Estimating the Lower Temperature Limit of Bottlenose Dolphins Along the North Carolina Coast

by

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Abstract

During winter, the coastal ecotype of bottlenose dolphins are at the northern limit of their range off the coast of North Carolina. In this study, the distribution of coastal bottlenose dolphins in North Carolina was evaluated in response to variation in sea surface temperature to determine whether the distribution of dolphins was limited directly or indirectly by winter temperature minima. Observations of dolphin distribution were obtained from monthly aerial surveys conducted along the North Carolina coast during February 2000 through July 2001. Sea surface temperatures were obtained for each survey from NOAA's Pathfinder satellite, using PO.DAAC Ocean ESIP Tool (POET). Where necessary, the sea surface temperature data was interpolated (krigged) over areas of cloud cover. The northern latitudinal and lower temperature distribution was determined for each survey. During winter months bottlenose dolphins were not distributed throughout their known range of 10-32 ˚C. Dolphins may be limited directly by temperature, due to the limits of their thermal neutral zone, or indirectly by temperature, through distribution of their prey. To determine how temperature is affecting dolphin distribution in the Western North Atlantic, future research should focus on determining the thermal neutral zone of dolphins in this region. In addition, it would be useful to build a model including other dynamic factors that may affect dolphin distribution. Although results suggest that more research is necessary, there is potential for using results from this type of analysis for management.

Key words: bottlenose dolphin; *Tursiops truncatus*; coastal; strategic stocks; distribution; sea surface temperature; North Carolina; Western North Atlantic; spatial analysis; geographical information systems.

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During winter, the coastal ecotype of bottlenose dolphins are at the northern limit of their range off the coast of North Carolina. In this study, the distribution of coastal bottlenose dolphins in North Carolina was evaluated in response to variation in sea surface temperature to determine whether the distribution of dolphins was limited directly or indirectly by winter temperature minima. Observations of dolphin distribution were obtained from monthly aerial surveys conducted along the North Carolina coast during February 2000 through July 2001. Sea surface temperatures were obtained for each survey from NOAA's Pathfinder satellite, using PO.DAAC Ocean ESIP Tool (POET). Where necessary, the sea surface temperature data was interpolated (krigged) over areas of cloud cover. The northern latitudinal and lower temperature distribution was determined for each survey. During winter months bottlenose dolphins were not distributed throughout their known range of 10-32 ˚C. All dolphins were observed in water warmer than 12.4 ˚C, and 95% of dolphins were observed in water warmer than 13.5 ˚C. Dolphins may be limited directly by temperature, due to the limits of their thermal neutral zone, or indirectly by temperature, through distribution of their prey. To determine how temperature is affecting dolphin distribution in the Western North Atlantic, future research should focus on determining the thermal neutral zone of dolphins in this region. In addition, it would be useful to build a model including other dynamic factors that may affect dolphin distribution. Although results suggest that more research is necessary, there is potential for using results from this type of analysis for management.

Introduction

Bottlenose dolphins (*Tursiops truncatus*) are the most well-studied of all cetaceans (Conner et al., 2000). The species complex inhabits tropical and temperate waters worldwide, in both coastal and offshore waters (Kenney, 1990). In the U.S. bottlenose dolphins are protected under the Marine Mammal Protection Act (MMPA) and managed by NOAA Fisheries.

The range of bottlenose dolphins is believed to be temperature related, either directly or indirectly, such as through distribution of prey (Wells and Scott, 1981). Off the coasts of North America, the species inhabits waters ranging from 10-32 ˚C (Wells and Scott, 1981). Williams et al. (2001) estimated that captive bottlenose dolphins acclimated to 15.4 ˚C had a lower critical temperature (T_{LC}) equal to 5.9 ˚C and an upper critical temperature (T_{UC}) equal to 23 ˚C. This range comprises their thermal neutral zone (TNZ), or temperature range in which their metabolic rate is not elevated to cool or warm the animals. The thermal neutral zone of bottlenose dolphins in the Western North Atlantic is unknown.

Coastal bottlenose dolphins in North Carolina inhabit the northern limit of the species range in the Western North Atlantic during winter (Wells and Scott, 1981). During summer months they travel as far north as Long Island, New York, but during winter months their northern range is limited to the North Carolina/Virginia border (Waring, Quintal, and Garrison, 2002).

Current research defines seven management units for the Western North Atlantic Coastal Bottlenose Dolphin Stock, although it is likely that more than seven exist (Waring, Quintal, and Garrison, 2002). This stock complex is comprised of the Central Florida, Northern Florida, Georgia, South Carolina, Southern North Carolina, Northern North Carolina, and Northern Migratory management units (Waring, Quintal, and Garrison, 2002). According to NOAA Fisheries, there are two strategic stocks—Summer Northern North Carolina and Winter Northern North Carolina/Northern Migratory Mixed management units. A strategic stock is one in which human-induced fishery-related mortality exceeds potential biological removal levels (Waring, Quintal, and Garrison, 2002). Research on the distribution of these stocks is a priority to provide more efficient protection and management.

In this study, Geographic Information Systems (GIS) were used to analyze the distribution of coastal bottlenose dolphins with respect to sea surface temperature. Currently, there is not much literature regarding this subject, although studies have been done analyzing sea turtle distribution in response to sea surface temperature (Coles and Musick, 2000). The aerial surveys used in this analysis were originally designed for the purpose of observing right whales, but the data set included all marine mammals sighted. This work is a pilot study for OBIS-SEAMAP (Ocean Biogeographic Information System - Spatial Ecological Analysis of Megavertebrate Populations), to demonstrate the type of research that can be performed when such data are made available for analysis. OBIS-SEAMAP is an online database for marine mammals, marine birds, and marine sea turtle data housed at Duke University (http://seamap.env.duke.edu).

The purpose of the present study was to estimate the winter limits of coastal bottlenose dolphins in the Western North Atlantic. The specific objective was to determine the winter northern latitudinal distribution limit and the winter minimum sea surface temperature limit, by testing the null hypothesis that bottlenose dolphins would be distributed throughout their known temperature range of 10-32 ˚C. Many dynamic factors contribute to bottlenose dolphin distribution, such as prey distribution, predator distribution, and distance from temperature fronts, but sea surface temperature was chosen because it is readily accessible via remote sensing and has the potential to be used in management.

Methods

Observational Data

Surveys were conducted in either single or twin-engine, Cessna 182 over-wing plane. These aircraft designs provided high wing visibility, easy maneuverability, and retractable landing gear. One aviation GPS was used by the pilot to navigate tracklines, while sighting positions were collected and stored on a Garmin 12XL GPS with an external antenna. All sighting data were also recorded on data sheets in real time. Sighting locations were downloaded to a computer following surveys with associated sighting data, effort data, and photography information. Standard event codes were used to differentiate between sighting events and effort events. Two observers sat in the rear seat monitoring sightings separately on the left and right side of the plane. A recorder sat in the co-pilots seat and each position in the plane was rotated at the noon break so that observers were never on effort for more than three hours at a time. The recorder collected data on sightings, cloud cover, visibility, Beaufort Sea State (BSS), and glare for each side of the plane on each trackline throughout the survey. All observers had at least one year of shipboard and/or aerial survey experience.

When an animal or group of animals was sighted, time and location on the trackline, species, and the maximum, minimum, and best estimate of the number of animals sighted were recorded. Sightings cues, including splash, fin, body, fluke, or blow were used as the initial observation. Observers used 7x50 Fujinon binoculars to confirm sightings. Small groups of dolphins on the trackline were generally identified and counted while remaining on effort. If large whales, or groups of dolphins, off the trackline were encountered, the track was broken and the plane circled over the sighting, collecting specific sighting locations and identification photographs. Group size was discussed and resolved to determine the best estimate. After identifying the species, the plane returned to the trackline at the position where it had left and continued the survey.

Surveys were conducted along the North Carolina coast from the South Carolina border north to the Virginia border (See Table 1 for flight dates). The plane flew at 230m and at 100 kts at a distance of approximately 500m parallel to the shoreline. The plane flew northerly along the coast so that the rear observer monitored from the trackline to the shore while the front seat recorder/observer monitored from the trackline offshore. The resulting study area consisted of a 1km strip along the entire North Carolina coast. These surveys were occasionally broken to transit around regions of military activities that required restricted airspace. Due to un-planned military activity and occasional weather limitations, some surveys were terminated before they were completed. Only complete surveys, defined as one full survey of the entire North Carolina coast in one day, were used in this analysis.

Data were edited and sorted in Excel and then transferred and stored in an Access database (Microsoft Corporation). All GIS analysis was conducted using Arc/Info (ESRI Version 8.0.1). Shapefiles of observation points were created for each survey, by importing data tables from Access. Grids of the observation points were created, with cell size 0.10 decimal degrees (DD), by summing the number of animals sighted within each grid cell using neighborhood statistics. Grid cells in which no sightings occurred received a value of zero. Only those observation grid cells, which intersected with the study area, were used in the analysis.

Sea Surface Temperature Data

AVHRR Oceans Pathfinder sea surface temperature data were obtained through the online PO.DAAC Ocean ESIP Tool (POET) at the Physical Oceanography Distributed Active Archive Center (PO.DAAC), NASA Jet Propulsion Laboratory, Pasadena, CA. (http://podaac.jpl.nasa.gov/poet). Raw data were processed by PO.DAAC at level 4, which includes model correction and cloud masking, and has an accuracy of 0.3-0.5 ˚C. An 8-day composite, daytime, 9km resolution grid, covering the geographic region from –79W to –75W and 33N to 37N, was downloaded for each survey. Analysis was conducted using an 8-day composite image, due to the inconsistency in cloud cover quality of daily images.

Sea surface temperature grids were converted to point coverages and a random subset of points in each coverage was used to create a semivariogram in ArcMap (version 8.0.1). The sea surface temperature was interpolated into a grid (0.10DD cell size), by ordinary kriging method, using model and parameters determined from the semivariogram analysis. Kriging is considered an optimal method of spatial interpolation (Cressie, 1993). It is a form of weighted local averaging and each interpolated value is unbiased and has an associated error value (Mason et al., 1994). Only those sea surface temperature grid cells, which intersected with the study area, were used in the analysis.

Analysis

All layers assumed a Geographic NAD 1983 projection, and therefore had units of decimal degrees (DD). To investigate the spatial relationships between bottlenose dolphin distribution and sea surface temperature, the coastline was divided into 0.10DD latitudinal bins. Due to the topography of the North Carolina coast, long stretches of east-west directed shorelines, such as around the capes, were sub-binned to avoid including large areas of sea surface. Sub-bins were created in areas that were separated by land, where grid cells were not adjacent, and where the difference in sea surface temperature was greater than 0.5 ˚C (see Figure 1).

The grid sample function was used to analyze the observation grid and sea surface temperature grid of each survey. The output reported the number of animals sighted and sea surface temperature within each 0.10 X 0.10 DD grid cell. Within each latitudinal bin and sub-bin, multiple grid cells were combined in order to find the total number of animals sighted and average sea surface temperature. Survey effort varied in each bin and sub-bin, but this source of variation was corrected for by dividing the total number of animals sighted by the distance of coast surveyed.

Plots were made of sea surface temperature vs. the cumulative sum of animals and latitude vs. cumulative sum of animals, using S-Plus (Professional Release 2, 2000). The northern-most latitude and lowest sea surface temperature at which bottlenose dolphins were observed was determined for each survey. In addition, the latitude and sea surface temperature below which 95% of the dolphins were present were determined for each survey. The 95th percentiles were used to determine the area in which most animals were present, excluding individuals or small groups that deviated from the typical distributional pattern. Sea surface temperature did not always increase consistently as latitude decreased. In instances where dolphins were present in colder sea surface temperatures south of the point at which 95% of dolphins were observed, then the colder temperature was reported.

Results

Thirty aerial surveys were completed from February 2000 to July 2001, with a total of 1,502 sightings of 13,696 individual bottlenose dolphins. At least one survey was completed for each month (except December 2000, due to poor weather conditions), with multiple surveys in some months (see Table 1). During both years, March had the lowest northern-most latitudinal limit of bottlenose dolphins and some of the coldest sea surface temperatures.

Sea surface temperature

Observed temperatures ranged from 10.4 to 28.3 ˚C, but no bottlenose dolphins were observed in water colder than 12.4 ˚C. Additionally, 95% of bottlenose dolphins were observed in waters warmer than 13.5 ˚C. During winter months, dolphins did not use the entire sea surface temperature range available (see Figure 2).

Latitudinal distribution

The latitude range along the North Carolina coast is approximately 33.83N to 36.56N, but during winter months no bottlenose dolphins were observed north of 36.51N. Additionally, 95% of bottlenose dolphins were observed south of 36.31N during winter months (see Figure 3). Bottlenose dolphins do occur north of North Carolina during the winter, but their presence in more northern waters is uncommon (A.J. Read, personal communication).

Discussion

During winter months bottlenose dolphins did not inhabit all available temperatures within their known range of 10-32 ˚C. However, it is important to keep in mind that this is a general temperature range referring to global distribution, not specific to the Western North Atlantic region. The available temperature range along the coast of North Carolina during this study was 10.4-28.3 ˚C, but all dolphins were observed only within a range of

12.4-28.1 ˚C. The range of this species could be directly limited by temperature, or indirectly limited by temperature through other dynamic factors.

Dolphins may be limited directly by temperature, due to the limits of their thermal neutral zone (Barco et al., 1999). If this is the case, the data suggest that the lower limit of their TNZ may be within 12.4-13.5 ˚C, where 95-100% of dolphins were observed. However, this estimate is based on weekly averaged sea surface temperature, since daily data was unreliable, and sea surface temperature was interpolated over areas with no data due to cloud cover. Unfortunately, we have no direct measurements of the TNZ for bottlenose dolphins in the Western North Atlantic. The 5.9-23 ˚C thermal neutral zone, estimated by Williams et al. (2001), was derived for bottlenose dolphins acclimated to the relatively cold temperatures of Monterey Bay, California (ranging from 10-18˚C (Wells et al., 1990)). Barco et al. (1999) found that bottlenose dolphins were present in the vicinity of Virginia Beach, only when water temperatures exceeded 16.0 ˚C. However, this analysis was based on monthly mean temperatures and dolphins were occasionally sighted in temperatures below 16.0 ˚C (Barco et al., 1999). When the lower limit of the available temperature range was 16.0 ˚C or higher, dolphins were observed throughout the study area. These results, along with those from Barco et al. (1999), suggest that there may be something significant with regards to16.0 ˚C. To determine whether dolphins are being directly limited by temperature, it would be necessary to perform metabolic experiments to determine the TNZ for bottlenose dolphins in the Western North Atlantic.

Alternatively, bottlenose dolphins may be indirectly limited by temperature, such as through distribution of their prey (Barco et al., 1999). During winter months, when the lower range of available temperature was less than 16 ˚C, 95% of dolphins were not observed using the entire range available. These results may suggest that dolphin distribution is not being directly limited by temperature, but instead limited indirectly by some other factors. To understand the influence of such other factors, it would be necessary to build a model including other dynamic explanatory variables, such as prey distribution, predator distribution, and distance from fronts. The availability of sea surface temperature data, such as used in this study, allows dynamic factors such as temperature fronts to be readily determined. Currently, data pertaining to relevant predator and prey distribution can be difficult to obtain (Hastie et al., 2004). However, with the possibility of tools such as vessel monitoring systems for fishing boats, detailed data on prey and predator species may be available for analysis in the future.

During winter months, dolphins were observed progressively further south as water temperatures cooled. This was most pronounced in March of both years, when 95% of the dolphins were seen south of 35.5 N. March is the coldest month because the ocean holds heat longer compared to terrestrial systems, and therefore experiences a time lag with regards to terrestrial temperature cooling. Latitude may be a more useful metric of seasonal distribution limits than temperature. For example, the northern limit of bottlenose dolphins in the Western North Atlantic during the winter season may be better characterized by six separate monthly averaged latitudinal limits. Considering the migration in distribution during winter months, the existence of a migrating latitudinal range limit, based on a monthly time scale, would provide more detailed information for the management of seasonal fisheries that interact with strategic stocks of coastal bottlenose dolphins. However, this would require long-term analysis in order to obtain representative monthly averages.

In the future, analysis covering a longer time span would be useful to capture inter-annual variation. As technology continues to advance, newer satellites collect and disseminate data at finer spatial scales. For example, the MODIS/Aqua satellite, available from December 2002 to the present, offers data at 4km resolution, compared to the 9km resolution of the Pathfinder satellite used in this study. Subsequently, analysis of more recent data may provide increased detail of variables such as sea surface temperature, distance from fronts, and primary productivity.

Previous studies have analyzed the affect of environmental variables on species distribution and used the results to aid in management of the species. For example, sea surface temperature has been used as a tool to aid in the management of marine sea turtles in the Southeast Atlantic (Epperly et al., 1995a and b). When temperatures in an area reach the point when sea turtles are known to be present, fisheries known to interact with sea turtles are required to modify their fishing practices, such as implementing the use of turtle excluder devices (TEDs) or tow time restrictions. This type of management has potential to be used with strategic stocks of coastal bottlenose dolphins. Results from future research, explaining the relationship between sea surface temperature and dolphin distribution, may allow temperature to be used in predicting seasonal presence of bottlenose dolphins. This could then be used to implement seasonal modifications in fishing practices that minimize dolphin by-catch.

It is important that we work towards a detailed understanding of strategic stocks, in order to effectively manage and protect them. In this study geographical information systems were used to analyze the spatial distribution of bottlenose dolphins as affected by sea surface temperature. Results should be considered provisional, but suggest that during winter months in the Western North Atlantic, 95% of bottlenose dolphins do not inhabit waters colder than 13.5 ˚C. Although results suggest that more research is necessary, there is potential for using results from this type of analysis for management.

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Table 1. Summary of survey details and analysis results.

Survey Date	Number of Sightings	Total Animals Sighted	SST range (ºC)	Coldest SST Sighted (ºC)	95% Cold SST (ºC)	Northern-most Sighted Lat.	95% Northern Lat.
Feb-23-2000	46	296	10.8 - 20.7	14.5	15.7	35.99	35.58
Mar-01-2000	92	633	10.8 - 19.7	15.6	16.6	35.64	35.42
Apr-01-2000	63	441	14.2 - 21.1	16.0	16.0	36.09	36.05
May-06-2000	70	318	18.7 - 21.9	18.7	18.9	36.51	36.45
May-09-2000	12	72	18.1 - 21.8	18.1	18.1	36.51	36.51
May-26-2000	61	191	20.5 - 24.3	20.5	20.5	36.62	36.56
Jun-01-2000	42	393	20.6 - 25.0	20.6	20.8	36.32	36.23
Jun-17-2000	8	18	23.4 - 27.1	23.5	23.5	36.27	36.27
Jun-22-2000	3	27	23.7 - 27.6	23.7	23.8	36.53	36.53
Jun-30-2000	25	130	23.6 - 27.6	23.6	23.6	36.51	36.51
Jul-03-2000	7	48	23.7 - 27.3	23.7	23.7	36.55	36.55
Aug-15-2000	24	227	23.5 - 28.3	23.5	23.5	36.48	36.48
*Aug-19-2000	3	7	24.2 - 27.3	26.7	26.7	34.47	34.47
Sep-20-2000	23	155	24.6 - 27.9	24.6	24.6	36.55	36.55
Oct-04-2000	34	367	21.9 - 25.3	21.9	21.9	36.45	36.34
Oct-13-2000	102	1746	20.2 - 24.7	20.8	22.7	36.22	35.56
Oct-20-2000	81	1118	19.4 - 23.8	19.4	19.9	36.55	36.20
Nov-13-2000	96	861	16.2 - 23.8	16.3	16.3	36.37	36.31
Nov-27-2000	38	191	15.5 - 23.0	20.1	20.1	35.85	35.85
Nov-29-2000	82	963	15.5 - 23.0	19.7	20.1	35.94	35.89
Jan-17-2001	79	664	12.2 - 21.8	14.6	14.6	36.07	36.07
Feb-02-2001	87	1031	10.6 - 21.0	12.4	13.5	36.23	35.86
Mar-23-2001	84	517	10.4 - 16.4	12.9	13.6	36.27	35.51
Apr-20-2001	103	944	15.3 - 21.1	15.3	17.6	36.51	36.08
May-14-2001	52	420	16.6 - 21.8	16.6	16.6	36.55	36.51
May-30-2001	22	138	20.1 - 24.2	20.1	20.1	36.36	36.36
Jun-12-2001	26	260	23.0 - 26.3	23.0	23.0	36.53	36.53
Jun-19-2001	40	443	22.8 - 27.2	22.8	22.8	36.54	36.53
Jun-26-2001	56	522	24.6 - 28.2	24.6	24.6	36.51	36.51
Jul-16-2001	41	555	24.8 - 28.2	24.8	24.9	36.55	36.30

* Results are skewed for this survey due to only 3 sightings.

Figure 1. Illustration of study area along the coast of North Carolina. Shows division of bins and sub-bins, along with the 0.10 X 0.10 DD grid cells which intersected with the 1km study area along the coastline.

Figure 2. Graph representing the 95% results for sea surface temperature. Bars represent the sea surface temperature in which 95% of the dolphins were observed for each survey. The black arrows represent the temperature range available during each survey. Pink bars are surveys during winter months (Nov-Apr), and blue bars are surveys during summer months (May-Oct). During the majority of winter months, dolphins were not observed using the total available temperature range.

Figure 3. Graph representing the 95% results for latitude. Bars represent the latitude in which 95% of the dolphins were observed for each survey. Pink bars are surveys during winter months (Nov-Apr), and blue bars are surveys during summer months (May-Oct). The March surveys are highlighted bright green because they represent the southern-most latitudinal limit in each year (ignoring the Aug 19, 2000 survey in which the results are skewed due to only 3 sightings).

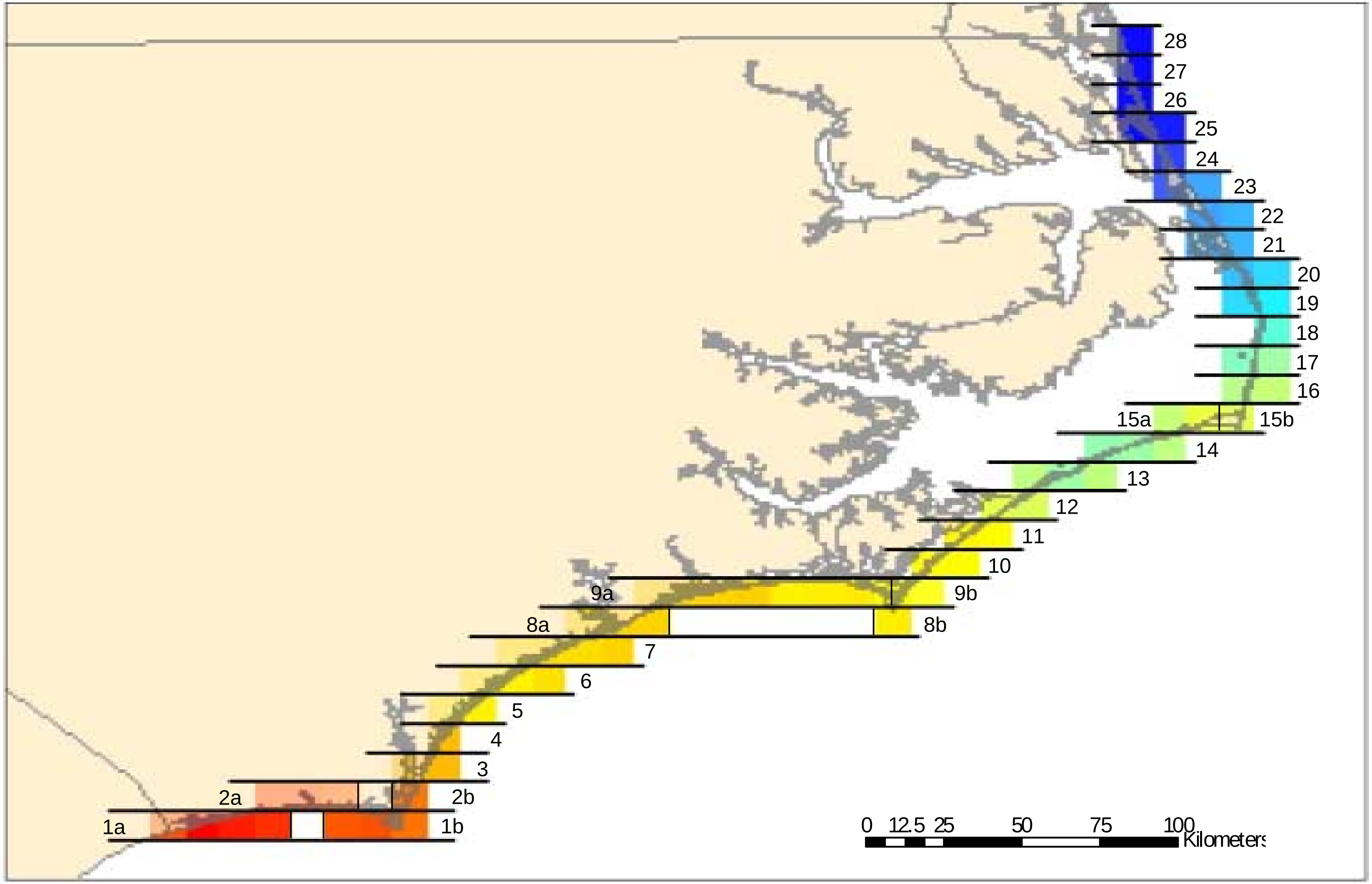
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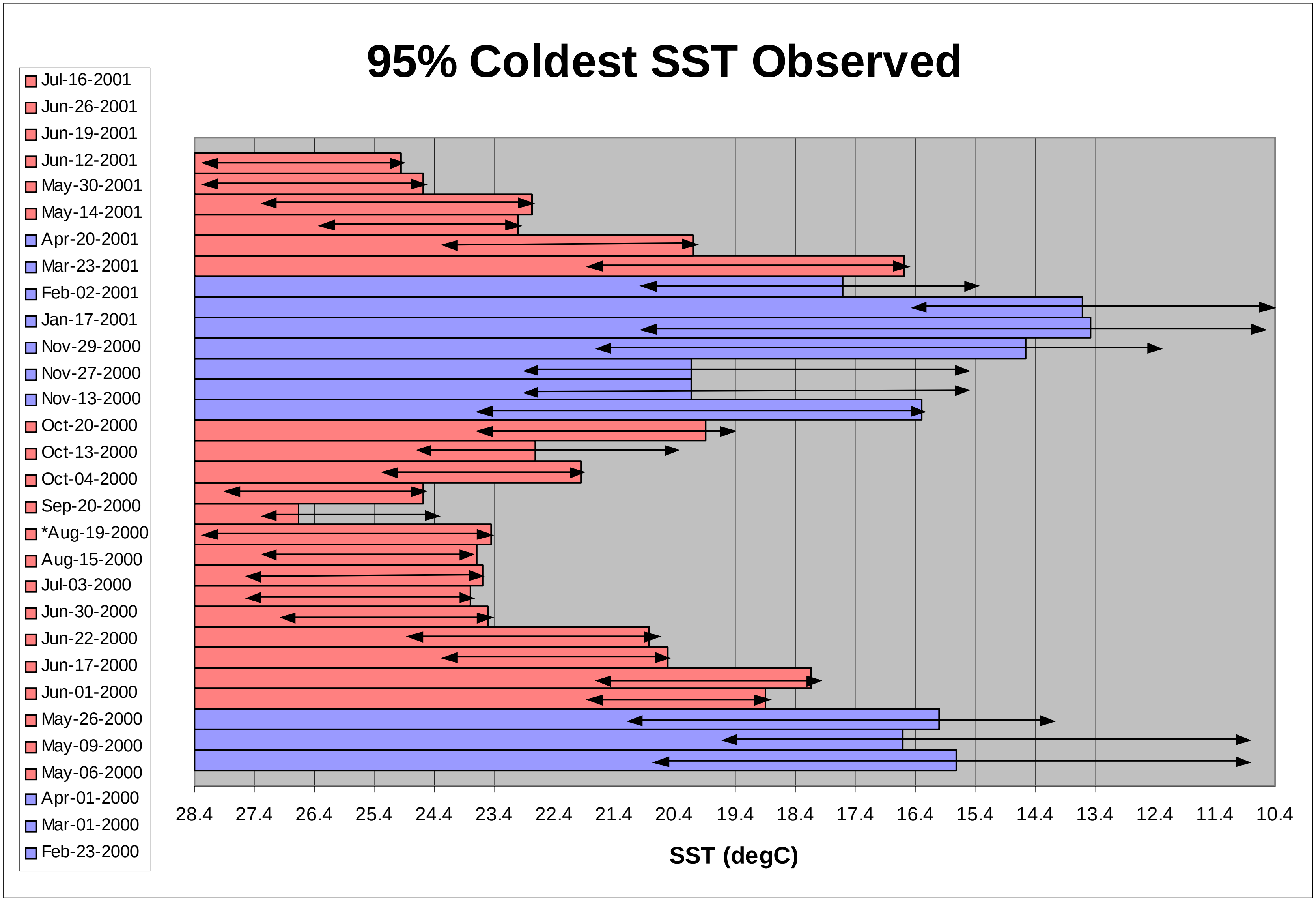
Figure 1.


95% Coldest SST Observed
Jul-16-2001
Jun-26-2001
Jun-19-2001
Jun-12-2001
May-30-2001
May-14-2001
Apr-20-2001
Mar-23-2001
Feb-02-2001
Jan-17-2001
Nov-29-2000
Nov-27-2000
Nov-13-2000
Oct-20-2000
Oct-13-2000
Oct-04-2000
Sep-20-2000
*Aug-19-2000
Aug-15-2000
Jul-03-2000
Jun-30-2000
Jun-22-2000
Jun-17-2000
Jun-01-2000
May-26-2000
May-09-2000
May-06-2000
Apr-01-2000
Mar-01-2000
Feb-23-2000
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20.4
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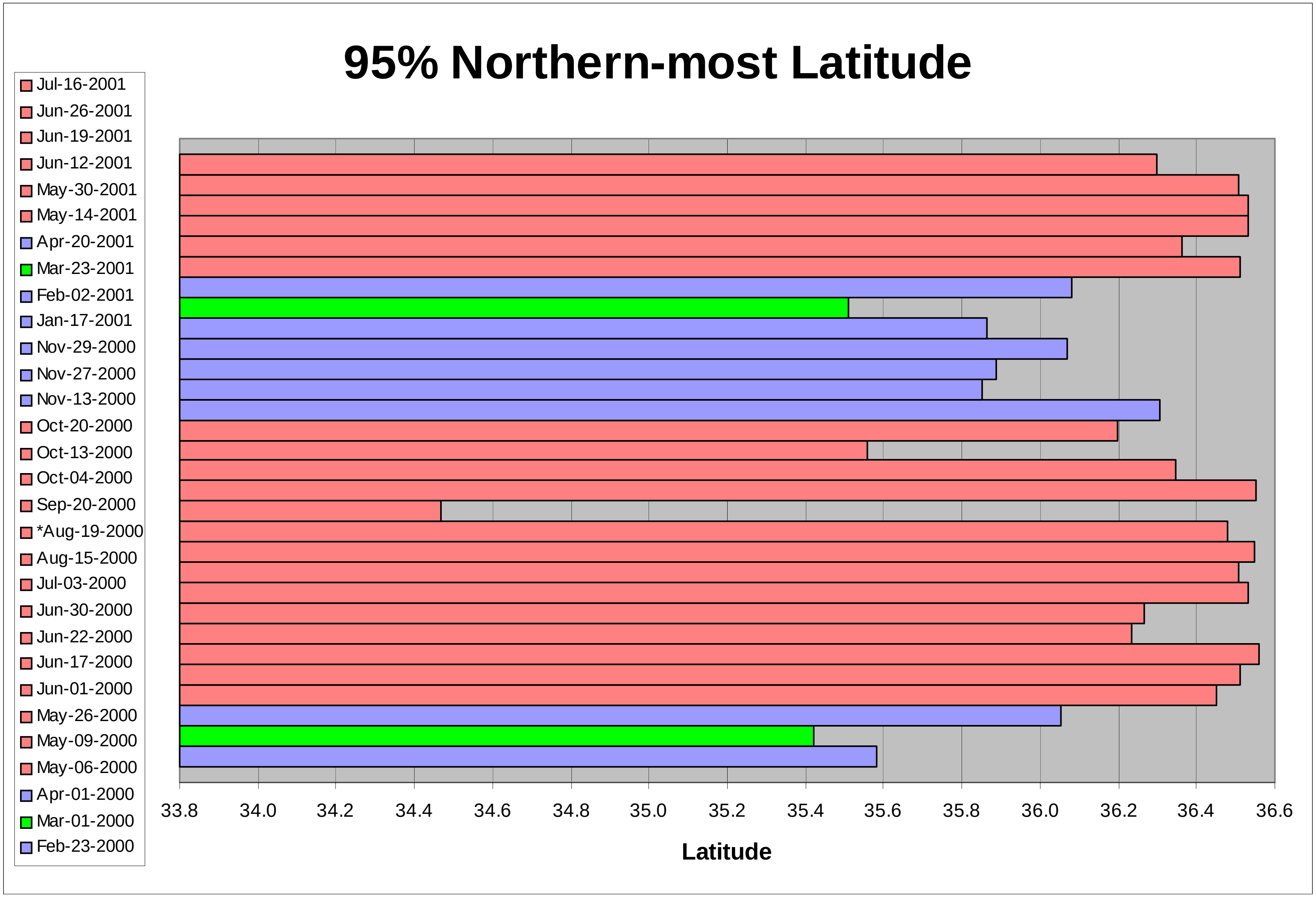
11.4
10.4
SST (degC)

Figure 2.


95% Northern-most Latitude
Jul-16-2001
Jun-26-2001
Jun-19-2001
Jun-12-2001
May-30-2001
May-14-2001
Apr-20-2001
Mar-23-2001
Feb-02-2001
Jan-17-2001
Nov-29-2000
Nov-27-2000
Nov-13-2000
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36.0
36.2
36.4
36.6
Latitude

Figure 3.