BERING SEA THERMAL FRONTS FROM PATHFINDER DATA: SEASONAL AND INTERANNUAL VARIABILITY

I.M. Belkin, P.C. Cornillon

Graduate School of Oceanography, University of Rhode Island (URI), USA
Email: ibelkin@gso.uri.edu

Thermal fronts were studied from Pathfinder satellite SST fields, 1985-1996, obtained from AVHRR 9-km resolution twice-daily images (8,364 images in total). Fronts were detected from each image using the Cayula-Cornillon edge detection and cloud masking algorithms. Long-term (1985-1996) frontal frequencies (normalized on cloudiness) were computed for each 9-km pixel. Analysis of synoptic frontal SST maps together with long-term frequency maps revealed a number of new fronts and elucidated important features of some previously known fronts, especially with regard to their spatial structure and seasonal and interannual variability. While the coastal, upper shelf and inner shelf fronts are mostly isobathic, the mid-shelf and outer shelf (shelf-slope) fronts do not follow any specific isobath as they extend over progressively deeper waters toward the west. This finding is consistent with recent hydrographic data and numerical models (e.g. Johnson et al., 2004). Integral monthly frontal index F1 for the entire Bering Sea was computed from twice-daily synoptic (“instant”) frontal maps, January 1985 through December 1996. Over this period the F1 index increased 50% that signals rapid intensification of fronto-genetic processes.

INTRODUCTION

Hydrographic structure of the Bering Sea features several distinct thermohaline fronts observed mostly over the vast eastern shelf and along the shelf break. The fronts' importance is well documented in the SE Bering Sea, where three prominent fronts, inner, middle, and outer, were distinguished and associated with the 50, 100, and 170 m (shelf break) isobaths respectively (Figure 1; Kinder and Coachman, 1978; Smith, 1986) and at the same time they are biotopes distinct biotopes (Iverson et al., 1979; Vidal and Smith, 1986) and at the same time they are biotopes per se (Kinder et al., 1983; Hansell et al., 1989; Russell et al., 1999). The primary and secondary biological productivity is enhanced at fronts that attract fish, birds, and mammals, including whales (Nasu, 1974; Schneider, 1982; Schneider et al., 1987; Springer et al., 1996; Russell et al., 1999; Tynan et al., 2001).

Our knowledge of these fronts is, however, rudimentary, except for, perhaps, the SE Bering Sea. Much less is known, however, about fronts of the northern Bering Sea (e.g. Gawarkiewicz et al., 1994). The northern Bering Sea fronts are intimately related to the SE Bering Sea fronts since the mean along-front flows are northwestward (Kinder and Schumacher, 1981b) so that northern fronts are essentially downstream extensions of the southern fronts (e.g. Coachman, 1986). At the same time, the northern Bering Sea frontal pattern continues to the Chukchi Sea via the Bering Strait. This connection is highly important since a large amount of nutrients and phytoplankton is brought by the Bering Slope Current associated with the shelf break (shelf-slope) front to the Gulf of Anadyr, from where it is transported by the Anadyr Current to the Chirikov Basin and eventually to the Chukchi Sea (Hansell et al., 1989; Walsh et al., 1997).

Notwithstanding the overwhelming importance of fronts in physical and biological processes that evolve in the Bering Sea, a reliable climatology of fronts is absent. The fronts' association with bottom topography and relations to principal ocean-atmosphere variables (ice, air temperature, wind, runoff, and Bering Strait exchange) has not been studied. The seasonal, interannual and decadal variability of the fronts are expected to correlate with the above-mentioned environmental parameters. For example, some of the fronts are located near the maximum extent of the sea ice cover, which fluctuates widely on the interannual time scale, between “warm” and “cold” years, with minimum and maximum development of the sea ice cover respectively (Niebauer, 1998; Wyllie-Echeverria and Ohtani, 1999). Consequently, parameters of such fronts are expected to be different during “warm” and “cold” years. Possible “regime shifts” in the study area's frontal pattern and its characteristics might be linked to the known regime shifts in the North Pacific (Graham, 1994; Polovina et al., 1994; Niebauer, 1998; Brodeur et al., 1999; Benson and Trites, 2002; Hunt and Stabeno, 2002; Luchin et al., 2002; Overland and Stabeno, 2004).
Satellite observations of surface fronts in high-latitude seas are hampered by seasonal ice cover and persistent cloudiness. Nonetheless, several studies have demonstrated the great potential of remote sensing, including infrared imagery (e.g., Belkin and Cornillon, 2003; Belkin et al., 2003), in observing surface manifestations of oceanic phenomena (fronts, eddies, upwelling etc.) such as the Warm Coastal Current in the Chukchi Sea (Ahlénás and Garrison, 1984), coastal upwelling off St. Lawrence and St. Matthew islands in the Bering Sea (Saitoh et al., 1998), the St. Lawrence Island Polynya (SLIP; Lynch et al., 1997), and spring blooming in the Bering Sea (Maynard and Clark, 1987; Walsh et al., 1997).

In this paper we report on an exploratory study of the Bering Sea fronts from satellite SST data. The approach and data used in this study are introduced in Section 2, followed by a description of seasonal variability of frontal pattern in Section 3 that contains a complete set of frontal maps and frontal paths for the Bering Sea based on a 12-year satellite data set. These maps and digital frontal paths, together with Matlab plotting programs, are available from the authors upon request and can also be downloaded from our research Web page: http://www.po.gso.uri.edu/~belkin/index.html. Seasonal and interannual variability of frontal activity integrated over the entire Bering Sea is characterized by an integral frontal index (Section 4). Principal results of the study are summarized in Section 5. This paper presents a provisional description of time-space variability of the Bering Sea thermal fronts. A detailed analysis will be published elsewhere.

METHOD AND DATA

Our approach is based on histogram analysis of satellite imagery. Since every front separates two relatively uniform water bodies, frequency histograms of any oceanographic characteristic, e.g. SST, in the vicinity of a front should have two frequency modes that correspond to two water masses separated by the front, while the latter corresponds to a frequency minimum between the modes. Front detection and tracking is performed at three levels: window, image and sequence of overlapping images. The edge (front) detection algorithm uses all pixel-based SST values within each window to compute a SST frequency histogram for the given window. For each window that contains a front, the corresponding SST histogram would have a frequency minimum identified with the front.

This basic idea has been implemented by Cayula and Cornillon (1992, 1995, 1996) and Ullman and Cornillon (1999, 2000, 2001); the reader is referred to these works for pertinent details. Fronts were derived from the Pathfinder SST fields (Vazquez et al., 1998) for the period 1985–1996. These fields were obtained from the Advanced Very High Resolution Radiometer (AVHRR) Global Area Coverage data stream (two 9.28 km resolution fields per day) and are available from the Jet Propulsion Laboratory. SST fronts were obtained from the cloud-masked SST fields with the multi-image edge detection algorithm (Cayula and Cornillon, 1996; Ullman and Cornillon, 1999, 2000, 2001). The cloud masking and front detection algorithms were applied to each of the 8,364 SST images in the 12-year data set. To derive a long-term (climatological) seasonal frontal pattern, frontal data were aggregated monthly, e.g., the long-term January map is based on 12 Januarys taken together, from January 1985 through January 1996. Two basic types of frontal maps are used in the analysis: long-term frequency maps and quasi-synoptic composite maps. The long-term frequency maps show the pixel-based frequency $F$ of fronts normalized on cloudiness: For each pixel, $F = N/C$, where $N$ is the number of times the given pixel contained a front, and $C$ is the number of times the pixel was cloud-free. Thus, frequency maps (shown in Section 3) are best suited for displaying most stable fronts. At the same time, frontal frequency maps underline some fronts associated with time-varying meandering currents. In such cases quasi-synoptic composite maps (not shown) are most useful since they present synoptic snapshots of “instant” fronts detected in individual SST images within a given time frame (e.g., week, month, or season), without any averaging or smoothing. Frontal composite maps thus allow one to detect most unstable fronts that are not conspicuous in the frontal frequency maps. Finally, long-term (1985-1996) monthly frontal schematics are produced (shown in Section 3) based largely on frontal frequency maps and, in rare cases and only locally, on quasi-synoptic frontal composite maps.

SEASONAL VARIABILITY OF FRONTAL PATTERN

The Bering Sea frontal pattern changes dramatically as the season progresses (Figure 2). Since the Bering Sea has significant ice cover from December through April (e.g., Gloersen et al., 1992), SST fronts can only be unambiguously identified from May through November. These fronts appear as high frequency bands (“hot spots” of yellow, orange or red) in long-term monthly frontal frequency maps (Figures 3 to 9, top). These high frequency bands have been digitized to facilitate the ensuing description of frontal variability and comparison of frontal paths (Figures 3 to 9, bottom). In May, several fronts (##1-9) extend from Bristol Bay westward to Cape Navarin. A major front is located over shallow depths (~50 m) in Bristol Bay, where it can be classified as the mid-shelf front; the same front, however, continues over the outer shelf (100-200 m depth) farther west. Thus the front location does not correspond to any of the major fronts (inner, middle, and outer) identified by earlier researchers since these fronts were believed to be isobathic (e.g., Coachman et al., 1980; Coachman, 1986). The front configuration is however remarkably similar to the sea ice cover's edge in May; the edge is
located about 1° of latitude to the north of the front. The front thus appears to be related to the marginal ice zone processes (Muench and Schumacher, 1985). Shallow fronts, tentatively identified as inner or upper shelf and coastal fronts, are observed off Alaskan coast, namely #10 off Kuskokwim Bay (persists through November) and #11 in Shpanberg Strait and off Norton Sound (disappears by October). Shallow fronts (#12-13) are observed off Anadyr Gulf; front #13 persists through November. Shelf-slope fronts #14-15 are associated with the Kamchatka Current that flows along the shelf break off Koryak Coast and off Karaginsky and Olyutorsky bays. Front #16 hugs Komandorsky Islands. In June, shallow fronts persist off Kuskokwim Bay, Norton Sound, and Anadyr Gulf (#4-6). The shelf-slope front (#2) is markedly non-isobathic. In July, the Norton Sound-Shpanberg Strait Front (#2) reaches south to Nunivak Island. Three shallow fronts (#1, 6, and 7, or the coastal, upper shelf and inner shelf fronts, respectively) emerge in Bristol Bay. In August, the entire Alaskan coast is rimmed by coastal and upper shelf fronts (#1, 2, 7, and 8). A seasonal shelf-slope (shelf break) front (#4) develops off Koryak Coast that persists through November. In September, the Norton Sound-Shpanberg Strait Front (#2) begins its retreat to the north, whereas the Kuskokwim-Bristol Bays front remains intact. The Bering Strait front (#3) connects the Bering Sea to the Chukchi Sea. In October, the inner shelf front (#1) appears along 50-m isobath while the mid-shelf front (#2) extends along 70-80m isobath. Both fronts persist through November (#2 and 3 respectively), when they are joined by a 30-m isobath upper shelf front (#6) and shallow coastal fronts off Kuskokwim Bay (#8) and north of Nunivak Island (#9). Two fronts in the northwest correspond to the northward Anadyr Current (#5) and southward Kamchatka Current (#4), both being branches of the Bering Slope Current.

Figure 2 shows all long-term monthly frontal paths combined. It reveals the most persistent fronts, namely (from west to east), the Koryak, Anadyr, and Bering Strait fronts off Siberia’s coast; the Norton Sound-Shpanberg Strait front and Kuskokwim-Bristol bays front off Alaska’s coast; the inner shelf front along the 50-m isobath, and the mid-shelf front approximately along the 70-80 m isobath. Other fronts are notably less persistent, especially the shelf-slope (shelf break) front commonly believed to be associated with the 170 m isobath. The main reason for the shelf-slope front instability is likely the very rugged bottom relief of the shelf break/continental slope areas. Indeed, this area is incised by a series of huge submarine canyons (Figure 1) that belong to the largest canyons in the World Oceans, namely Zhemchug Canyon (5,800 km³, canyon volume), Navarin Canyon (5,400 km³), Pervenets Canyon (1,700 km³) and Pribilof Canyon (1,300 km³) that dwarf the largest NW Atlantic slope incision, Hudson Canyon (300 km³) (Karl et al., 1996, Table 17-2).

SEASONAL AND INTERANNUAL VARIABILITY OF FRONTAL ACTIVITY REVEALED BY INTEGRAL FRONTAL INDEX

In order to characterize spatially-integrated frontal activity within our study area, the simplest possible frontal index has been calculated. This index, F1, is a sum of frontal appearances within a study area. In our case, F1 is the total number of times each 9-km x 9-km pixel contained an SST front. Since we focus on seasonal and interannual variability of fronts, daily values of F1 were integrated over respective months. The resulting monthly index F1 reveals an extremely strong seasonal variability that dominates interannual variations over a 12-year study period, 1985-1996 (Figure 10).

To separate seasonal and interannual variability, this time series has been time-averaged monthly and annually. Individual annual cycles (Figure 11) display a strong year-to-year variability that modulates a unimodal seasonal cycle, which typically peaks in mid-summer. This seasonal pattern becomes apparent after long-term monthly averaging (Figure 12).

Long-term variability is revealed by annual averaging (Figure 13) that makes obvious an ascending trend of F1, which increased approximately 50% from 1985 through 1996.

SUMMARY

Five types of SST fronts have been provisionally identified over the Eastern Bering Shelf and Slope, loosely associated with certain depths or rather depth ranges, namely (1) outer shelf front or shelf-slope front (150 m and deeper); (2) mid-shelf front (70-80 m); (3) inner shelf front (40-60 m); (4) upper shelf fronts (25-35 m) and (5) coastal fronts (10-20m). The Norton Sound-Shpanberg Strait front, Kuskokwim front and Bristol Bay front are seasonally persistent. In the western Bering Sea, the Koryak-Kamchatka front and especially Anadyr Gulf front are most robust. The entire frontal pattern changes notably on the monthly scale. Most fronts are not strictly isobathic. The inner shelf, upper shelf and coastal fronts are approximately isobathic, whereas the mid-shelf front and especially the shelf-slope (outer shelf) front do not follow any specific isobath as they extend over progressively deeper waters toward the west. The integral monthly frontal index F1 for the entire Bering Sea exhibits an extremely strong seasonal variability, with a ten-fold increase from spring to summer and an abrupt drop in September. The annual mean monthly frontal index F1 increased approximately 50% from 1985 through 1996, apparently signaling a concomitant intensification of some yet unidentified fronto-genetic processes.
Figure 1. Base map of the Bering Sea. Bottom relief is shown by three selected isobaths (blue lines), 50, 100 and 200 m. Acronyms: BS, Bering Strait; NI, Nunivak Island; PI, Pribylol Island; SLI, St. Lawrence Island; SMI, St. Matthew Island; SS, Shpanberg Strait. Red polygon shows the frontal index F1 computation area.

Figure 2. Seasonal variability of SST fronts, May-November, 1985-1996.
Figure 3. SST fronts in May: long-term frequency (top), and frontal schematic (bottom)
Figure 4. SST fronts in June: long-term frequency (top), and frontal schematic (bottom)
Figure 5. SST fronts in July: long-term frequency (top), and frontal schematic (bottom)
Figure 6. SST fronts in August: long-term frequency (top), and frontal schematic (bottom)
Figure 7. SST fronts in September: long-term frequency (top), and frontal schematic (bottom)
Figure 8. SST fronts in October: long-term frequency (top), and frontal schematic (bottom)
Figure 9. SST fronts in November: long-term frequency (top), and frontal schematic (bottom)
Figure 10. Temporal variability of the monthly frontal index F1

Figure 11. Annual cycles of the monthly frontal index F1
Figure 12. Mean seasonal cycle and its standard deviation (SD) of the monthly frontal index F1, 1985-1996

Figure 13. Interannual variability of the mean monthly frontal index F1
ACKNOWLEDGMENTS

Comments by Steve Okkonen and two anonymous reviewers helped us improve the manuscript. This study was funded by NASA through grants NAG 53736 and NAG 512741 and by NOAA through the Cooperative Institute for Arctic Research under NOAA Cooperative Agreement No. NA17RJ1224. The support of both agencies is greatly appreciated.

REFERENCES


