 (850m isobath) and 46047 (1400m isobath). Each buoy was 13 km from a CalCOFI station. Presented in Figure 5 is the comparison of monthly mean NDBC buoy 46047 data with the CalCOFI station 90053 harmonic daily time series for year 2000. For this year the CalCOFI harmonics consistently under predicted the temperature by roughly 0.5°C. Despite this bias we still feel that the CalCOFI field represents the observed seasonal trends fairly well. Agreement was better for the shallower station (buoy # 46025 and CalCOFI 87040); the standard deviation of the monthly mean NDBC data was generally (9 months out of 12) within one standard deviation of the CalCOFI harmonic data with no bias. NDBC hourly data provides finescale resolution in time, resolving wind-driven events and the daily cycle. Given the small amplitude of these changes, however, the CalCOFI (and thus also MODAS) fields adequately capture the variability in the SCB for the purposes of the ESME Workbench.

3.3 Interannual variability

The SCB is subject to interannual variability from El Nino and La Nina events. To quanity the effect of these events on the sound speed field, we selected strong El Nino (January 1998) and La Nina (January 1999) events to examine. During these two time periods, synoptic sections were collected as part of the CalCOFI program. We generated anomaly sections by subtracting the mean (harmonic) section data from the in situ data. The resulting "warm" (El Nino) and "cool" (La Nina) plots are shown on Figure 6.

The strong El Nino event was limited to the upper 200m of the water column, and produced a maximum sound speed anomaly of 15 ms^{-1}. The La Nina event was also observed most strongly in the upper 200m, but was much weaker—the anomaly was a maximum of 5 ms^{-1}. These anomalies show that interannual variability in the form of ENSO events may strongly affect the sound speed field. Prior knowledge of inter-annual patterns such as El Nino or the North Atlantic Oscillation is useful in selecting possible scenarios. However, there are few long-term data sets with regular sampling such as CalCOFI, so that in many regions of the world one does not have the capability of selecting hydrographic data from known maximal inter-annual anomalies.

4. Comparison of Fields for the Middle Atlantic Bight

4.1 Winter Conditions

Three different data sources are used to analyze a winter (early February) cross-shelf sound velocity field in the MAB from 1997 (Figure 7). The winter environment in the MAB is characterized by a cool, fresh, generally well-mixed shelf water mass, strong vertical and cross-shelf temperature and salinity gradients at the shelfbreak (the shelfbreak front) and a warm, saline slope water mass. A comparison of three different winter cross-shelf fields appears in Figure 7—dynamic MODAS for February 1, 1997, Linder & Gawarkiewicz 1998 climatology (LG98), and synoptic Shelfbreak PRIMER SeaSoar data from February 1, 1997. LG98 and PRIMER show the steep winter front stretching from its outcrop at the shelfbreak to its termination at the surface, while MODAS shows a broad diffuse front. In the MODAS field, the sound speed difference across the frontal region is roughly 20 ms^{-1}, compared to nearly 30 ms^{-1} for both LG98 and

PRIMER. This is due to the slope temperature and salinity in MODAS being much lower than observed (Figure 8A,C). The LG98 field also underestimates the cross-shelf temperature and sound velocity gradients for the same reason.

In general, the shelfbreak front provides a severe test of the MODAS fields. Correlation scales for the front are order 8 km and 1 day (Gawarkiewicz et al., 2003), and in the absence of high resolution hydrography it is difficult to accurately capture both the cross- and alongshelf thermal and sound speed structure within the front. Underestimating the gradients affects acoustic mode coupling within the front, which will be discussed in Section 5.

4.2 Summer Conditions

In summer, insolation creates a strong seasonal thermocline and pycnocline in the upper 40m of the MAB (Figure 9). The shelfbreak front is still present, but the cross-shelf thermal and sound speed gradients in the upper 40 m of the water column are substantially reduced due to warming. However, gradients beneath the upper 40 m remain large and comparable to sub-surface gradients during the winter (Figure 8B,D). Differences in sound speed between the shelf water "cold pool" and the warmer slope waters can be almost 50 ms^{-1} across only 15 km. This is roughly comparable to a 10 °C temperature difference across the front, which is fairly common. While the MODAS field captures the vertical stratification quite well (Figure 10), the cross-shelf gradients are once again underpredicted compared to the synoptic PRIMER observations (Figure 8B,D). The cross-shelf gradients are slightly stronger within the LG98 climatology, but still are not as large as in the synoptic observations, where the temperature and salinity rose 7°C and 1.5 PSU in 5 km.

5. Discussion

We will briefly discuss limitations of the MODAS fields in the two test regions, focusing on physical processes which are not resolved in the fields. We note that high-frequency processes such as internal solitary waves are treated in a separate study (Colosi and Lynch, this issue). We will conclude by discussing possible future directions for the oceanographic inputs to the ESME Workbench.

The cross-comparison between the MODAS data and the CalCOFI data is somewhat biased because the CalCOFI data is sampled with a fairly coarse spatial resolution. Thus smaller scale eddies such as those recently studied by Oey et. al. (2004) would not be resolved in the CalCOFI data. Similarly, the structure of the wind stress curl near Point Conception gives rise to some complicated alongshelf variability for coastal upwelling (e.g. Brink and Muench, 1986). During periods of cloud and fog free conditions, the surface thermal data assimilation should provide useful information for the MODAS fields, but periods of extended fog or cloud cover would be problematical in resolving the alongshelf variability of the upwelling. In addition, adjacent to the coast temperature and sound speed fluctuations adjacent to the coast due to barotropic and baroclinic tides and diurnal sea breezes off land are not resolved (Lerczak et al., 2001, 2003).

Overall, however, the dynamic MODAS fields provide a daily varying three-dimensional sound speed field that shows good agreement with CalCOFI fields. Particularly in the deep water portions of the domain, the fields should provide good representations of seasonal and mesoscale thermal and sound speed structure.

The shallow water case in the Middle Atlantic Bight is complicated because of the presence of the shelfbreak front. Correlation scales are order 8 km and 1 day (Gawarkiewicz et al., 2003). A significant amount of data is necessary even to initialize a three-dimensional time-dependent model. However, we have seen that both dynamic MODAS as well as the LG98 climatology underestimate the thermal and sound speed gradients (Figure 8). This has a number of implications for acoustic propagation. First, mode coupling is strongly affected by the horizontal gradients within the front. Smoother fields result in less transfer of energy between modes within the frontal zone (Lynch et al., 2003). Second, meandering of the shelfbreak front also modulates the amplitude of shoreward propagating internal solitary waves (Colosi et al., 2001). While these internal waves are not present in our sound speed fields, they are present in the ocean and would lead to a variety of effects including scintillation. Third, the appreciable relative vorticity (large lateral velocity shear) within the front also traps inertial motion within the frontal zone (Kunze, 1985) and affects the internal tide. Each of these effects would tend to increase the uncertainty of the transmission loss obtained from the ESME Workbench relative to sound propagation in the real ocean at the shelfbreak.

While resolving horizontal gradients is difficult in such an energetic frontal zone, the dynamic MODAS does well in capturing the vertical gradients of temperature and sound speed over the shelf (Figure 10). For both winter conditions with weak stratification over the shelf and the highly stratified summer conditions over the shelf, the dynamic MODAS field provides an accurate vertical structure for the sound speed field, which is important for modal structures and coupling.

To estimate the variability that MODAS can resolve, we examined the standard deviation of the temperature, salinity, and sound speed of a summer climatology field. The standard deviation was a maximum at mid-depth (30-50 meters), agreeing well with PRIMER observations, but was spread equally over the shelf, shelfbreak, and slope (Figure 11A). The Shelfbreak PRIMER observations and LG98 climatology both show a strong local peak in the variance of sound speed within the front, which is surface-trapped in winter and centered beneath the seasonal pycnocline at 30 m depth in summer (Figure 11B,C). This is consistent with frontal modal structures computed from a linear stability model (Gawarkiewicz, 1991).

In the future, the use of regional time-dependent models with higher horizontal resolution (order 1 km) would be useful in resolving the coastal ocean response to synoptic wind forcing and would help resolve processes such as the baroclinic tides. Eventually, if the ESME Workbench is used in fixed locations, the assimilation of data from fixed sites such as coastal oceanographic observatories or Naval test ranges would be extremely useful in augmenting global products and models.

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Figure Captions

Figure 1: Southern California Bight study area (denoted by the box), and the location of data used in the study (triangles are CalCOFI stations, squares are MODAS stations, asterisk is NDBC buoy). The bottom topography (m) is contoured in gray.

Figure 2: Middle Atlantic Bight study area (denoted by the box), and the location of data used in the study (diamonds are MODAS stations, western line is summer PRIMER transect, eastern line is winter PRIMER transect). The bottom topography (m) is contoured in gray.

Figure 3: A winter sound speed section from the SCB study area. (a) Dynamic MODAS field from 1/15/2001 and (b) CalCOFI harmonic mean field from 1/15.

Figure 4: A summer sound speed section from the SCB study area. (a) Dynamic MODAS field from 7/15/2000 and (b) CalCOFI harmonic mean field from 7/15.

Figure 5: Comparison of NDBC monthy mean buoy SST with CalCOFI harmonic daily mean SST.

Figure 6: Synoptic CalCOFI sound speed anomaly sections from the SCB study area. (a) January 1998 El Nino minus CalCOFI mean and (b) January 1999 La Nina minus CalCOFI mean.

Figure 7: A winter sound speed section from the MAB study area. (a) Dynamic MODAS field from 2/1/1997, (b) Linder & Gawarkiewicz 1998 climatology, and (c) PRIMER 2/1/1997 synoptic section.

Figure 8: Cross-shelf (a) winter temperature, (b) summer temperature, (c) winter salinity, and (d) summer salinity gradients at 40 meters depth from PRIMER (green), Linder & Gawarkiewicz 1998 climatology (blue), and dynamic MODAS (red) fields.

Figure 9: A summer sound speed section from the MAB study area. (a) Dynamic MODAS field from 8/1/1997, (b) Linder & Gawarkiewicz 1998 climatology, and (c) PRIMER 8/1/1996 synoptic section.

Figure 10: (a) winter and (b) summer buoyancy frequency (stratification) at the 100m isobath from PRIMER (green), Linder & Gawarkiewicz 1998 climatology (blue), and dynamic MODAS (red) fields.

Figure 11: Summer MAB sound speed variance of (a) MODAS climatology, (b) Linder & Gawarkiewicz 1998 climatology, and (c) 18 cross-shelf synoptic sections with the SeaSoar.

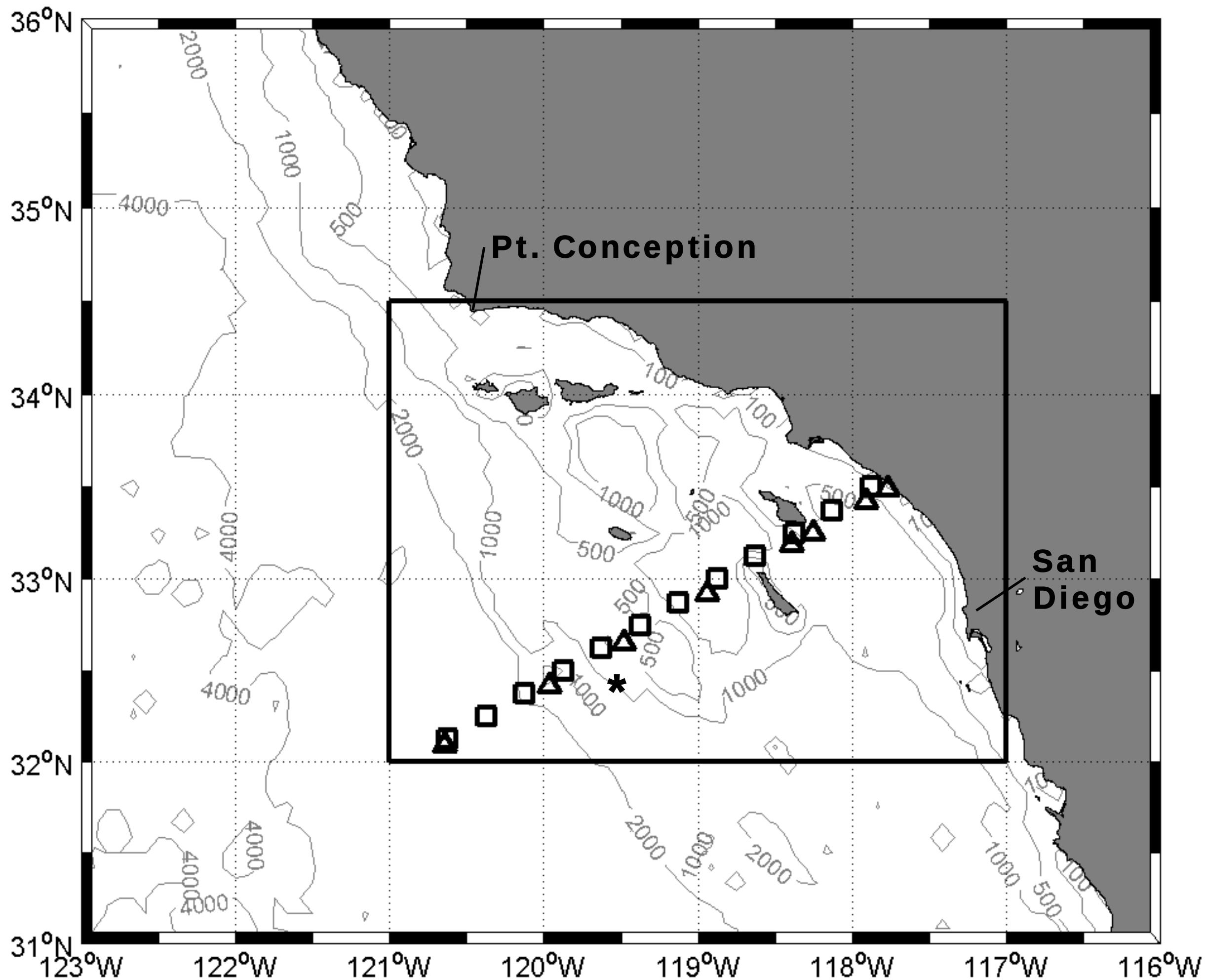
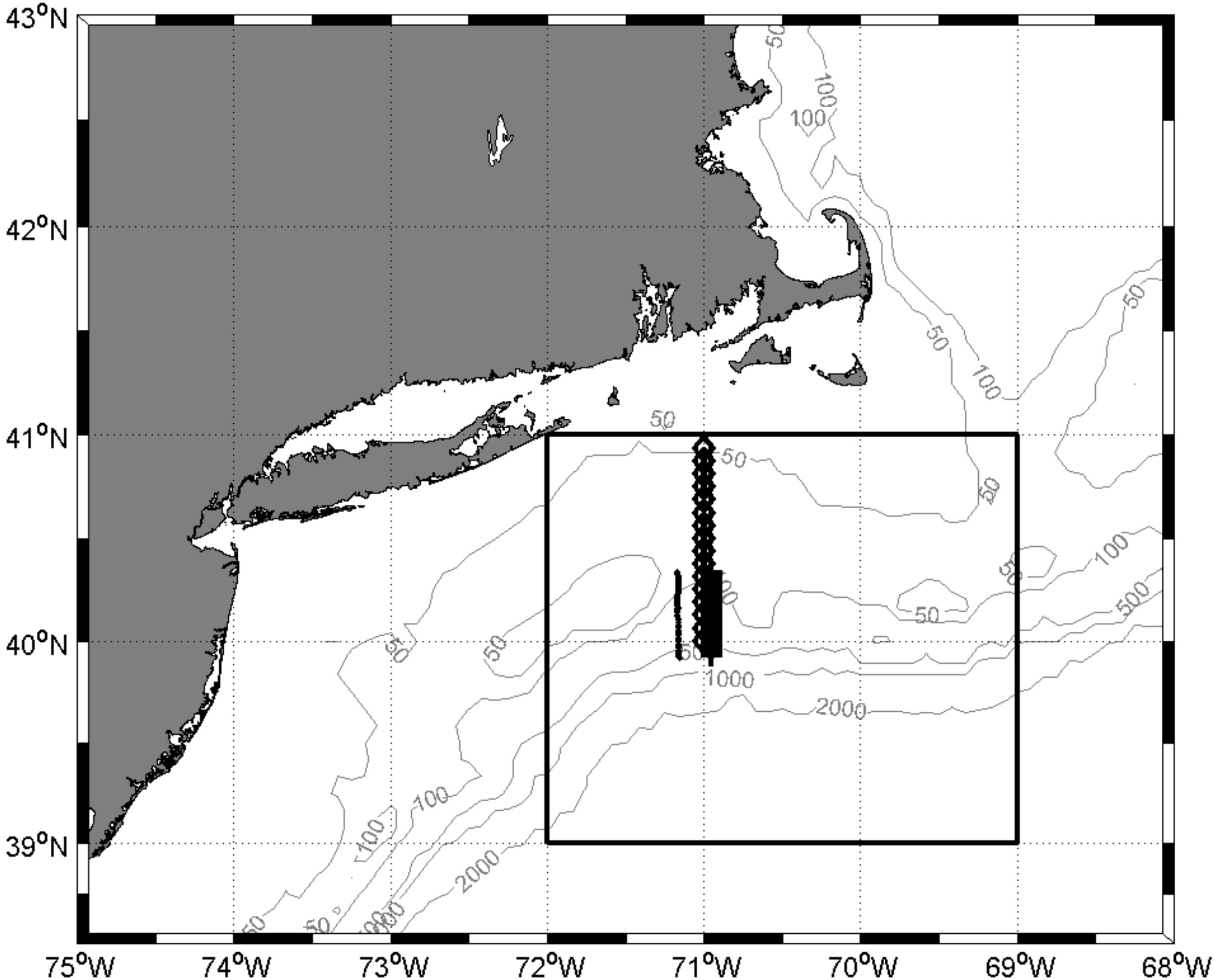
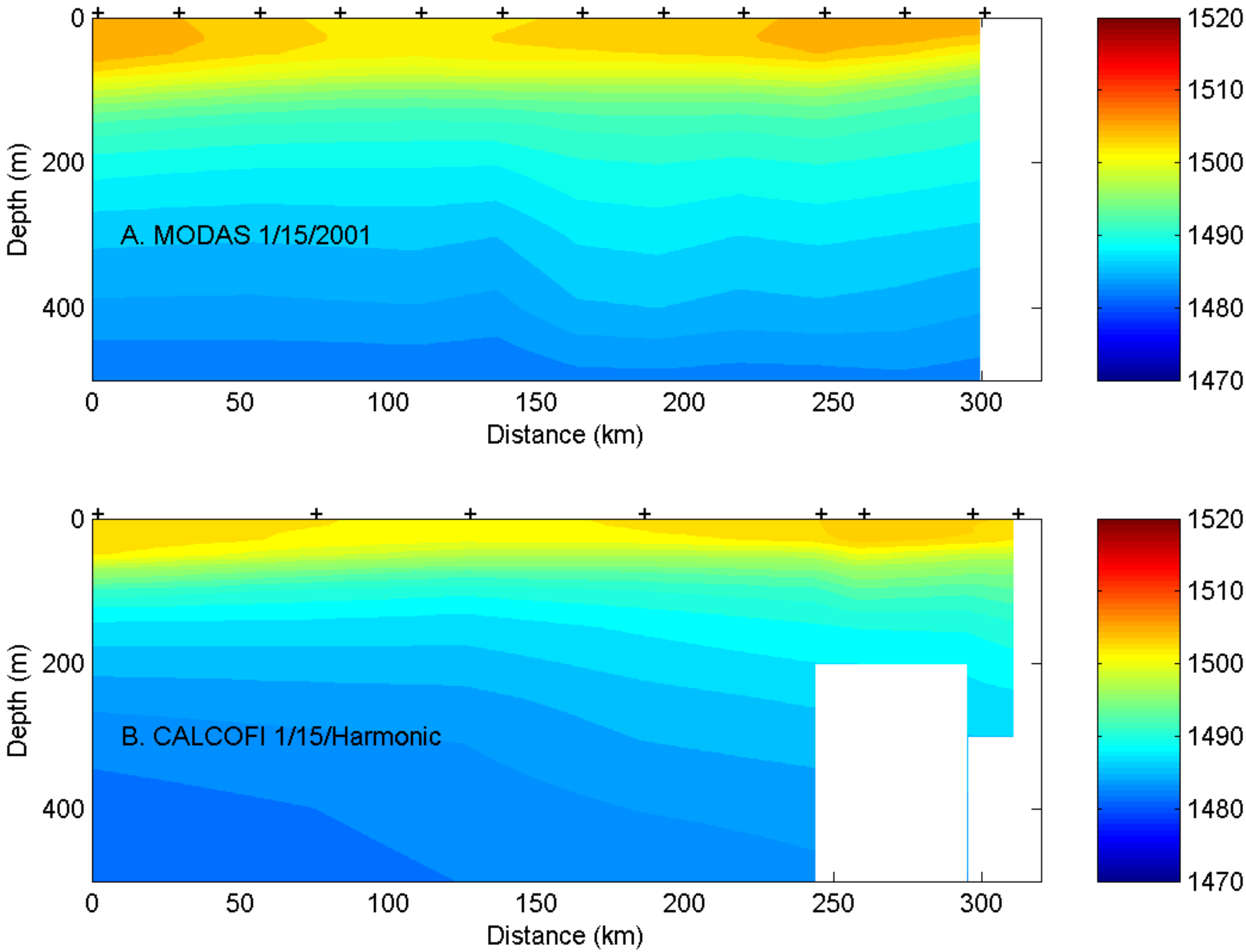

36°N
35°N
34°N
33°N
32°N
31°N
123°W
122°W
121°W
120°W
119°W
118°W
117°W
116°W
Pt. Conception
San Diego
2000
1000
500
4000
100

Figure 1



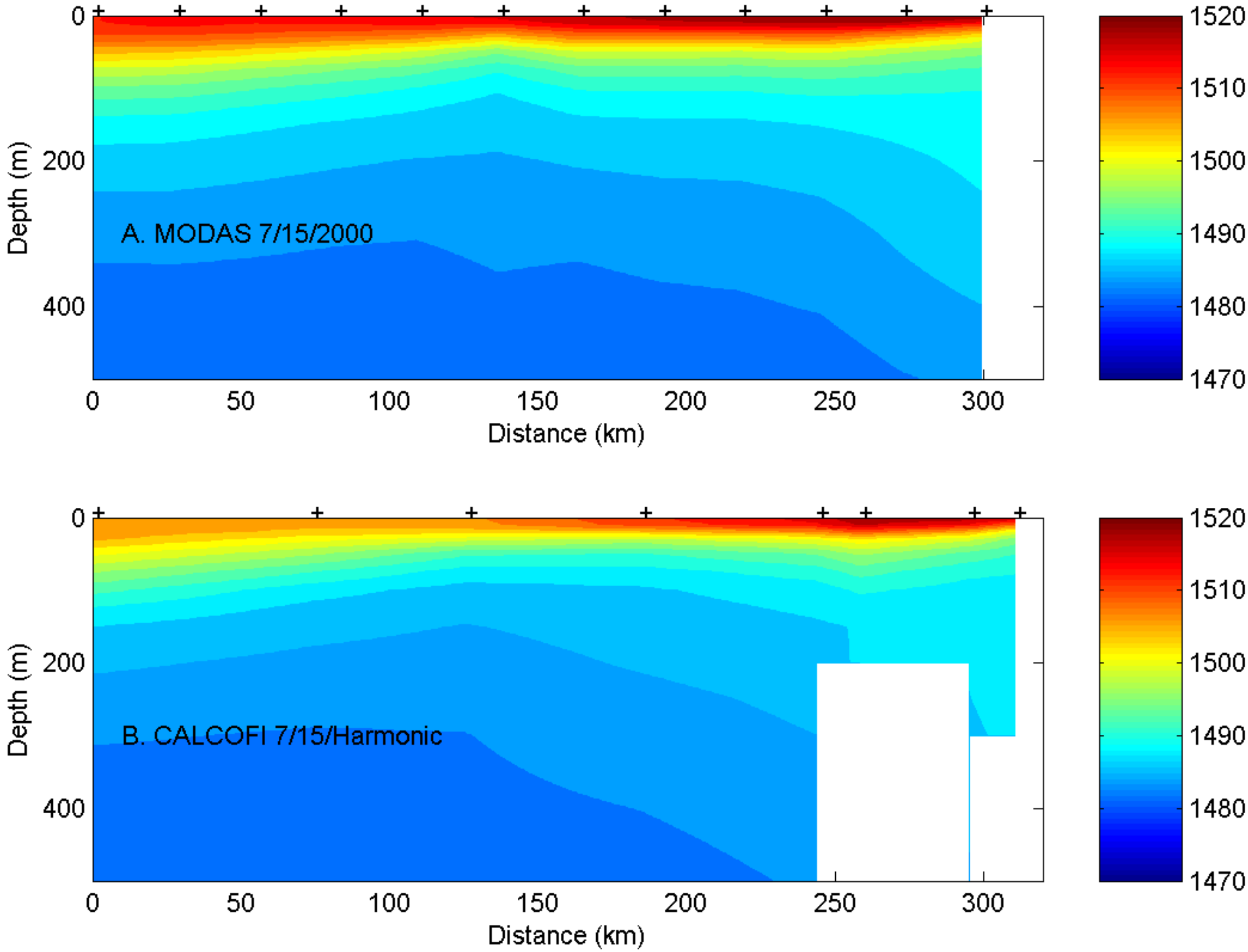
43°N
42°N
41°N
40°N
39°N
75°W
74°W
73°W
72°W
71°W
70°W
69°W
68°W
50
100
500
1000
2000

Figure 2



A. MODAS 1/15/2001
Depth (m)
0
200
400
0
50
100
150
200
250
300
Distance (km)
1520
1510
1500
1490
1480
1470
B. CALCOFI 1/15/Harmonic
Depth (m)
0
200
400
0
50
100
150
200
250
300
Distance (km)
1520
1510
1500
1490
1480
1470

Figure 3



A. MODAS 7/15/2000
Depth (m)
Distance (km)
0
200
400
0
50
100
150
200
250
300
1520
1510
1500
1490
1480
1470
B. CALCOFI 7/15/Harmonic
Depth (m)
Distance (km)
0
200
400
0
50
100
150
200
250
300
1520
1510
1500
1490
1480
1470

Figure 4

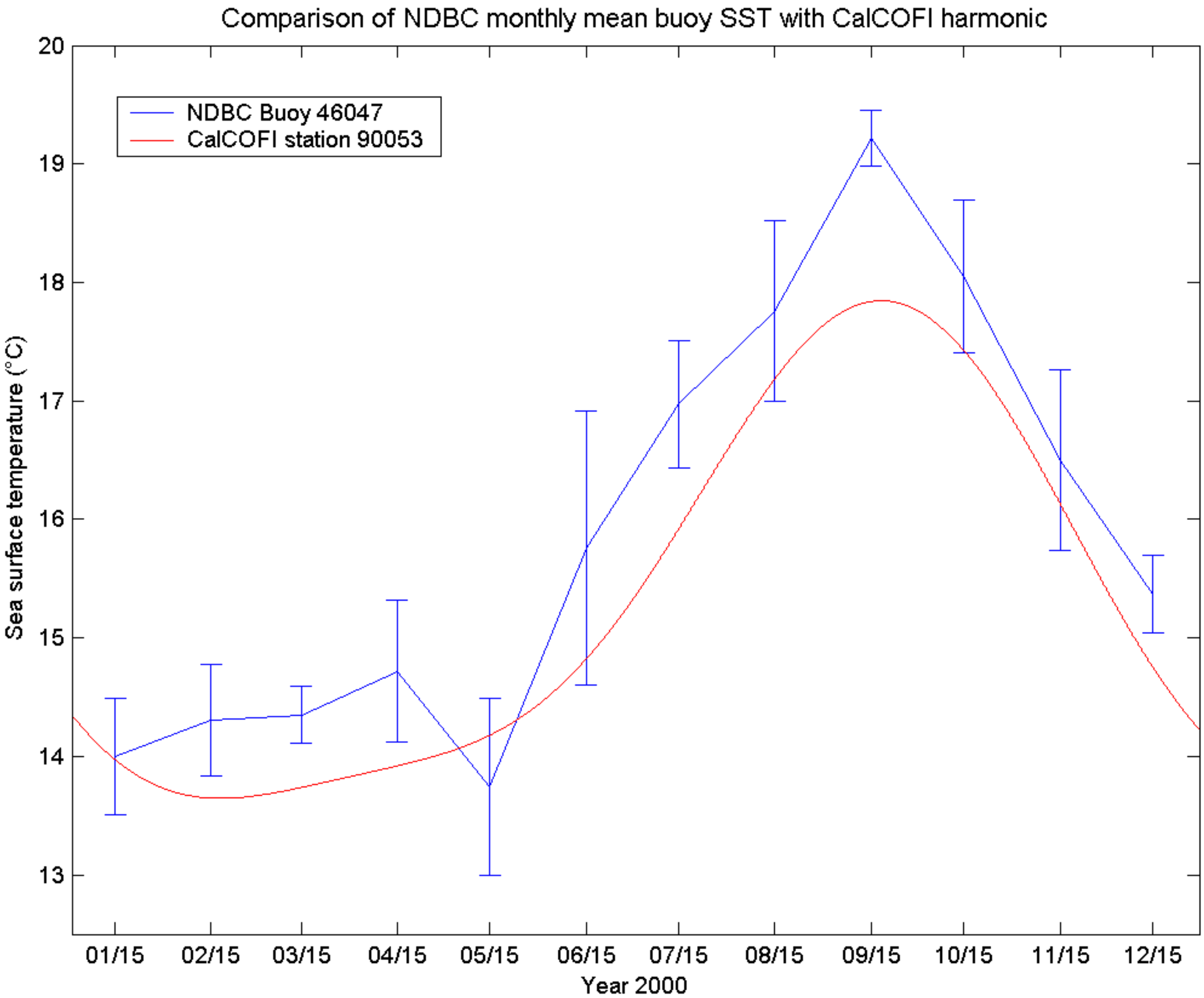
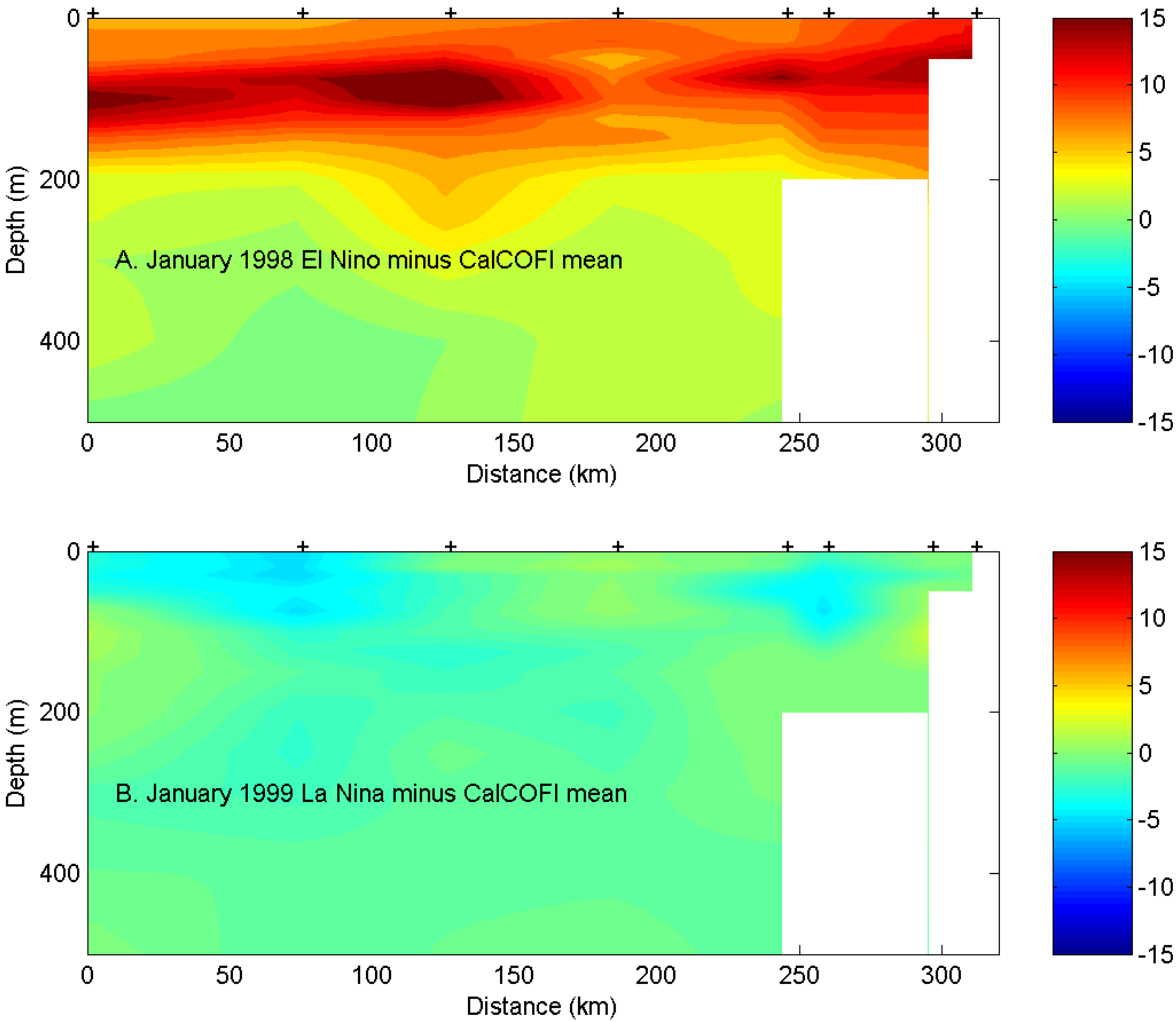
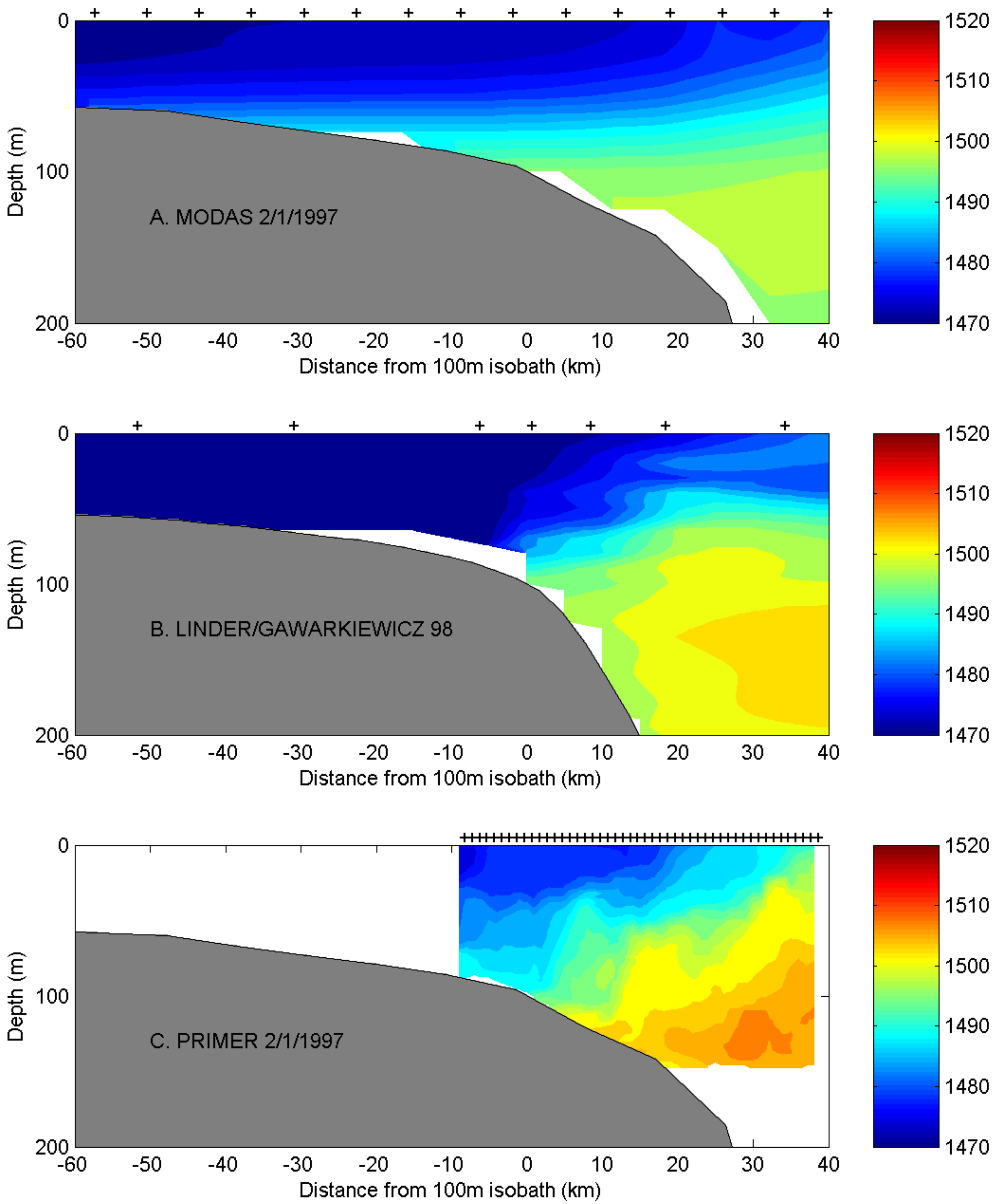

Comparison of NDBC monthly mean buoy SST with CalCOFI harmonic
NDBC Buoy 46047
CalCOFI station 90053
Sea surface temperature (°C)
20
19
18
17
16
15
14
13
01/15
02/15
03/15
04/15
05/15
06/15
07/15
08/15
09/15
10/15
11/15
12/15
Year 2000

Figure 5



0
200
400
Depth (m)
A. January 1998 El Nino minus CalCOFI mean
0
50
100
150
200
250
300
Distance (km)
15
10
5
0
-5
-10
-15
0
200
400
Depth (m)
B. January 1999 La Nina minus CalCOFI mean
0
50
100
150
200
250
300
Distance (km)
15
10
5
0
-5
-10
-15

Figure 6



A. MODAS 2/1/1997
Depth (m)
Distance from 100m isobath (km)
B. LINDER/GAWARKIEWICZ 98
C. PRIMER 2/1/1997
1520
1510
1500
1490
1480
1470

Figure 7

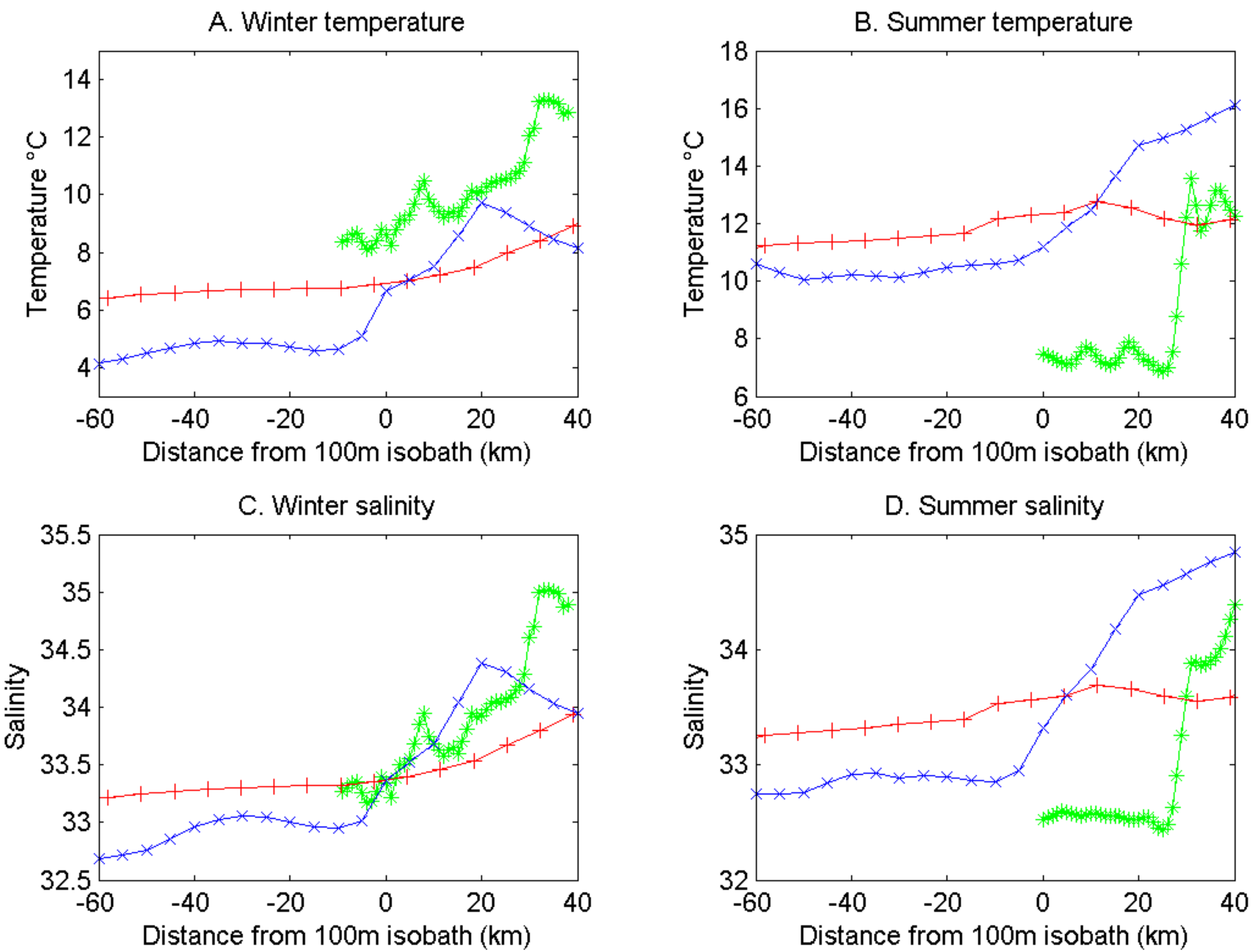

A. Winter temperature
B. Summer temperature
C. Winter salinity
D. Summer salinity
Temperature °C
Salinity
Distance from 100m isobath (km)
-60
-40
-20
0
20
40
4
6
8
10
12
14
16
18
32
32.5
33
33.5
34
34.5
35
35.5

Figure 8

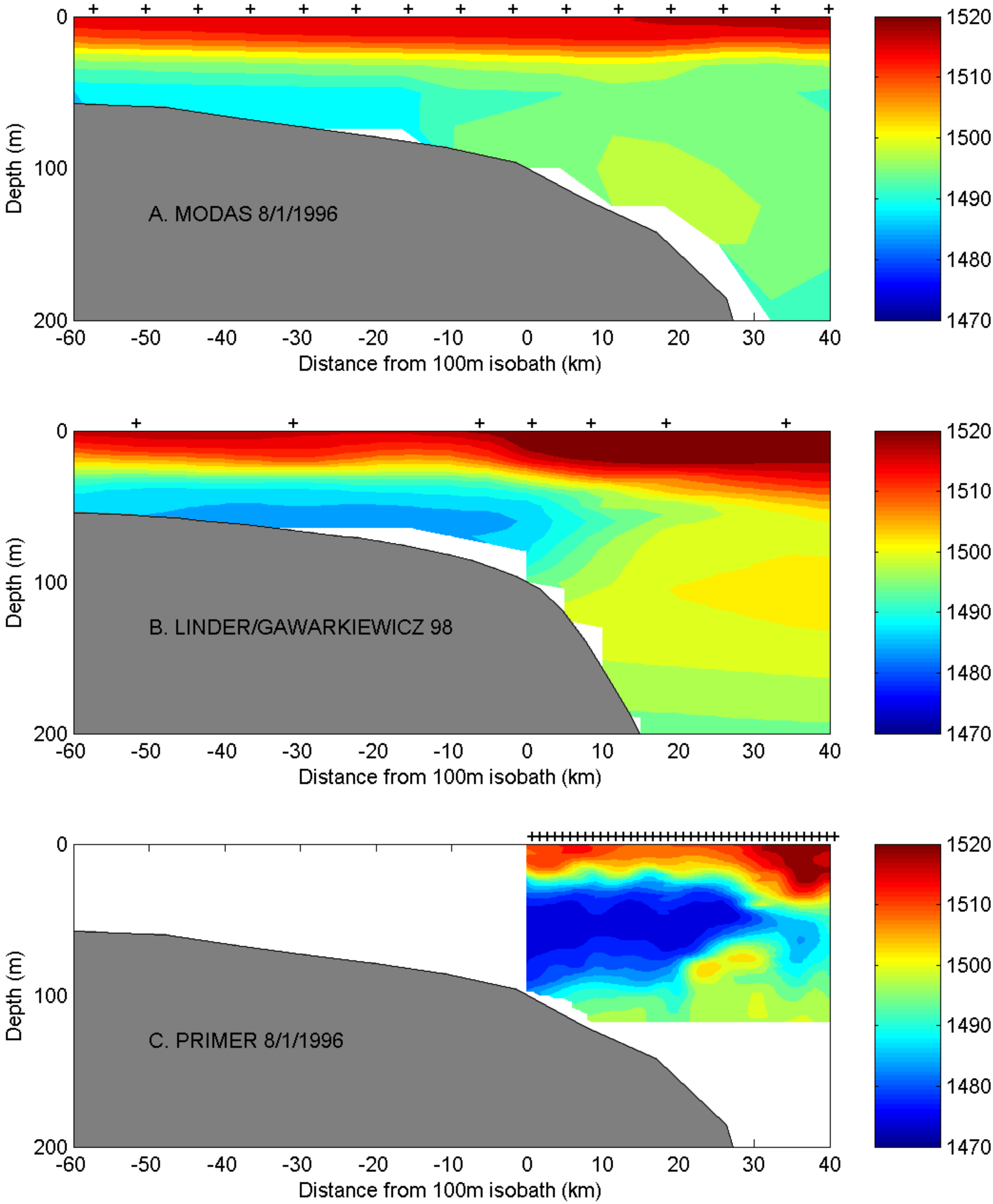

A. MODAS 8/1/1996
B. LINDER/GAWARKIEWICZ 98
C. PRIMER 8/1/1996
Depth (m)
Distance from 100m isobath (km)
0
100
200
-60
-50
-40
-30
-20
-10
0
10
20
30
40
1520
1510
1500
1490
1480
1470

Figure 9

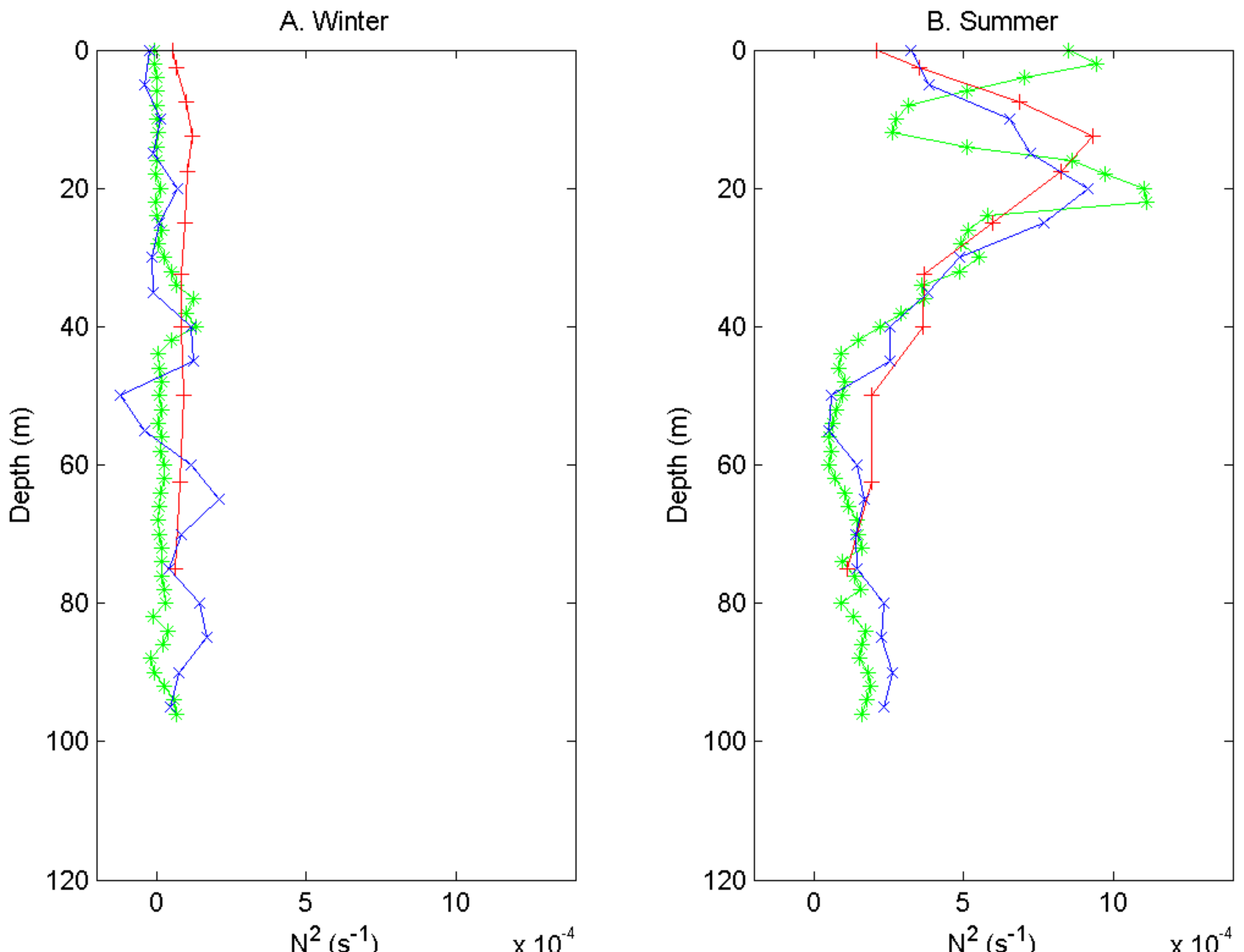


Figure 10

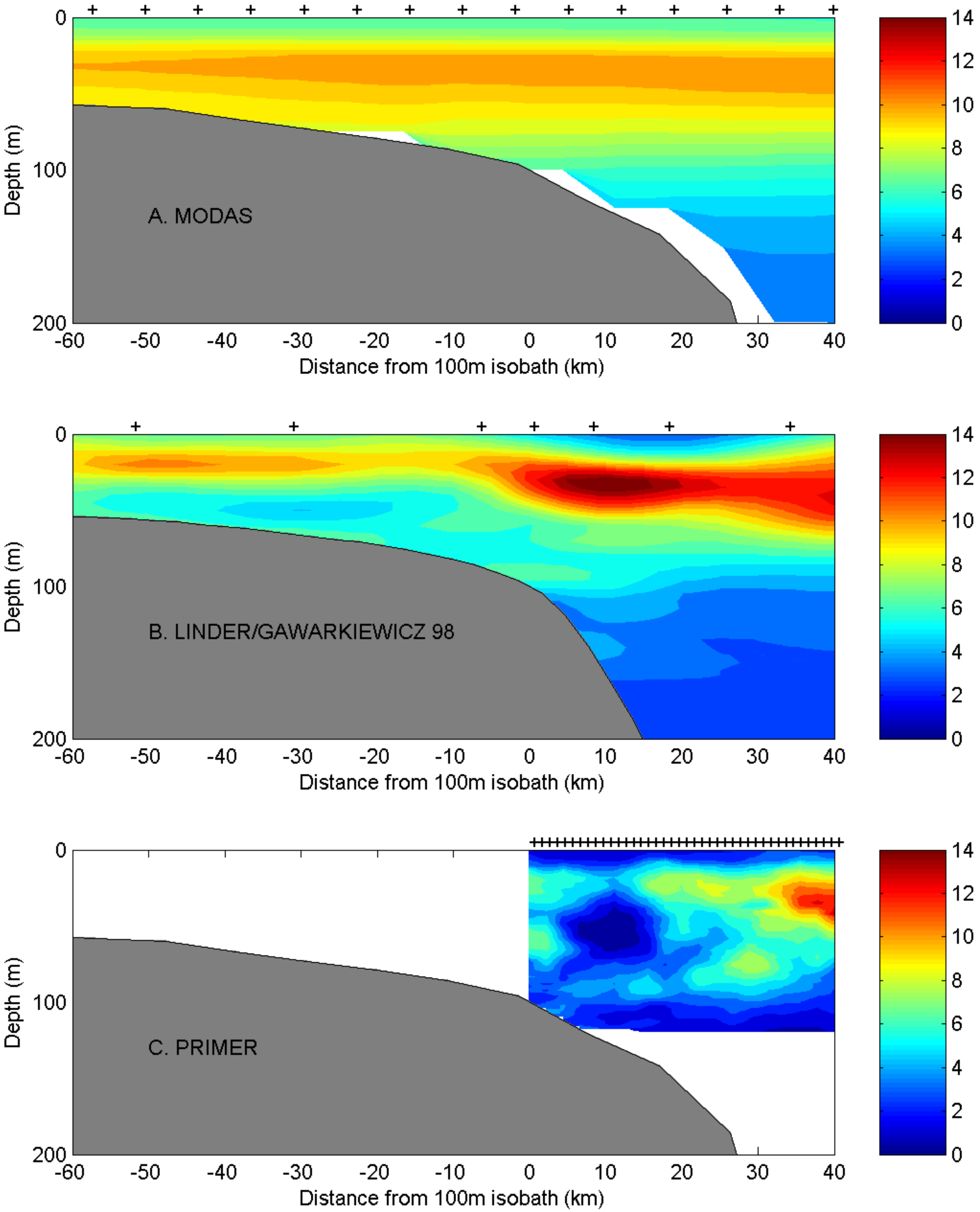

A. MODAS
B. LINDER/GAWARKIEWICZ 98
C. PRIMER
Depth (m)
Distance from 100m isobath (km)
0
100
200
-60
-50
-40
-30
-20
-10
0
10
20
30
40
0
2
4
6
8
10
12
14

Figure 11