Sea Surface Temperature Variability
In the Northwestern Hawaiian Islands Region

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We certify that we have read this thesis and that, in our opinion, it is satisfactory in scope and quality as a thesis for the degree of Bachelor of Science in Global Environmental Science.

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Much Mahalo and keep the Aloha!

Abstract

The first massive coral bleaching event reported in the Northwestern Hawaiian Islands (NWHI), the world's second largest coral reef reserve, occurred during summer 2002. Bleaching at these remote coral atolls is believed to be related to elevated surface temperatures. The temporal and spatial variability of near-surface temperatures at the NWHI are analyzed using Reynolds Sea Surface Temperature (SST) (1 week averages, 11/1981-11/2003), and in situ temperature measured within the coral atolls (15 minute averages, 9/ 2002 – 8/2003) as part of the Northwestern Hawaiian Islands Reef Assessment and Monitoring Program (NOWRAMP). The focus is on conditions leading to high SST anomalies during the peak of the seasonal heating cycle (August-September). Comparison of Reynolds and in situ data shows reasonable correlations (0.83-0.99), regression coefficients (0.81-1.14), and residual errors (0.39-1.30°C). During summer months, mean differences between in situ and Reynolds SST do not show a consistent bias between the two instruments. These results suggest that Reynolds SST is a reasonable indicator of temperature variability at the coral atolls. Lacking in situ data before or during the 2002 bleaching event, Reynolds SST is used to characterize summer surface temperature variability at the NWHI, and to identify possible bleaching periods. Anomalously high SSTs occurred during summer 2002, but only at the three most northern atolls: Kure, Midway, and Pearl & Hermes. SSTs at the other NOWRAMP study sites were similar to long term conditions. The summer of 2002 was the only period of sustained high temperatures during the 22 year record. The intensity and duration of coral bleaching periods have been examined in terms of accumulated heat stress based on estimated thermal thresholds for bleaching at every NOWRAMP station. Again, only the 2002 event appears to have been significant, although the accumulated heat stress values barely reached 20 Degree Heating Days. Comparison with NCEP Reanalysis wind anomalies shows that the generation of high SSTs during summer 2002 is associated with a decrease in wind speeds, which occurs over short spatial scales. The

wind relaxation is caused by mid-latitude synoptic variations, which are essentially weather related with low predictability. The conclusion is that the 2002 bleaching event was caused by an unusual summer cessation of the Northeast Trades over the northern most NWHI region, causing enhanced surface heat flux and warming of the surface layer.

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List of Abbreviations

- CRW: NOAA Coral Reef Watch Program
- DAR: Division of Aquatic Resources
- FFS: French Frigate Shoals
- NCEP: National Centers for Environmental Prediction
- NESDIS: National Environmental Satellite, Data and Information Service
- NMFS: National Marine Fisheries Service
- NOAA: National Oceanic and Atmospheric Administration
- NOWRAMP: NWHI Reef Assessment and Monitoring Program
- NWHI: Northwestern Hawaiian Islands
- P&H: Pearl and Hermes Atoll
- SST: Sea Surface Temperature
- STR: Subsurface Temperature Recorder

1. Introduction

Coral bleaching is a condition that can seriously damage and ultimately kill entire reef systems. All species of hermatypic corals contain microscopic plants called zooxanthellae that color their tissues and provide them with energetic photosynthetic products. It is a symbiotic relationship as the coral skeletons provide zooxanthellae with a habitat. Without these tiny plants, corals cannot survive or lay down the huge amounts of limestone in their skeletons. When corals become stressed, the protection afforded the zooxanthellae is jeopardized and they can be lost from the community: corals expel the zooxanthellae and turn white. The white skeleton becomes visible through the transparent coral tissue giving the organisms a "bleached" appearance (Hoegh-Guldberg, 1999). Because of the increasing intensity and geographic scale of recent bleaching events, mass bleaching is considered by most reef scientists to be a serious challenge to the health of the world's coral reefs.

Corals tend to live in nutrient poor waters and have certain zones of tolerance to water temperature, salinity, UV radiation, opacity and nutrient quantities. Although they are highly sensitive to a variety of biological and physical changes to their environment, most evidence currently indicates that elevated temperature is the primary cause of mass bleaching events. Six major episodes of coral bleaching over the past 20 years have been caused by periods of increased water temperature (Hoegh-Guldberg, 1999). Many studies show a close association between warmer than normal conditions (at least 1°C higher than the usual summer maximum) and the incidence of bleaching. Moreover, increased temperatures affect coral populations by reducing their reproductive capacity and their ability to grow (Hoegh-Guldberg, 1999). Temperature warmer than normal causes zooxanthellae to become supersensitive to light. Rising temperatures also block the photosynthetic reaction that converts carbon dioxide into sugar, resulting in the accumulation of products poisonous to the zooxanthellae. Then the coral releases the zooxanthellae to save itself, leaving the coral a bleached color. In fact, the bleached coral can recover, but only if cooler temperatures return and the algae are able to grow again. Finally without the symbiotic zooxanthellae, the coral starves to death. Generally, environmental conditions in which coral reefs prosper are characterized by a high degree of stability (Hoegh-Guldberg, 1999). Seasonal and diurnal fluctuations in tropical sea temperature are generally small, but recent evidence suggests that tropical oceans have varied by less than 2ºC over the past 18,000 years (Thunnell et al., 1994). Yet many coral atolls are located in the subtropics where sea surface temperatures can vary seasonally between approximately 18ºC and 29ºC.

The first detailed reports of coral bleaching at the Hawaiian Archipelago were from Kaneohe Bay on the island of Oahu during summer 1996 (Jokiel et al., 2004). The event was well monitored during the entire period of bleaching and recovery. The occurrence of coral bleaching on smaller scales is not well understood, although it seems likely that such events must have occurred prior to 1996 (Barton et al., 2004).

During the summer of 2002, the first mass coral bleaching event was reported in the ecosystems of most of the Northwestern Hawaiian Islands (NWHI) (Aeby et al., 2003). Substantial bleaching (greater than 20% of the corals) was observed on reefs of the three most northern atolls of the Hawaiian Archipelago: Kure, Midway and Pearl and Hermes (Figure 1).

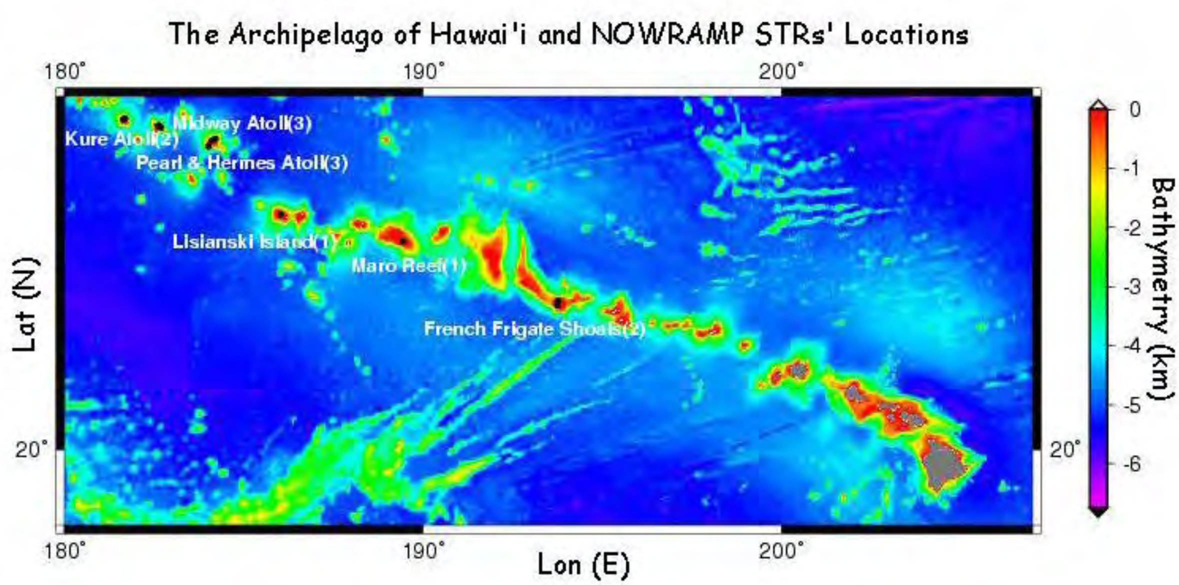


Figure1. The Archipelago of Hawai'i with the locations of NOWRAMP surface temperature recorders.

Less bleaching was observed at the adjacent reefs: Lisianski Islands and Maro Reef. The coral species affected were mostly in the scleractinian genera *Montipora* and *Pocillopora,* and to a lesser extent *Porites*.

Little was known about the health and dynamics of coral reef ecosystems in this remote region. To address these issues, the Northwestern Hawaiian Islands Reef Assessment and Monitoring Program (NOWRAMP) was developed to investigate the health of coral reefs ecosystems in this remote region of the Hawaiian Archipelago. NOWRAMP was launched in 2000, benefiting from the political and public support for coral reef protection and the advances in modern technology now available to assess, map, monitor and manage large remote marine ecosystems. The goal of the NOWRAMP expeditions is to assess the ecological condition and health (biodiversity, status and management needs) of the NWHI. As they describe it in their report, the NOWRAMP expeditions result from "a multi-agency and institutional partnership that brought together the best resources (people, equipment and funding) of both the resource trustees (State and Federal) and the academic community" (Maragos et al., 2002). The Division of Aquatic Resources (DAR), part the Department of Land and Natural Resources, the National Marine Fisheries Service (NMFS), Honolulu Laboratories (NOAA), the National Ocean Service (NOAA), the Hawai'i Coral Reef Initiative Research Program, the Oceanic Institute and members of the University of California at Santa Cruz and of the University of Hawai'i all work together to conduct rapid ecological assessments and bottom habitat mapping over vast areas (Maragos et al., 2002). As noted by Alan Friedlander, fisheries ecologist with the Oceanic Institute, "With coral reefs around the world in decline, it is extremely rare to be able to examine a coral reef ecosystem that is relatively free of human influence." Because of their relative isolation, the shallow reefs of the Northwestern Hawaiian Islands represent a large no-take zone, providing a unique opportunity to assess how 'natural' coral reef ecosystems function (Maragos et al., 2002).

NOWRAMP ultimately will provide quantitative information on in situ temperature variability and coral health, from which we can deduce the threshold of thermal tolerance for NWHI coral species. Currently, in situ data have not been collected during bleaching events. Until longer time series are available, we chose to investigate the variability of sea surface temperature (SST) in the remote Northwestern Hawaiian Islands Coral Reef Ecosystem Reserve using Reynolds Optimum Interpolation SST. Although bleaching may be caused by changes in a wide variety of parameters such as irradiance, spectral quality in the visible and ultraviolet ranges, low salinity, sedimentation, exposure at low tide, and exposure to toxic materials and infectious disease (Jokiel et al., 2004), we will focus solely on the variability of upper ocean heat content (i.e., the upper 4 m of the water column). This paper investigates the spatial and temporal variability of SST, identifies periods of suspected bleaching based on existing information of coral temperature tolerance, and seeks to determine the atmospheric conditions that contribute to bleaching events. We will show that the bleaching event of 2002 was a singular occurrence over the past 20 years. Thermal thresholds were exceeded during other summers, however, they were short in duration and much weaker in intensity compared to 2002. The 2002 event was associated with anomalously weak winds over a relatively small region associated with synoptic weather conditions. The predictability of these events is believed to be low, suggesting that this is more a random weather event rather than a climate induced phenomenon.

This paper is structured as follows. The data and methods used in this study are described in section 2. In section 3, the geography, coral types, mean winds and SST of the study region are briefly described. The results are described in section 4. In situ data are investigated in section 4.1; then a comparison of in situ temperatures from NOWRAMP and Reynolds SST is presented in section 4.2. The spatial and temporal variability of Reynold's SST anomalies is investigated in section 4.3. A thermal threshold is defined for all the NOWRAMP study sites and expected bleaching events are determined in section 4.4. The intensity of the bleaching events is measured in terms of an "accumulated thermal stress". The conditions leading to the strong 2002 bleaching event are considered in section 4.5. A summary and discussion follow in section 5.

2. Data and Analysis Methods

2.1 Data

Reynolds SST from November 1981 to November 2003 was obtained from the NOAA National Center for Environmental Prediction (NCEP) (ftp://ftpprd.ncep.noaa.gov/pub/cmb/sst/oisst_v2/). The data are weekly means interpolated onto a 1°x1° grid. Reynolds SSTs are reconstructed data from in-situ buoys and remote measurements collected by orbiting satellites equipped with AVHRR sensors. Optimum interpolation (OI) analysis is used to construct the gridded dataset, after adjusting for biases (Reynolds et al., 1994).

In-situ temperature data were provided by Rusty Brainard, Director of the NOWRAMP 2002. The measurements were collected using Seabird SBE 39 V 1.7 sensors (Figure 2), a type of subsurface temperature recorder (STR), at 12 different sites located around 6 major islands and reefs of the Northwestern Hawaiian Islands (Figure 1, Table 1). The data were collected every 15 minutes for about 10 months beginning in late summer 2002 during the NOWRAMP research cruise. The STRs were deployed to allow remote long-term monitoring of oceanographic and environmental conditions affecting NWHI coral reef ecosystems.

Figure 2. NOWRAMP STRs deployed within the NWHI coral reefs.

Thus, these in-situ SST time-series provide a unique record of the temperature variability in this remote region. During the NOWRAMP expedition, high-resolution IKONOS multi spectral images were acquired (Appendix II). The NWHI is actually the first large-scale coral reef ecosystem mapped using IKONOS satellite imagery.

Table 1. NOWRAMP STR stations from the most southern to the most northern location.

Location	Lon (°W)	Lat (°N)	Sensor Type	Depth (m)	Period of In-situ Data Collection After Clean-up
French Frigate Shoals FFS-STR 2	166-15.6839’	23-46.1343’	STR 1 3929252-0898	4	from 04 Oct 02 07:25:18 to 17 Jul 02 03:14:99
French Frigate Shoals FFS-STR 1	166-13.1804’	23-51.9668’	STR 2 3929252 -0905	2	from 12 Sep 02 00:30:00 to 16 Jul 03 03:14:99
Maro Reef MARO-STR	170-32.3832’	25-23.0501’	STR 3929252-0901	1.5	from 02 Oct 02 17:48:16 to 21 Jul 03 05:48:15
Lisianski Island-Neva LISI-STR	173-57.6597’	26-03.8205’	STR 3929252-0902	0.5	from 29 Sep 02 18:04:33 to 27 Jul 03 03:34:32
Pearl & Hermes Atoll PHR-STR 3	175-58.720’	27-46.489’	STR 3 3929252-0900	2.5	from 28 Sep 02 00:59:54 to 04 Aug 03 03:29:53
Pearl & Hermes Atoll PHR-STR 2	175-53.657’	27-54.710’	STR 3 3929252-0899	2	from 26 Sep 02 18:15:18 to 04 Aug 03 04:30:18
Pearl & Hermes Atoll PHR-STR 1	175-46.850’	27-57.450	STR 1 3929252-0906	1	from 25 Sep 02 21:48:32 to 30 Jul 03 05:48:32
Midway Atoll MID-STR 1	177-19.4006’	28-14.6621’	STR 1 3930159-0831	0.5	from 03 Dec 02 18:01:00 to 05 Aug 03 05:45:01
Midway Atoll MID-STR 3	177-23.16’	28-16.2625	STR 3 3930159-0833	0.5	from 03 Dec 02 18:01:00 to 06 Aug 03 00:51:00
Midway Atoll MID-STR 2	177-22.0705’	28-16.6645’	STR 2 3929252-0904	0.3	from 25 Sep 02 21:45:01 to 05 Aug 03 05:45:01
Kure Atoll KURE-STR 2	178-22.105’	28-25.756’	STR 2 3929252-0907	1	from 23 Sep 02 03:20:11 to 04 Aug 03 05:35:11
Kure Atoll KURE-STR 1	178-18.365’	28-26.844’	STR 1 3929252-0903	1	from 13 Sep 02 00:00:00 to 04 Aug 03 08:30:00

The locations of the STRs are shown on the IKONOS images (Appendix I). Weekly averages of the in-situ STR data were formed for comparison with Reynolds SST. Higher frequency fluctuations measured by the STRs were evaluated by removing weekly averages.

Surface wind and upper level wind (250 mb) data sets were obtained from the NOAA-Cooperative Institute for Research in Environmental Sciences (NOAA-CIRES), Climate Diagnostics Center, Boulder, Colorado, USA, from their website http://www.cdc.noaa.gov/). The data are from the NCEP Reanalysis product.

2.2 Methods

Since 1997, the National Environmental Satellite, Data and Information Service (NESDIS) as part of NOAA's Coral Reef Watch (CRW) program has provided a global, 50-km resolution, empirical products to estimate the occurrence of coral bleaching ("SST Bleaching HotSpots"). A threshold temperature for coral bleaching is defined as the maximum monthly mean SST (MMMSST) + 1°C. An increase of SST by 1°C more than the maximum seasonal value can be very significant for corals living in conditions close to their thermal limits. An exposure of 30 days to temperatures of only 29-30°C will cause extensive bleaching in Hawaiian corals (Jokiel et al., 1990). We computed thermal threshold from the Reynolds SST time series at each location.

The concept of "accumulated thermal stress" also was investigated. CRW uses this as a measure of the cumulative effects of thermal stress on the coral reefs. The thermal stress index is measured in terms of a Degree Heating Week (DHW). DHW is the area of the temperature time series above the thermal threshold, integrated over 12 week intervals (Berkelmans, 2002). CRW have reported DHW values for the last two years when issuing satellite bleaching warnings.

To investigate SST variability, we computed anomalies at each location by removing an estimate of the seasonal cycle (annual sinusoid and mean fit to the data). Low frequency SST fluctuations were computed applying 1-year running mean filters to the anomaly data. Then NCEP wind anomalies were also computed by removing weekly means averaged over the period of study.

3. The NWHI Coral Reef Ecosystem Reserve

In this section, most of the information comes from the NOWRAMP 2002 report entitled "Coral Reef Ecosystems of the Northwestern Hawaiian Islands" (Maragos et al., 2002).

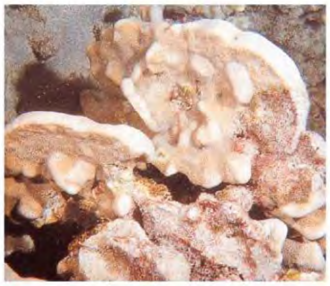
The NWHI Coral Reef Ecosystem Reserve, created in 2000 and managed by the National Oceanic and Atmospheric Administration (NOAA), is the second largest marine protected area in the world after the Australian Great Barrier Reef (Maragos et al., 2002). It includes a wide range of habitat for coral reef ecosystems that represent a unique marine wilderness of extreme importance.

3.1 NWHI Coral Species and Habitats

According to NOWRAMP, about 62 species of stony corals, *Acropora* species have been reported in the NWHI. These species include *Pavona duerdeni* (disk coral, at Kure Atoll and Maro Reef), *Acropora cytherea* (table coral, at French Frigate Shoals (FFS) and Maro Reef), *Porites compressa* (finger coral, at Kure, FFS, Midway Atoll and Pearl and Hermes Atoll), *Montipora turgescens* (blue encrusting coral in back reefs at Midway, Lisianski Island and Kure Atoll), *Porites lobata* and *P. evermanni* (massive lobe corals located on sheltered and back reefs at all atolls), *Montipora capitata* and some other *Porites* species (encrusting plate corals on deeper and semi-exposed reefs of all atolls) (Figure 3). In general, atoll lagoons offer greater protection from wave action and provide additional types of reef habitats (lagoon reef slope, perimeter reef crest, reef pass, back reef, patch reefs, etc…). In addition the largest NWHI atolls (Maro, FFS, Pearl and Hermes) provide more numerous habitats (Maragos et al., 2002). The distribution of live and dead corals and epiphytic algae at each of the six NOWRAMP study sites is displayed in Appendix II.

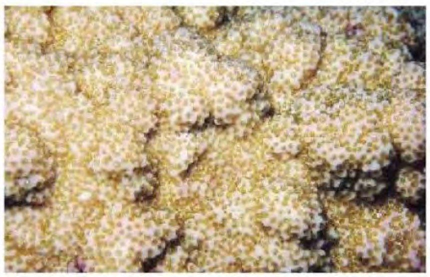
The tendency to bleach differs between colonies of different coral species. Reef-building corals are not all equally susceptible to the influence of increased temperature. Based on studies carried out after the 1996 bleaching event, it has been observed that different coral species showed different sensitivity to bleaching (Jokiel et al., 2004). Some coral species, such as those of the massive coral genus *Porites*, are relatively resistant to temperature stress, whereas the species of the genus *Acropora* (staghorn corals) show a great sensitivity to slight increases in water temperature and are very susceptible to bleach (Hoegh-Guldberg, 1999; Goenaga et al., 1998). Species showing highest resistance to bleaching were *Porites evermanni, Cyphastrea ocellina, Fungia scutaria*, *Porites brighami*. *Porites compressa*, *P. lobata*, *Montipora patula* and *M. capitata;* moderate resistant species include *Pocillopora* species (*P. damicornis, P. meandrina,* and P. *edouxi* mostly); *Montipora* species (predominantly *M. capitata*, *M. flabella and M. dilitata*) have very low resistance and were the most affected by bleaching (Jokiel et al., 2004).

Coral Species of the Northwestern Hawaiian Islands Coral Reef Reserve



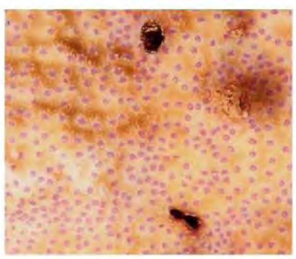
Pavona duerdeni (disk coral) (Hoover, 1999)

Acropora cytherea (table coral) (Hoover, 1999)



Montipora turgescens (blue encrusting coral) (reeftalk.com)

Montipora capitata (www7.plala.or.jp/poe-poe)



Montipora patula (Hoover, 1999)

Montipora flabella (Hoover, 1999)

Cyphastrea ocellina (Hoover, 1999)

Fungia scutaria (Hoover, 1999)

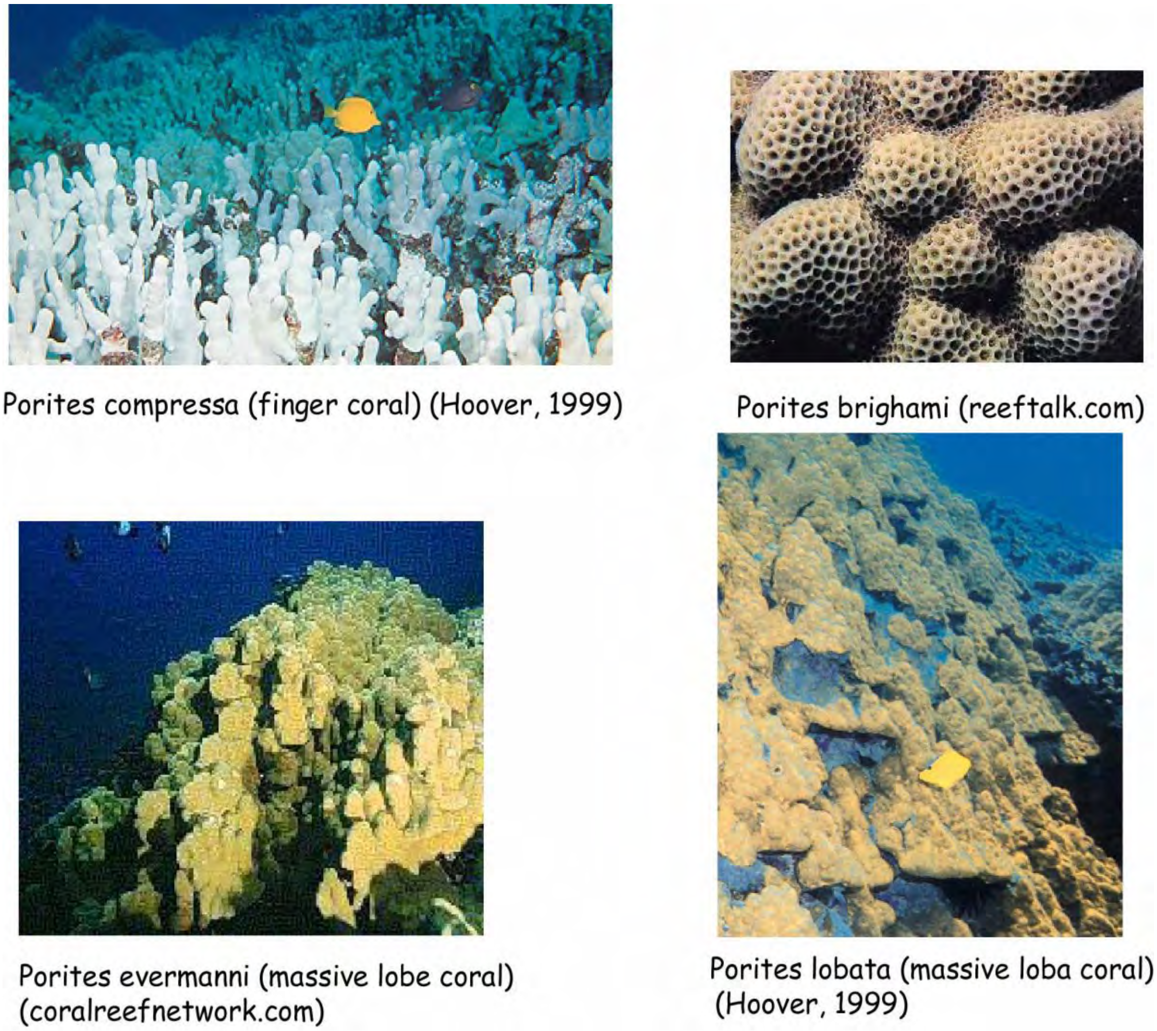


Figure 3. NWHI coral species (sources noted for each photograph).

3.2 Geography of the Major NWHI Atolls (from the southernmost to the northern most atolls)

Aerial IKONOS pictures of every atoll are available in Appendix II.

The most southern atoll, FFS, is a large open atoll with numerous islets including basalt features such as La Pérouse Pinnacle, covering a land area of 0.23 km² and a coral reef habitat of 733 km² to depths of 100 m. The perimeter reef protects the eastern part of the atoll, whereas the western rim of the atoll is open. This atoll has habitats ranging from ocean-facing reef slopes to patch reefs, with pinnacles and linear reefs throughout the eastern half of the lagoon. NOWRAMP reported forty-one species of stony coral. Rare table corals (*Acropora* species) are observed except in several lagoons and semi-protected areas that support large populations of *Acropora cytherea* (Maragos et al., 2002). Reticulated reefs with live finger and lobe corals (*Porites*) are located on the shallow eastern half of the lagoon. Much of the back reef area, to the east of the linear reefs shows lower coral cover but still shows isolated patches of large lobe and finger coral heads. The habitats created by coral species within the lagoon contain many macro and turf algae species, thus providing food for many reef herbivores.

The largest coral reef in the NWHI reserve, Maro Reef (1.5 km^2 to depths of 100 m) is a type of open atoll that lacks any emergent land. The interior reef shows large gaps that expose some portions of the lagoon area to wave action and re-suspension of fine sediments, causing the water in shallow reefs to be turbid during trade wind conditions and large northern winter swells. Maro Reef is difficult to access and lacks adequate survey sites prior to NOWRAMP surveys (Maragos et al., 2002).

Montipora capitata is dominant in the reef slopes forming large plates. Near the top of the reef slope, mounds of finger coral *Porites compressa*, large column of the disk coral *Pavona duerdeni*, *P. lobata* and other *Montipora* species are very common. Large table coral *Acropora cytherea* are also common. Many other sites of Maro Reef are actually dominated by coralline algae

Lisianski Island, together with Neva Shoals is a 1.46 km^2 large open Atoll with extensive coral reef habitats covering 979 km^2 (Appendix II, figure 4). It is a low coral island mostly encircled with a beautiful white sand beach covered with native beach vegetation. Most of the coral reef lies within the broad oval-shaped Neva Shoal to the south of the island. It generally consists of a radial pattern of elongated ridges oriented in a north and south axis. At present, 24 species of corals have been reported form Lisianski-Neva Shoal. Coral cover is high in particular along the deeper offshore sides of elevated reefs and on solid substrate patches located between reticulated reefs. Massive coral heads of *Porites lobata* and *P. evermanni* and finger coral heads of *P. compressa* are abundant. Elsewhere, sand and rubble patches are common and coral cover decreases in deeper and more exposed waters. Reef habitats close to the island are shallower and dominated by sand depressions and elevated mounds of the encrusting corals *Montipora* *turgescens* and *M. capitata*. Then various form of algae become predominant closer to shore, overgrowing corals (Maragos et al., 2002).

Pearl and Hermes Atoll has a land area of 0.36 km² with numerous small islets along the southern part of the atoll. Its reef area ranks second among the 6 atolls in the NWHI with 1,155 km² to depths of 100m. NOWRAMP counted 33 species of stony corals there. Mushroom corals such as *Fungia scutaria* are common in this area. Carbonate pavement and eroded spur and groove habitat are dominant in ocean-facing reefs, mostly with relatively low live coral cover. The northwestern facing reefs, facing the high winter surf, have amazingly deep vertical canyons frequently dropping to depths deeper than 100 feet. Due to the large size of P&H atoll, reef habitats are abundant and variable. Unique shallow doughnut-shaped reefs surrounding deep lagoon holes, creating isolated enclaves of organisms, have been observed within the larger lagoon environment. Gardens of finger coral (*Porites compressa*) are concentrated on patch reefs in the north central lagoon. In the southern lagoon reticulated reefs are very frequent. Southern back reef habitats and northwestern ocean and open lagoon pinnacles are covered with several species of *Pocillopora* corals.

Midway Atoll has a land area of 1.42 km² and a reef area of about 223 km² to depths of 100 m. The major fact about Midway Atoll is that it was substantially degraded during half of the century due to U.S. military occupation of the atoll dredging and excavating reef areas, and then bombing during WWII. Fuel spill, sewage discharge and chemical contaminants (PCBs, DDT) further degraded reef and land habitats. Nowadays only 16 coral species have been reported in the Midway Atoll although this might be an underepresentation of the coral species diversity. *Montipora turgescens*, blue encrusting coral is common in the shallow lagoon and back reef habitats (Maragos et al., 2002).

Finally at latitude 28.5ºN, and longitude 178ºW, is the northernmost atoll in the world, Kure Atoll. This small atoll has a total land area of 0.86 km² with two main islands, Sand Island and Green Island, and reef areas to 100m of 167 km². 2002 NOWRAMP has reported 27 coral species and high coral cover in some of the back reef and lagoons area. Yet coral cover is low on ocean-facing reefs and coralline algae are abundant. Although it was not expected, as Kure is the northernmost atoll, it provides a great diversity of corals. Large massive colonies of *Porites compressa, P. evermanni,* *Pavona duerdeni, M. capitata* and *M. turgescens* are found in many sites within the lagoon (Maragos et al., 2002).

3.3 Oceanography of the NWHI Reserve

The mean temperature and wind conditions of the region are considered using the Reynolds SST and NCEP surface winds. Mean SSTs show a strong north to south gradient, with the warmest temperatures in the southwest near the center of the sub-tropical gyre (Figure 4a). The northeastern part of the region experiences the greatest variability in monthly means, due to seasonal changes, with standard deviations near 0.9°C at the most northern atolls (P&H, Midway and Kure) (Figure 4b).

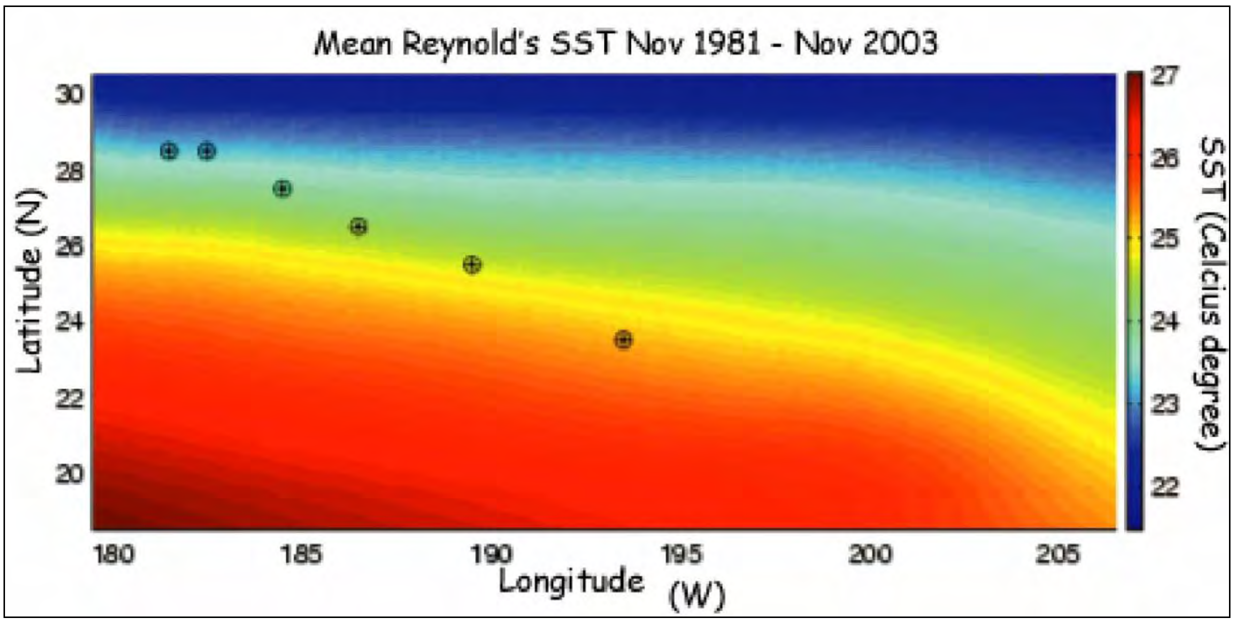


Figure 4a. Mean SST (Nov 1981-Nov 2003) from Reynolds SST. (The dots represents the study sites, the major NWHI atolls).

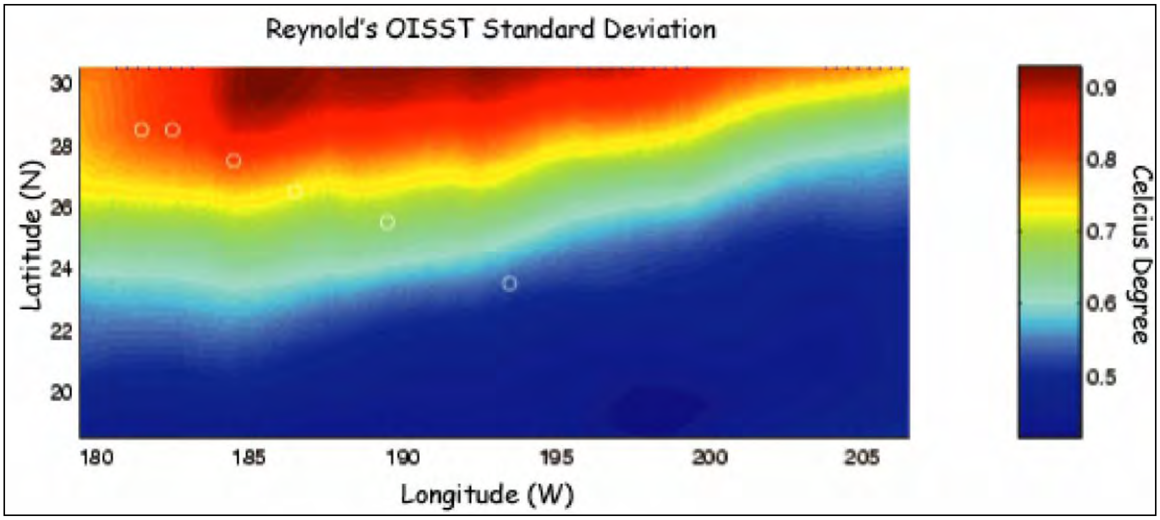


Figure 4b. SST standard deviation (Nov 1981-Nov 2003) from Reynolds SST.

We further characterize seasonal variations by computing long-term (1981-2003) averages for each month of the year (Figure 5). The seasonal variation increases to the north, with a range of nearly 7°C at Midway and Kure, compared to 3.5°C at FFS. Corals in the northernmost atolls thus experience considerably higher SST variations over the year. During the late summer, however, when SST reaches an annual maximum, the temperature values are very similar over the study site. This is consistent with the finding of Coles et al., (1977), who estimate a mean summer monthly temperature of 27°C±1°C in the Hawaiian region. As a result, although differences in bleaching sensitivity between coral species exist, differences in bleaching thresholds for Hawaiian coral species over the whole chain have not been detected since summer maximum SSTs for reefs over the entire NWHI region are about the same (Jokiel et al., 2004). In other words, it appears that the relatively homogeneous distribution of maximum temperatures over the NWHI discourages the development of coral populations with different high-temperature bleaching thresholds.

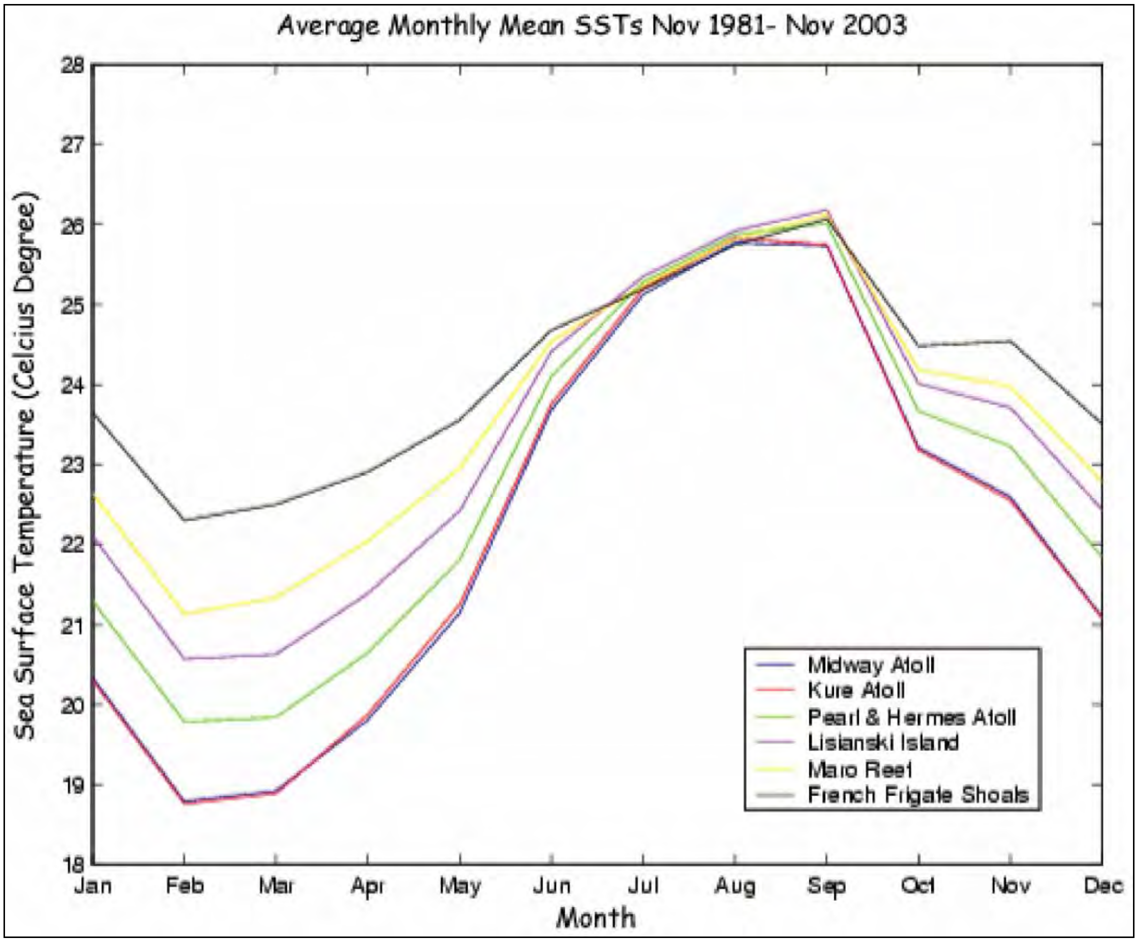
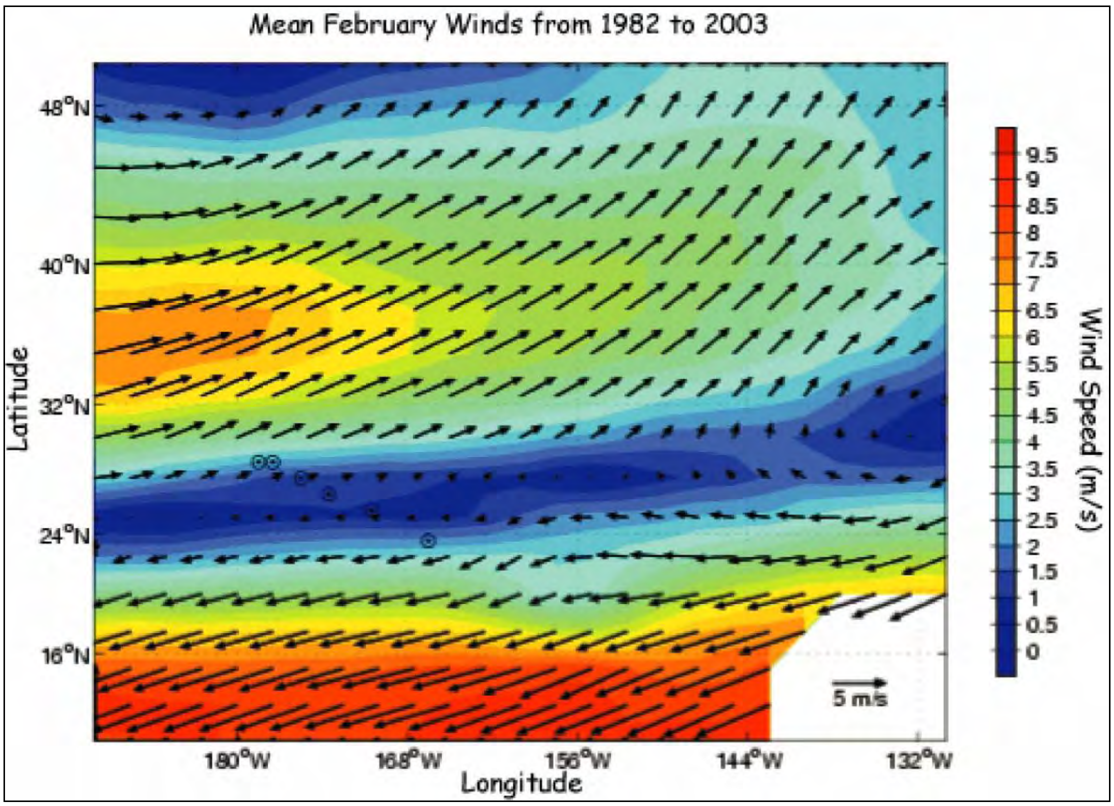


Figure 5. Monthly Average SST (Nov1981-Nov 2003) at the STR study sites. Peak summer SSTs (August-September) are similar over the NWHI.

We use SST as a proxy for temperatures at the depths relevant for live coral. In the NOWRAMP study, the temperature recorders are all shallower than 4m. Polovina et al. (1995) have analyzed historic hydrographic data to determine the depth of the mixed layer in the NWHI. They find a seasonal variation with the mixed layer depth at ~20m in May, deepening to 80m in December. Their estimates of seasonal variations in mixed layer temperature at the NWHI agree with changes in SST. Thus, the STR study sites are generally well within the mixed layer. At a coral atoll, however, there are other processes that can affect the depth of the surface mixed layer (e.g., swell, tidal mixing, upwelling). We will return to the relationship between SST and the STR data in section 4.2.

In anticipation of the importance of wind stress in determining SST, we examine mean surface winds during the winter and summer seasons (Figure 6). In the winter, the NWHIs lie between the northeasterly trade winds to the south, and the westerlies to the north. Wind speeds in the NHWI study region are only 1-3 m/s. In the summer, the northeasterly trades reach as far north as the NWHI, and wind speeds increase to 4-7 m/s. The circulation follows the North Pacific anticyclone, which shifts northward in summer, when trade winds intensify and reach 35°N on average, and southward in winter, when westerlies extend southward up to 28°N.



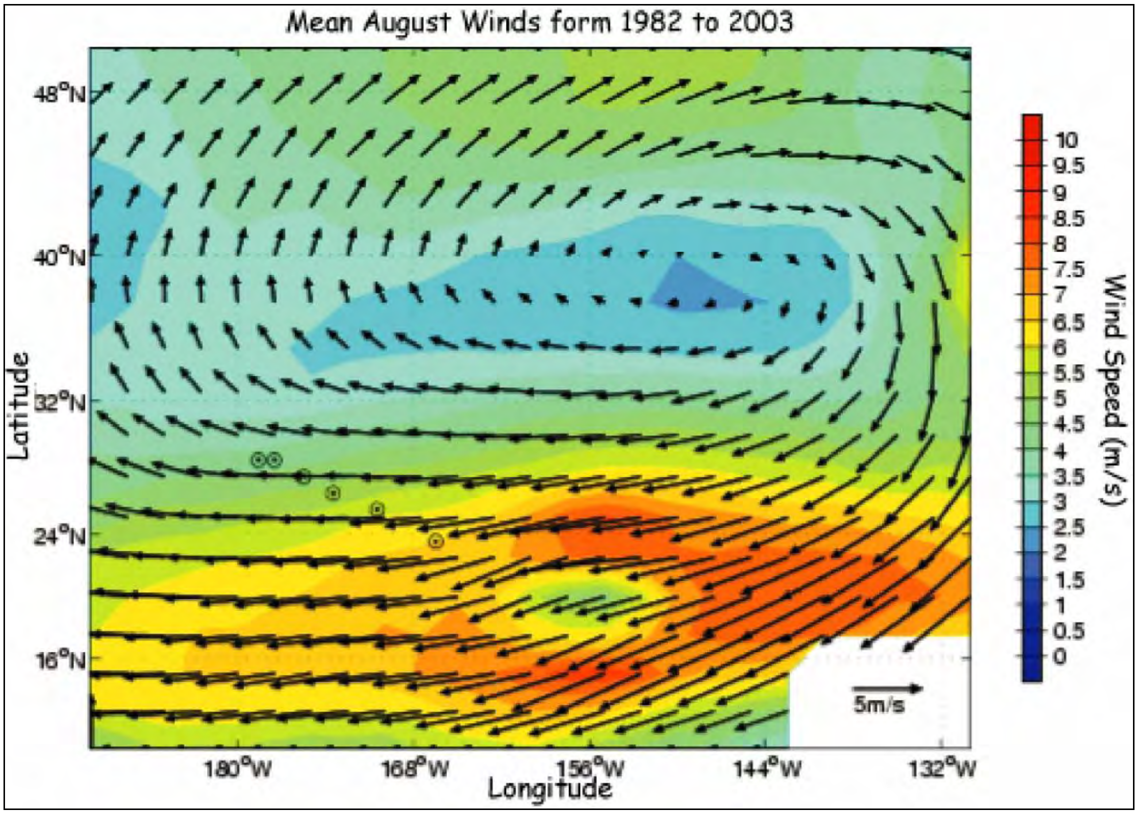


Figure 6. Average Surface Winds over the NWHI Region: February (winter) and August (summer) Winds (NCEP Wind Data November 1981-November 2003).

The average surface currents in the NWHI region are associated primarily with the subtropical gyre, centered at about 28°N, 180°W, which is actually very close to the most northern islands. At the latitudes of the Hawaiian Islands chain, the circulation is approximately from east to west and intensifies southward (Flament et al, 2001). This said, at the surface, currents driven by the wind and eddy motions combine with geostrophic currents to yield more complicated flow patterns. Evaporation exceeds precipitation over the whole NWHI region, and there is a net heat loss from the ocean to the atmosphere. Surface salinities reflect the difference between precipitation and evaporation with an average of 35.2 ppt at about 26°N. Interannual sea level variations in the NWHI are on the order of 10 cm. Tidal variations are mixed diurnal/semidiurnal with amplitude ranges on the order of approximately 60 cm.

4. Results:

4.1 Description of in-situ STR data

In general, all the STR time series show more or less the same fluctuations; even over a bit less than a year of record the seasonal cycle is obvious (Figure 7). Also there seems to be more high frequency fluctuations during spring and summer than during fall and winter, particularly at Pearl & Hermes, Midway, and Kure.

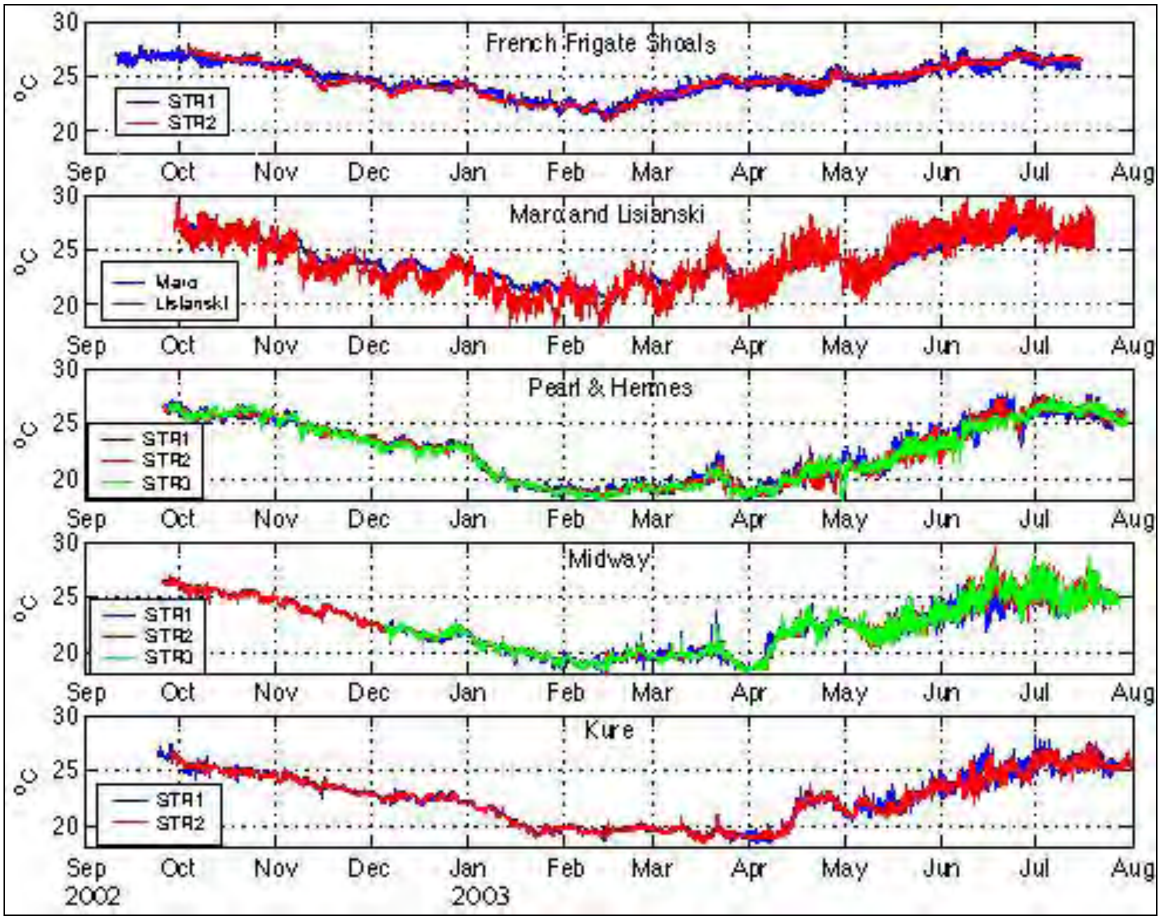


Figure 7. STR Time Series for every NOWRAMP sites.

For example for the three Midway STRs, the maximum summer fluctuations are ± 3°C whereas during winter the fluctuations are only ± 0.5°C (Figure 8).

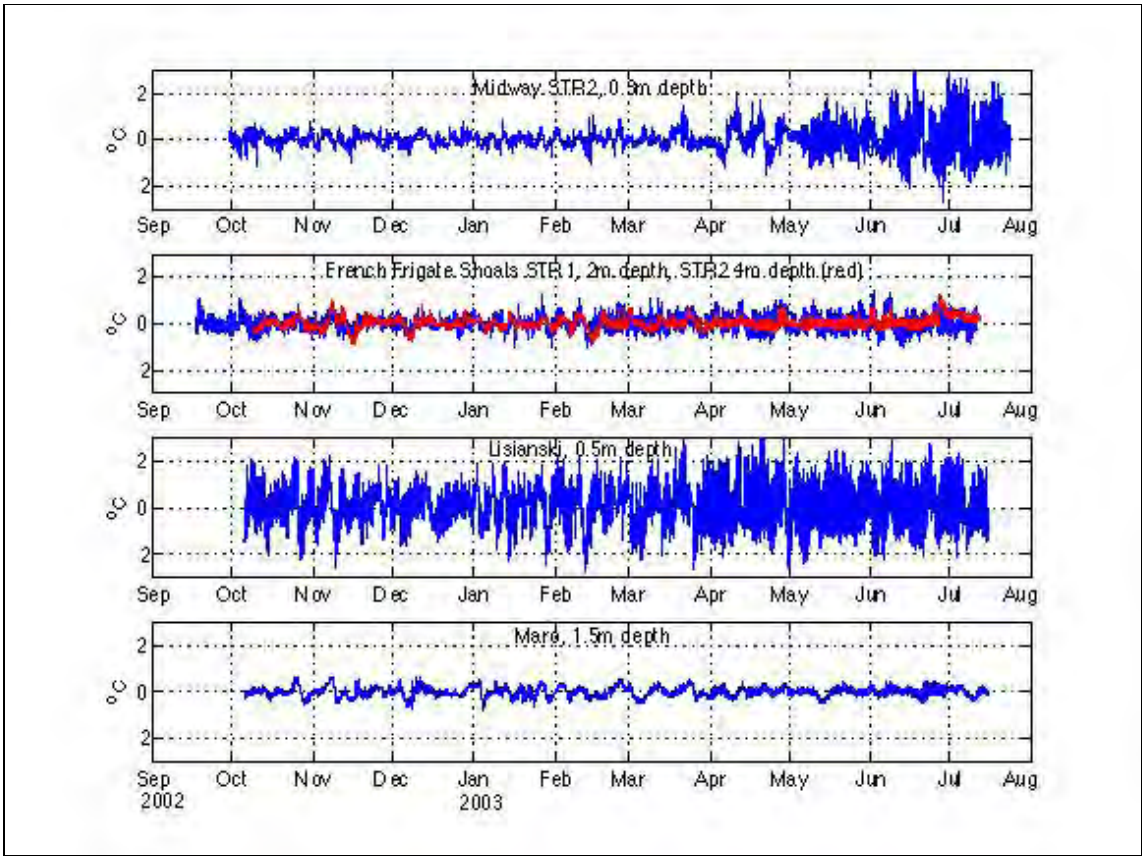


Figure 8. STR fluctuations (high pass filtered) at some selected NOWRAMP sites.

The most energetic high frequency fluctuations occur at 1 cycle per day due to the diurnal cycle of solar radiation (Figure 9), with highest temperature occurring at ~ 2pm HST. Secondary peaks occur at semidiurnal and higher tidal frequencies, due presumably to variations in sea level causing the STR to be closer to the surface during low tide. The strength of the diurnal cycle varies considerably from site to site. One explanation for this variation may be sensor depth. For example, at French Frigate Shoals, the STRs located at 2m and 4m depth show significantly weaker diurnal fluctuations than at Midway where the sensors are at 0.3m and 0.5 m depth.

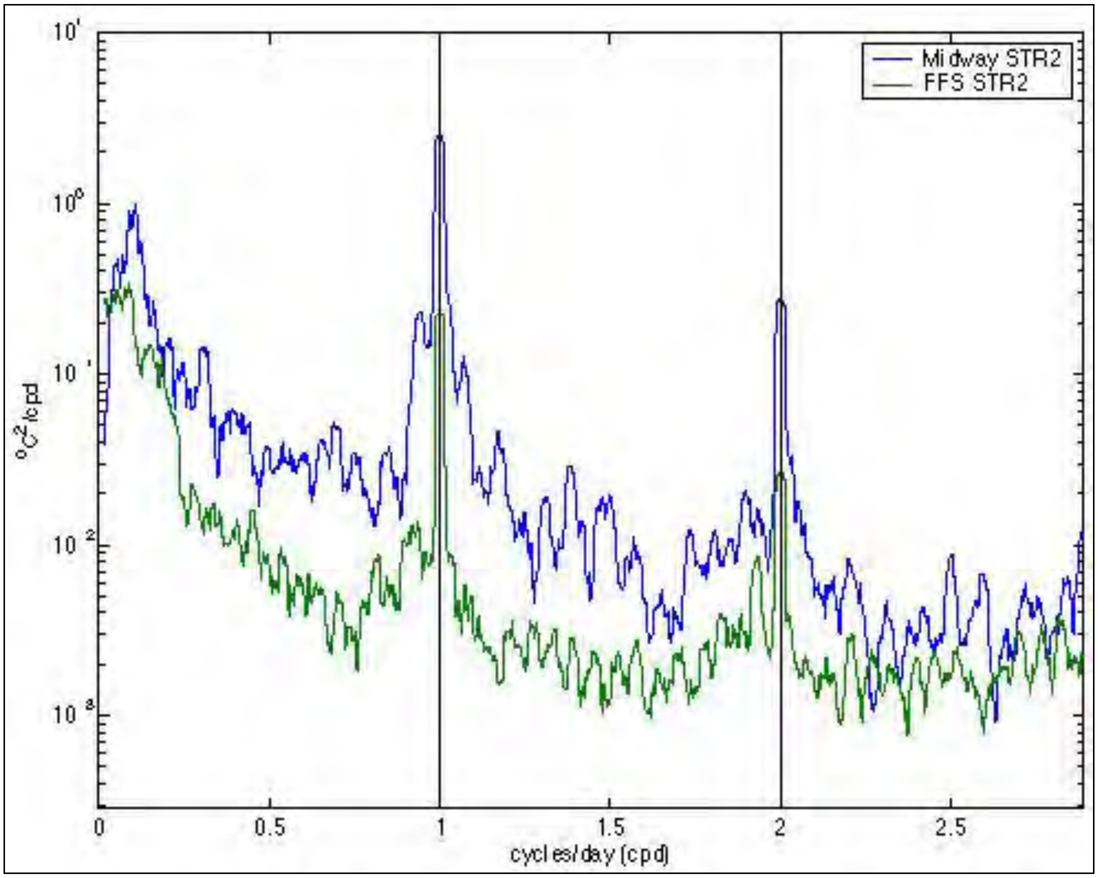


Figure 9. FFS and Midway Atoll In-situ STR Spectra.

Kure and Midway show a similar relationship in the strength of diurnal heating cycle, with the Kure sensors located at 1m depth. The depth of the instrument does not account completely for the strength of the diurnal heating cycle. At Maro Reef, the STR is at 1.5m depth, similar to Kure, yet the diurnal cycle is nearly absent (Figure 7). In contrast at Lisianski (0.5 m depth), the diurnal cycle is the most energetic of all the STR records, with strong fluctuations occurring throughout the year, i.e., not just during spring/summer. Likewise, the strength of the diurnal signal is not clearly related to latitude since Lisianski and Maro Reef are both located near the middle of the study site. The anomalous diurnal signals at Lisianski (highest amplitude) and Maro (lowest amplitude) may be related to the geography of each site. Lisianski is an isolated island (Appendix II figure 4) whereas Maro is a broad reef complex rather than a well-developed coral atoll (Appendix II, figure 3). The details of the diurnal heat budget are beyond the scope of this study; however, a combination of factors clearly is important (i.e., depth, geography, vertical mixing rates, solar irradiance, etc.).

4.2 Comparison of in-situ STR and Reynold's SST data

Before analyzing the variability of Reynolds SST, we compare the data to the in situ STR measurements collected as part of NOWRAMP. The STR data was collected after the 2002 bleaching event, and so we do not have field validation of SST for the bleaching time period. Nevertheless, the STR time series are nearly one year in length, and they provide direct measurements at the study sites of interest. This said, the comparisons are of very different measures of temperature; the STR data are point measurements made very close to the coral reefs, while the satellite derived SSTs are averages over 1° by 1° spatial area. We make the comparisons for the nearest SST grid point to the STR location. We note that even though we will assess historic bleaching events based on the Reynolds SST product, the offshore SST is only a first approximation of inshore reef conditions (Jokiel et al., 2004). In our case, we will be comparing 7 days averages of temperature (the averaging period of Reynolds SST data), and so we will be neglecting the contribution of the diurnal signal on the coral bleaching indices.

The time series plot for Kure (STR1) shows a typical comparison between the STR and Reynolds SST data (Figure 10).

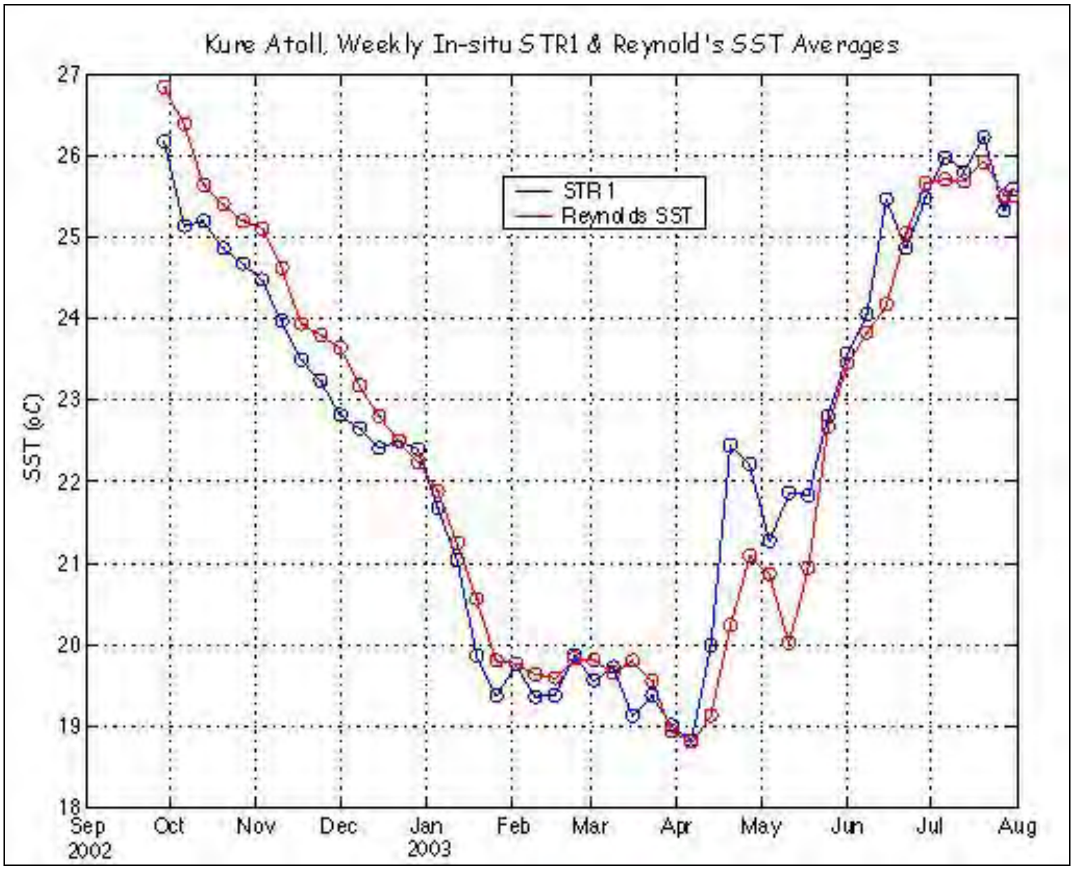


Figure 10. Comparison between In-situ STR-1 and Reynold's SST at Kure Atoll.

In general, the Reynolds SSTs are warmer than in-situ SSTs during the winter (Dec-Feb) and more similar during the summer (June-Sep). This may be due in part to localized warming and cooling in shallow reef areas where the water circulation is restricted (Jokiel et al., 2002).

We further compare the in situ and Reynolds SSTs by computing a linear regression (SST = a * Reynolds SST+b) for each location (e.g., Kure STR1, Figure 11).

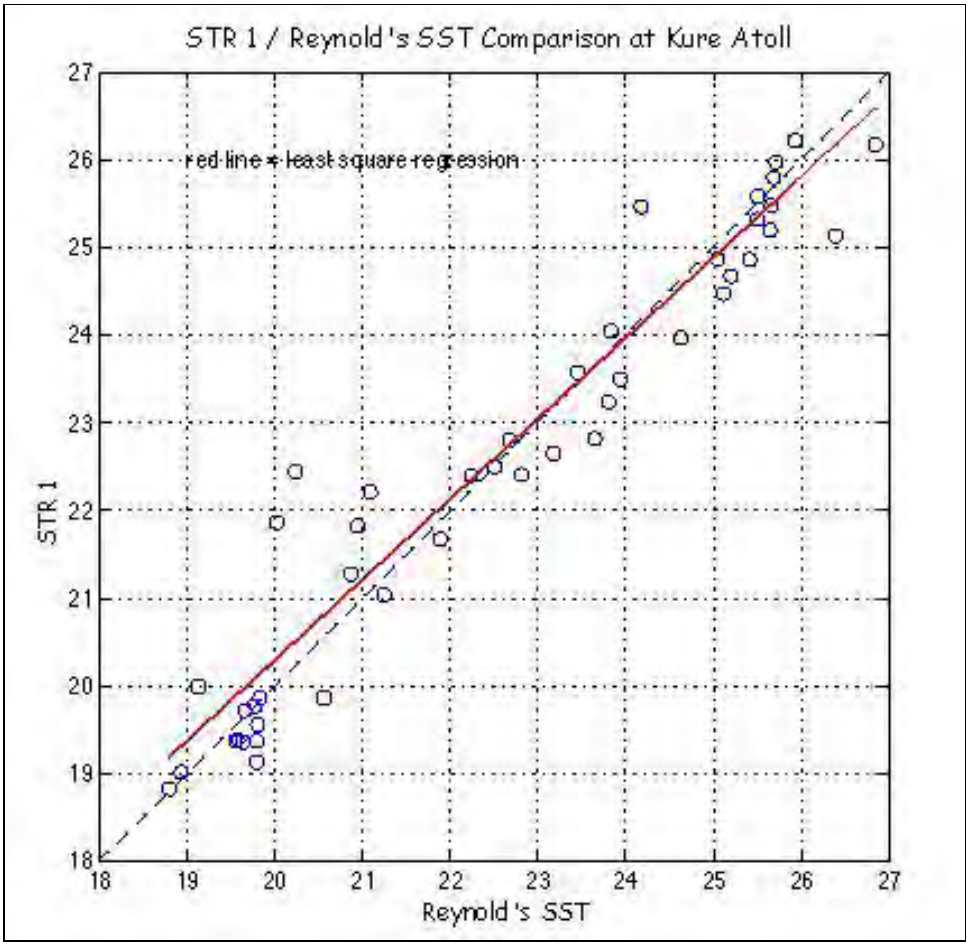


Figure 11. Comparison between In-situ STR 1 and Reynold's SST at Kure Atoll, with the computation of a linear regression.

The regression values range from 0.81 to 1.13 with the best correspondence (a~1) at French Frigate Shoals, Maro Reef and Lisianski Island. The slopes are consistently less than 1 at Kure Atoll and particularly Midway, and greater than 1 at Pearl and Hermes Atoll. Correlations are typically greater than 0.9, except at Lisianski. The standard deviation of the residual error (STR-Reynolds SST) is typically less than 1 °C, except at Lisianski (1.30°C). Because bleaching events tend to occur in summer, we compute the bias error (STR-Reynolds SST) for the months June-September. Here we find that the errors are typically small (± 0.2), except at Lisianski, Maro, and Midway (STR1). We do not find a consistent bias amongst the stations, indicating that the Reynolds SST is not biased low or high on average compared to the STR data. We therefore analyze the temporal variability of Reynolds SST without adjusting this data to match the in-situ data.

In-Situ Data	Slope	Y Intercept (°C)	Corr Coef	Standard Deviation of the Residual (°C)	Summer Bias (°C)
French Frigate Shoals FFS-STR 2	1.03	-1.06	0.93	0.54	0.09
French Frigate Shoals FFS-STR 1	1.01	-0.48	0.96	0.39	-0.06
Maro Reef MARO	0.98	0.42	0.94	0.63	0.44
Lisianski Island-Neva LISI-STR	0.96	1.00	0.83	1.30	1.07
Pearl & Hermes Atoll PHR-STR 3	1.12	-3.41	0.98	0.51	-0.13
Pearl & Hermes Atoll PHR-STR 2	1.14	-3.83	0.98	0.51	0.05
Pearl & Hermes Atoll PHR-STR 3	1.10	-2.98	0.99	0.47	-0.11
Midway Atoll MID-STR 1	0.81	4.01	0.90	0.91	-0.52
Midway Atoll MID-STR 3	0.87	2.83	0.90	1.01	-0.07
Midway Atoll MID-STR 2	0.86	3.08	0.93	0.86	-0.15
Kure Atoll KURE-STR 2	0.90	2.23	0.97	0.56	-0.16
Kure Atoll KURE-STR 1	0.92	1. 89	0.96	0.64	0.11

Table 2. Reynold's SST/ NOWRAMP in-situ SST Correlation Coefficients

4.3 Description of Reynolds SST

We now examine the temporal and spatial variability of Reynolds SST for the time period 1981 through 2003. The time series near Midway typifies the temporal variability of the NWHI region (Figure 12a). The seasonal cycle is the dominant fluctuation, with an approximate 10°C range. The highest recorded weekly averaged temperature occurs during the summer of 2002. The SST anomaly (SST with annual cycle averaged over the last two decades removed) near Midway shows multi-year oscillations with 1-2°C amplitudes (Figure 12b). Decadal time scales are evident, as anomalies rarely exceed 1°C during the mid-1990s, whereas during the early 2000's anomalies are often greater than 1°C. Superimposed on this low frequency signal are short-term heating events, with amplitudes are large as 3°C. The short-term heating events at times add to the summer high, such as the summer of 2002 when a 2°C anomaly occurred. Some of the larger short-term anomalies (e.g., 1999, 2000) occurred during the winter months, and so they did not lead to high temperatures. In general, peak temperatures are due to a combination of summer high temperatures, which typically occur during August and September, short-term anomalies, and low frequency modulations.

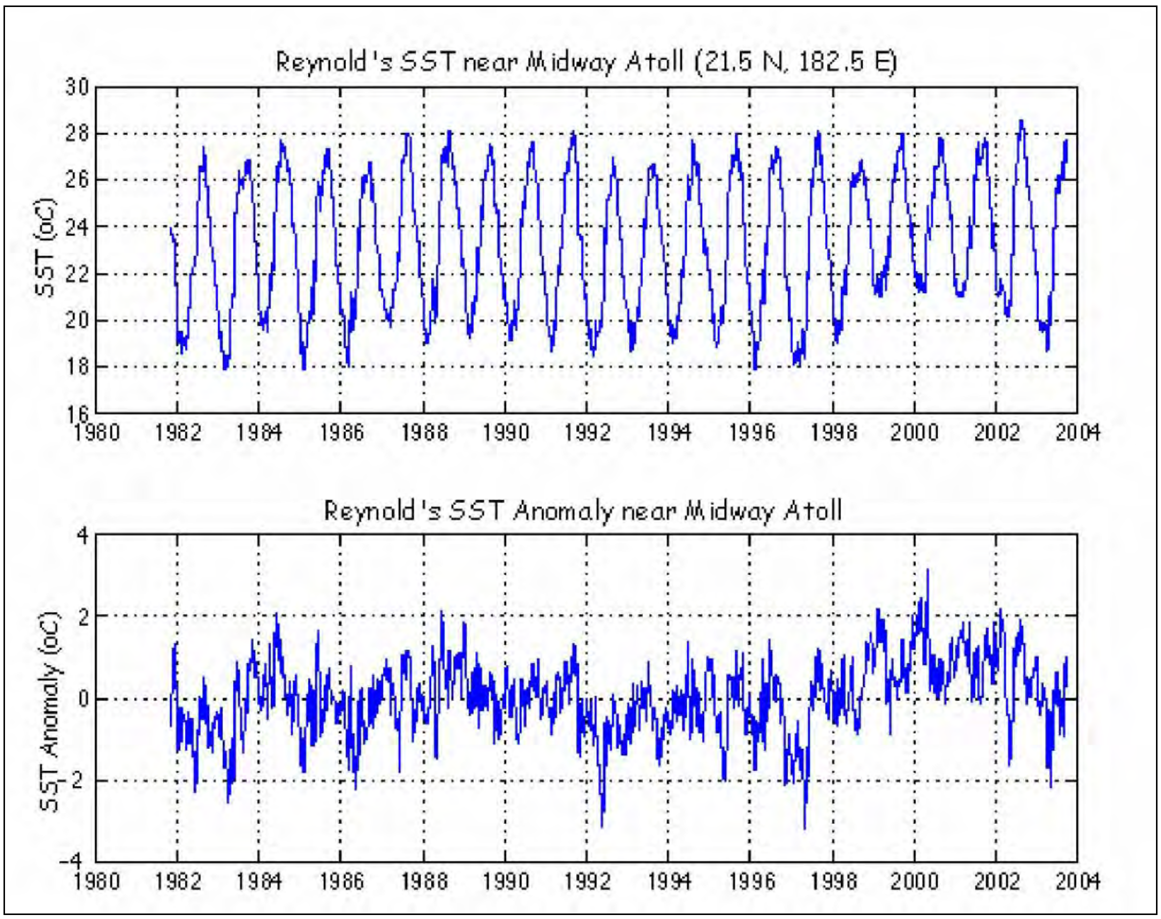


Figure 12 a&b. Reynold's SST and SST Anomaly Time-series at Midway Atoll.

Monthly averaged SST anomalies during summer (August) and winter (February) are only weakly correlated (0.49 at Midway) over the study period (Figure 13). Thus, temperature anomaly fluctuations in summer are not necessarily related to those in winter. For example during the winters of 1999-2002, anomalies were consistently high, whereas only the 2002 summer showed a strong positive anomaly. The summer and the annual mean anomalies are also poorly correlated (0.42). This suggests that the highest temperature event observed in the NWHI (summer 2002) is a short-term event, unrelated to winter or longer-term conditions.

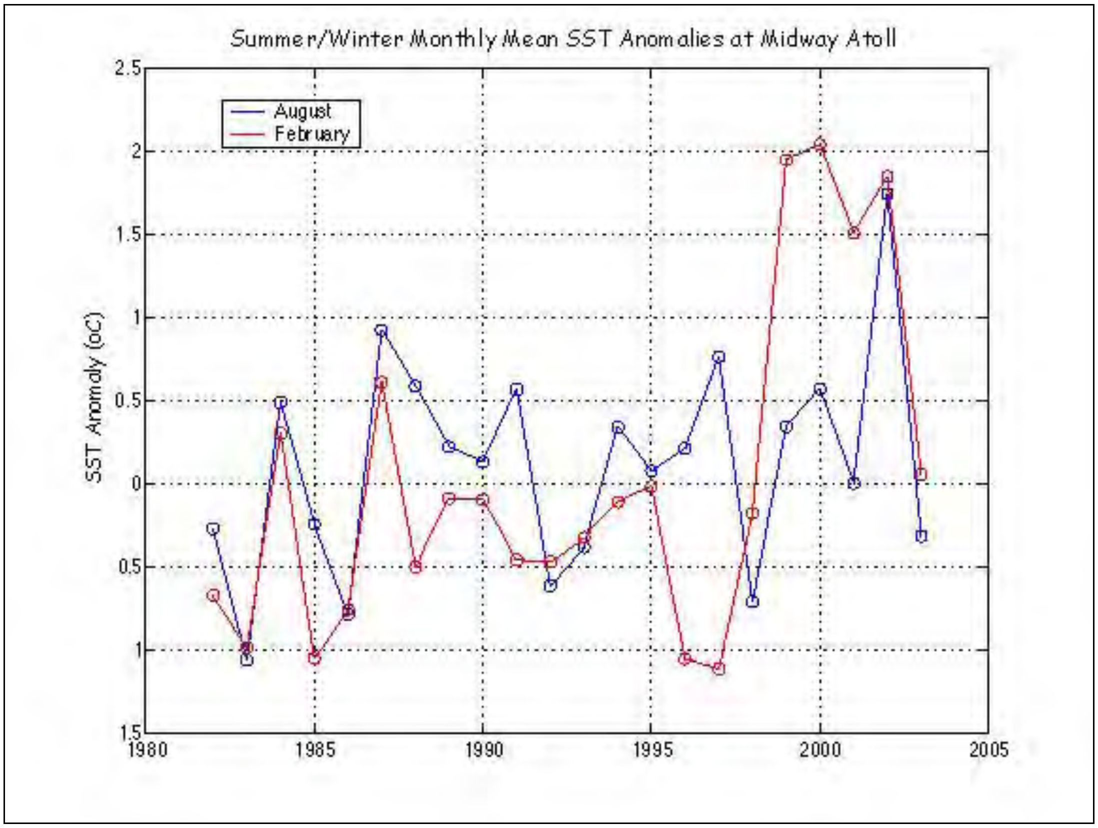


Figure 13. Midway Atoll Monthly Average SST Anomalies during summer and winter.

The spatial variations of SST are examined using summer (August) anomaly maps for 1982-2003 (Appendix III plots of August SST from 1982 to 2003). Summer temperature anomalies exhibit significant spatial structure. In general, variations in the NWHI are not related to variations at the main islands. The occurrence of high SST anomalies seems to be quite localized relative to the length of the Hawaiian Archipelago. Even for the STR stations, significant differences in temperature can occur for a given summer. For example, in 1996 French Frigate Shoals and the main Hawaiian Islands experienced nearly 1°C anomalies, while temperatures were close to long-term means (zero anomaly) at the northernmost NWHI atolls. This was the year of reported coral bleaching at Kaneohe Bay, Oahu, and on the island of Maui (Jokiel, 2004). Looking at the spatial patterns of SST anomaly fluctuations over the last two decades, it appears likely that other coral bleaching events occurred prior to 1996. For example, possible locations and times of coral bleaching include Midway and Kure in 1987, FFS in 1996, and Maro Reef in 1997. We observe that the 2002-bleaching event in the Northwestern Hawaiian atolls corresponds to a prolonged significant positive SST anomaly during summer, 1 to 2°C greater that the seasonal summer temperature. The affected area included the three most northern atolls: Midway, Kure, and Pearl and Hermes. Indeed, as reported by Aeby et al., 2003, vast areas of the back reef and other lagoon habitats at Pearl and Hermes Atoll, Midway Atoll and Kure Atoll were severely bleached, with many areas observed to have suffered greater than 50 % coral mortality.

4.4 Thermal Thresholds and Accumulated Thermal Stress

Impact thresholds for a variety of climate variables must be identified to assess risks to coral reefs and to combine them with climate model forecasts to evaluate the probability that such thresholds will be exceeded (Pittock, 1999). SST appears to be one of the most important environmental criteria affecting the existence of coral reefs. Yet, defining the upper thermal limits of coral species in anything but general terms has proved surprisingly difficult (Berkelmans, 2002). To date, the only threshold reported for the NWHI is a 28°C threshold for the Midway atolls by the Coral Reef Watch Program. One long-term purpose for deploying the STRs is to establish such a threshold empirically for each location. Until this project is complete, we compute thermal thresholds from the Reynolds SST for the entire NWHI region (Figure 14, algorithm described in section 2).

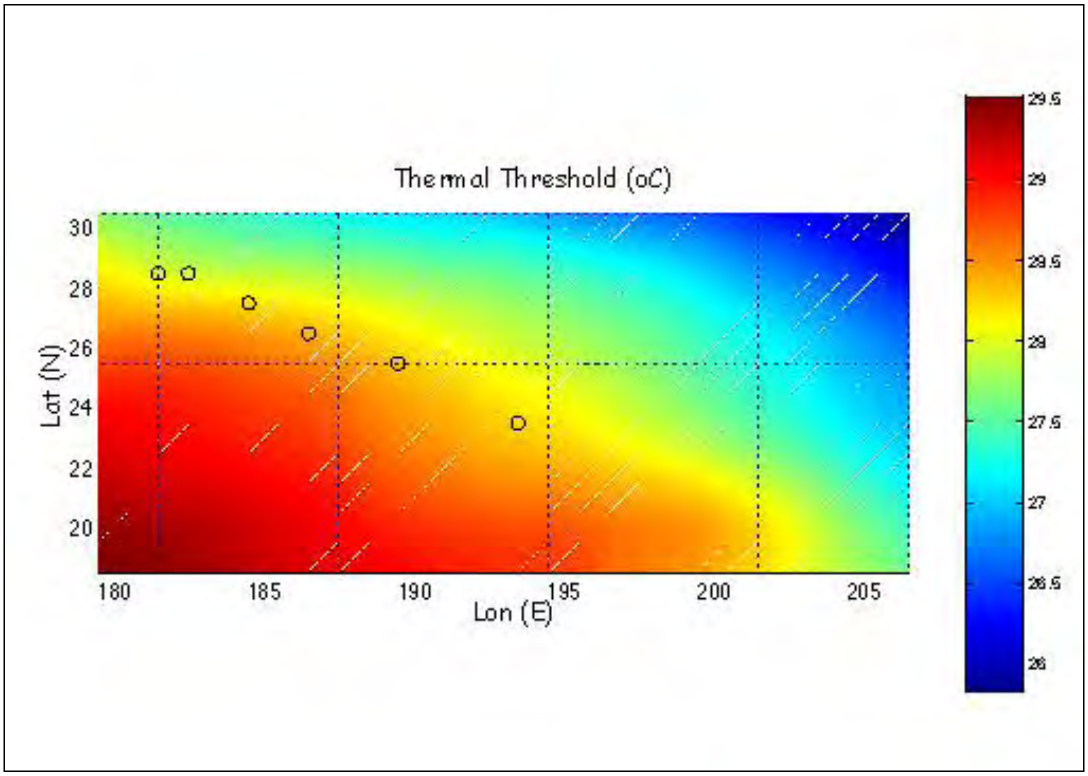


Figure 14. Computed Thermal Threshold over the Entire NWHI Region

The values at the STR sites range from 27.94ºC at Midway Atoll to 28.37°C at Lisianski Island (Table 3). The thresholds are similar at the main Hawaiian Islands.

Location	20-yr mean SST of the warmest month (°C)	Thermal Threshold (+ 1°C)	Degree-Heating-Days (degree-days) during summer 2002.
Kure Atoll	27.007	28.007	20.006
Midway Atoll	26.94	27.94	19.600
Pearl & Hermes Atoll	27.197	28.197	5.705
Lisianski Island	27.37	28.37	0.910

Maro Reef	27.31	28.31	0
French Frigate Shoals	27.25	28.25	0

Table 3. Thermal Threshold Values (ºC) and computed Accumulated Thermal Stress (DHD) at every NOWRAMP Locations.

For each STR site, we plotted the complete Reynolds SST time series with the thermal threshold indicated to estimate the occurrences of possible bleaching events (Appendix IV, Reynolds SST time-series at every location). At Midway Atoll, we observe that the so established thermal threshold has been slightly exceeded during the summers of 1987, 1988, 1991, 1995, 1997, 1999 and significantly exceeded during summer 2002. For Kure Atoll, the threshold has been slightly exceeded by the weekly SST mean during summers 1987, 1988, 1991 and more clearly exceeded during summer 2002. Analysis of weekly mean SST for the NWHI chain for the last two decades (Reynold's SST) reveals that 2002 is a year when the highest seasonal temperatures have been recorded for the most northern Northwestern Hawaiian Atolls (28.60°C, 28.65°C and 28.40°C in August respectively at Midway, Kure and Pearl & Hermes Atolls). Similar results are found for the other sites, except French Frigate Shoals where the threshold is never exceeded, even during the summer 1996 event.

Based on the evaluation of thermal threshold, we next consider the accumulated thermal stress (described at the Coral Reef Watch Program website). This parameter takes into consideration that the threshold is not only exceeded, but it accounts for the duration and intensity of the high SST event. The accumulated thermal stress is computed for each of the STR sites using the closest Reynolds SST time series. Over the last two decades, year 2002 clearly stands out as being a year with favorable conditions for coral bleaching to occur (Figure in Appendices IV and V). Moreover, the DHD values show that only the northern Hawaiian Atolls, in particular Midway and Kure Atolls, were affected by this high SST event. The other NW Hawaiian atolls appear to have been less affected by the 2002 event. Maro Reef and Lisianski Island show other periods of accumulated thermal stress (1984 and 1997); however, the values are quite low compared to the 2002 values for Midway and Kure. At French Frigate Shoals, the warmest SST of years 1997 and 1998 do not have an associated accumulated thermal stress signal.

The Accumulated Thermal Stress value obtained for Midway and Kure Atoll are significant but relatively low. The Coral Reef Watch Program estimates that coral bleaching can be expected when the accumulated thermal stress reaches 4 DHWs, equivalent to about 28 DHDs. For accumulated thermal stress values of 10 DHWs, about 70 DHDs, severe bleaching and possibly mortality are expected. Based on the Reynolds SST data, the 2002 bleaching event observed at the NWHI fell just below the Coral Reef threshold for bleaching to occur. Although the values are weak, coral bleaching in Kure and Midway has been observed (Aeby, 2003). Recent reports suggest that the affected corals may have recovered since 2002 (personal communication, J. Gove, 2004), suggesting that the event was not severe, consistent with the results from Reynolds SST.

4.5 Description of the 2002 High SST Anomaly at the NWHI

Based on the Reynolds SST weekly averaged dataset, the warmest recorded temperatures in the NWHI occurred during August 2002. In terms of Accumulated Thermal Stress, the three northern most STR sites (Midway, Kure, and Pearl & Hermes) experienced by far the highest values over the past 22 years (table 3 and appendix V). The STR stations to the south did not record a warming event of this magnitude. For example, temperatures at French Frigate Shoals did not exceed the established thermal threshold. Monthly mean Reynolds SST show the localized nature of this warming event (Figure 15 a&b). During July 2002, anomalously high temperatures occurred in a region encompassing the three northernmost atolls, with typical values of 1-1.5°C. At the southern part of the NWHHI, temperature anomalies are near zero. In August, the high SST pattern persists and extends further east and south. A more detailed depiction of week-to-week changes in SST over the region is included in Appendix VI. Even on a weekly basis, only Midway, Kure, and Pearl & Hermes are affected by temperature anomalies approaching 1.5°C.

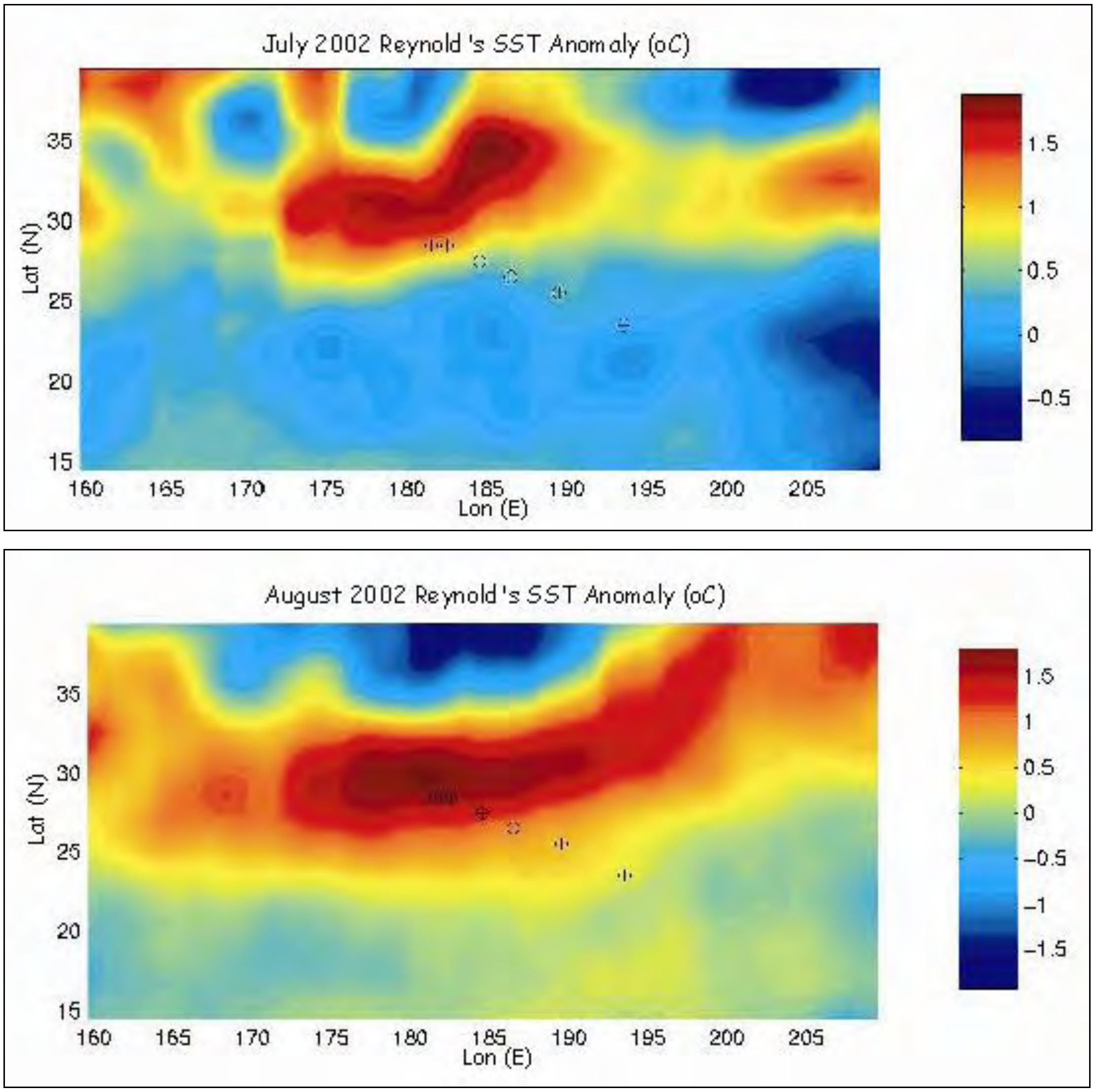


Figure 15 a&b. July and August 2002 Monthly Mean Reynold's SST Anomalies.

Although a variety of factors can affect near surface temperatures, low wind speeds are commonly associated with reef-wide bleaching events (Berkelmans, 2002). Wind speed anomalies for the region were obtained from the NCEP Reanalysis dataset. The July and August 2002 anomalous surface wind vectors and anomalous wind speeds show areas of reduced wind speed (1-2 m/s reduction) that correspond to the observed positive SST anomalies (Figure 16 a&b). The anomaly corresponds to a reduction in the Northeast Trade winds, which have typical speeds during July and August of 4.5 to 6 m/s in this region. The similar localized patterns of wind and SST suggest that reduced wind speeds contributed directly to the warm NWHI event. In general, reduced wind speeds correspond to reduced evaporation and latent heat loss from the ocean, and a decrease in turbulent mixing in the surface layer, which all lead to increased surface temperatures. It is of interest to note that such localized (limited in scope) changes in wind pattern can be responsible for warming the SST within a few days of onset.

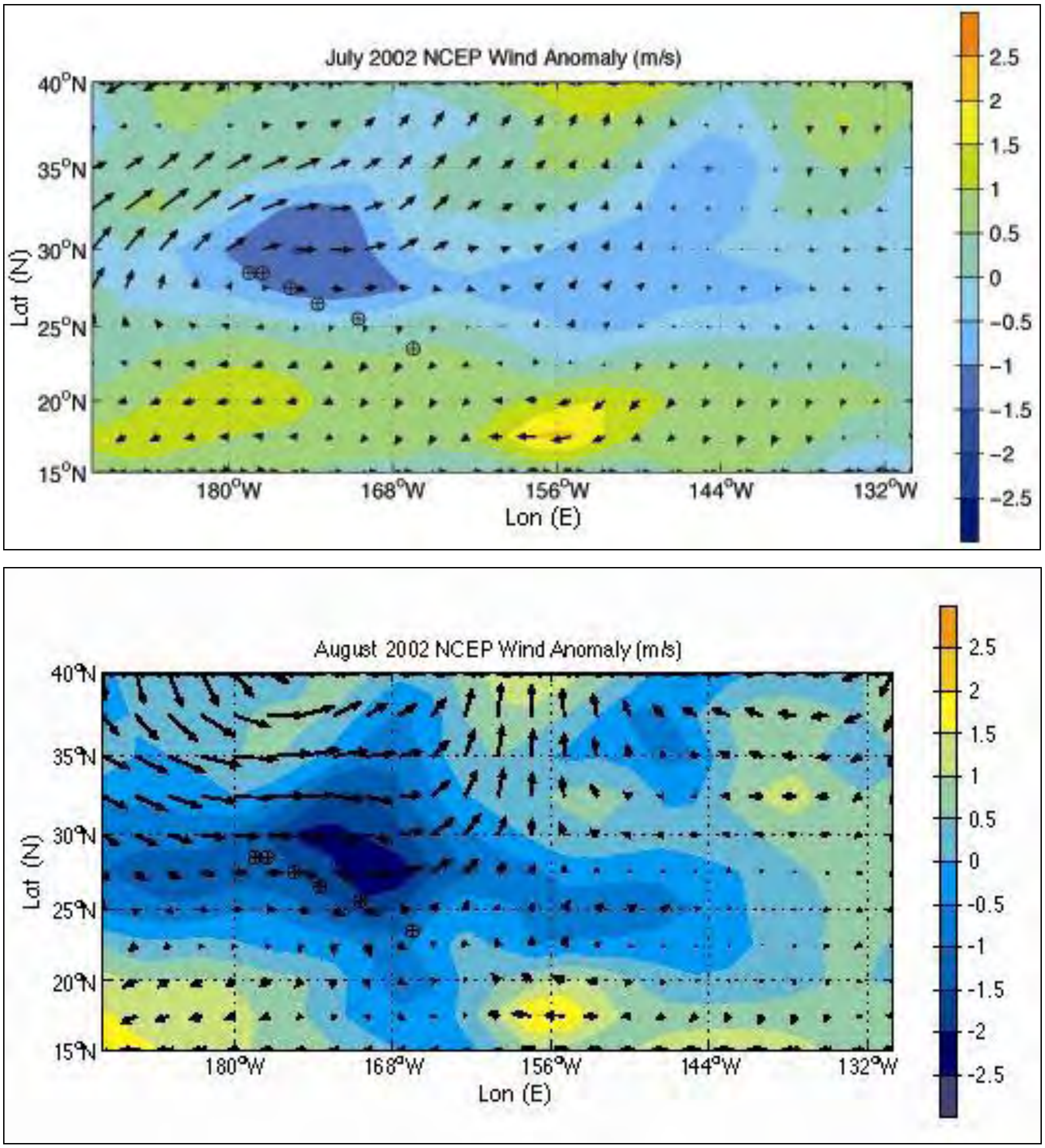


Figure 16 a&b. July and August 2002 NCEP Wind Anomalies.

Attempts to relate wind speed anomalies and SST anomalies over longer time spans show a weak negative correlation (-0.42) at the NWHI (Figure 17). In the case of winds and SST near Midway, the relationship is not always obvious (e.g. summer 2000). This suggests that wind speed is not the only factor affecting SSTs. Although many factors are influencing conditions favorable to coral bleaching, the action of the winds in the NWHI region appears to be closely related to changes in SSTs.

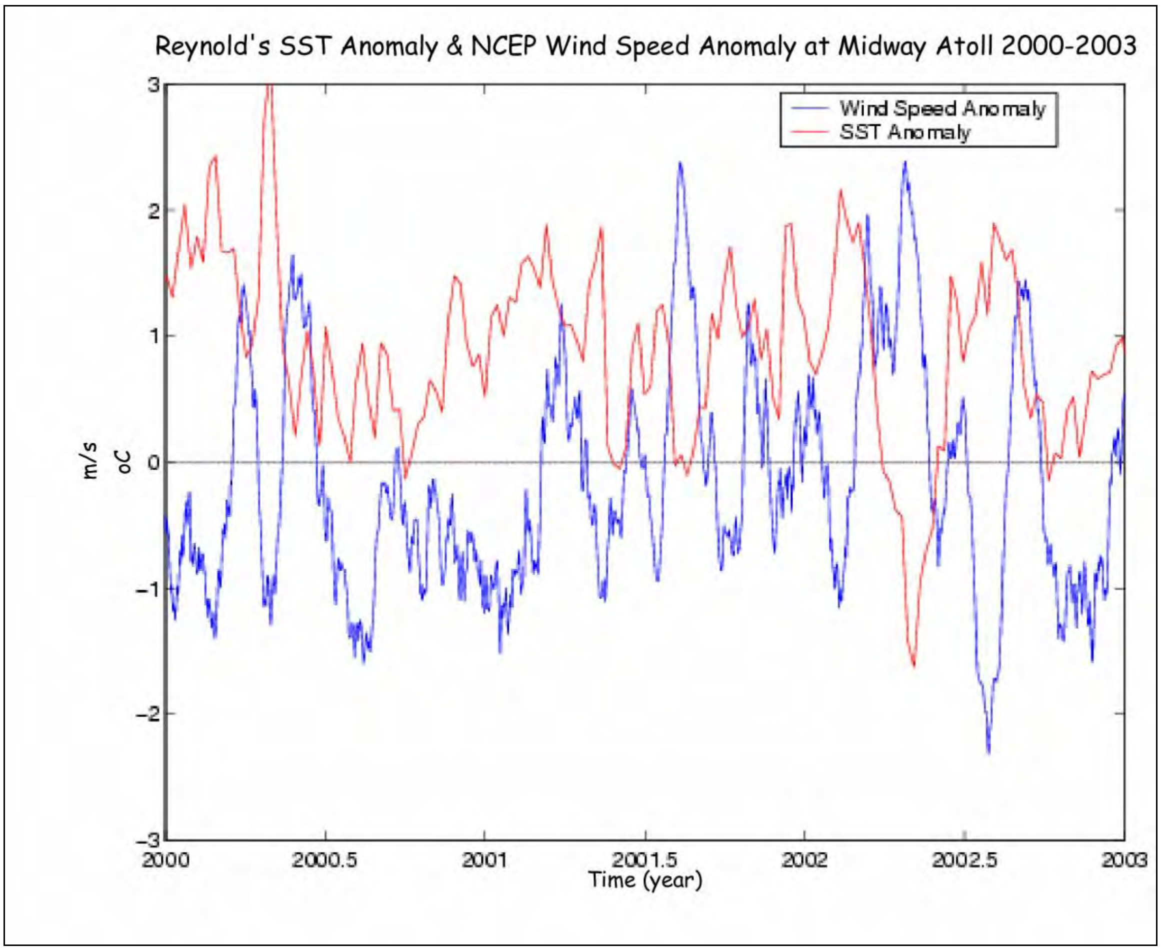
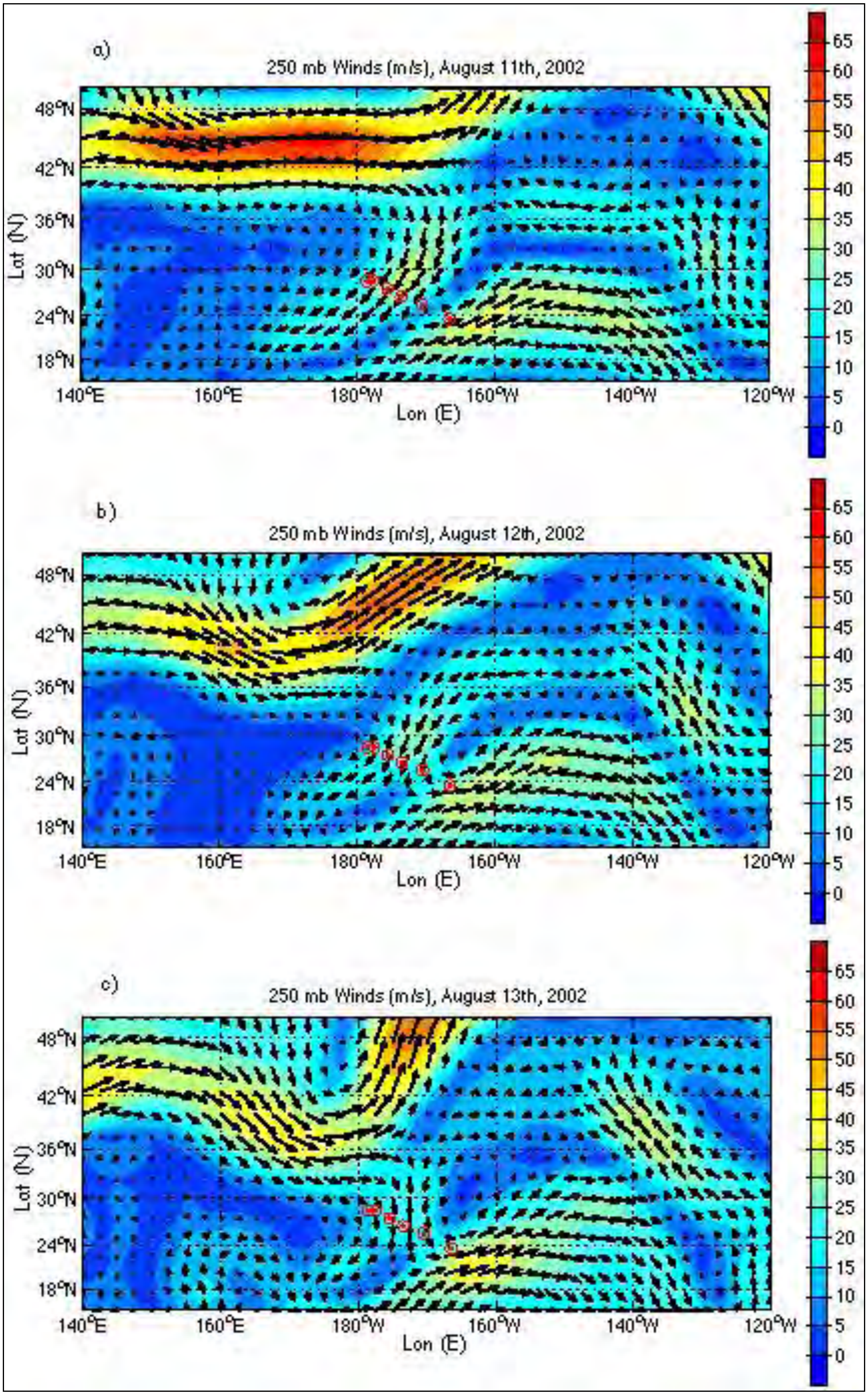


Figure 17. Comparison between Variations of Reynold's SST Anomaly and NCEP Wind Speed Anomaly at Midway Atoll.

We next consider the causes of the summer 2002 wind relaxation in the NWHI. Higher in the atmosphere (250 mbar), anomalous westerly winds occur above 40°N, which vary considerably from day to day. For example, in mid-August, the winds veer strongly toward the south and loop to the north just above the NWHI (Figure 18). At the surface, the manifestation of this event is a cyclonic wind anomaly, averaged over the month, causing weakened Trade winds over the northern NWHI. This appears to be a synoptic scale, mid-latitude “weather” event. In that sense, it is relatively unpredictable in that it is short-term and limited in spatial extent.


a)
250 mb Winds (m/s), August 11th, 2002
b)
250 mb Winds (m/s), August 12th, 2002
c)
250 mb Winds (m/s), August 13th, 2002
Lat (N)
Lon (E)
48°N
42°N
36°N
30°N
24°N
18°N
140°E
160°E
180°W
160°W
140°W
120°W
65
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20
15
10
5
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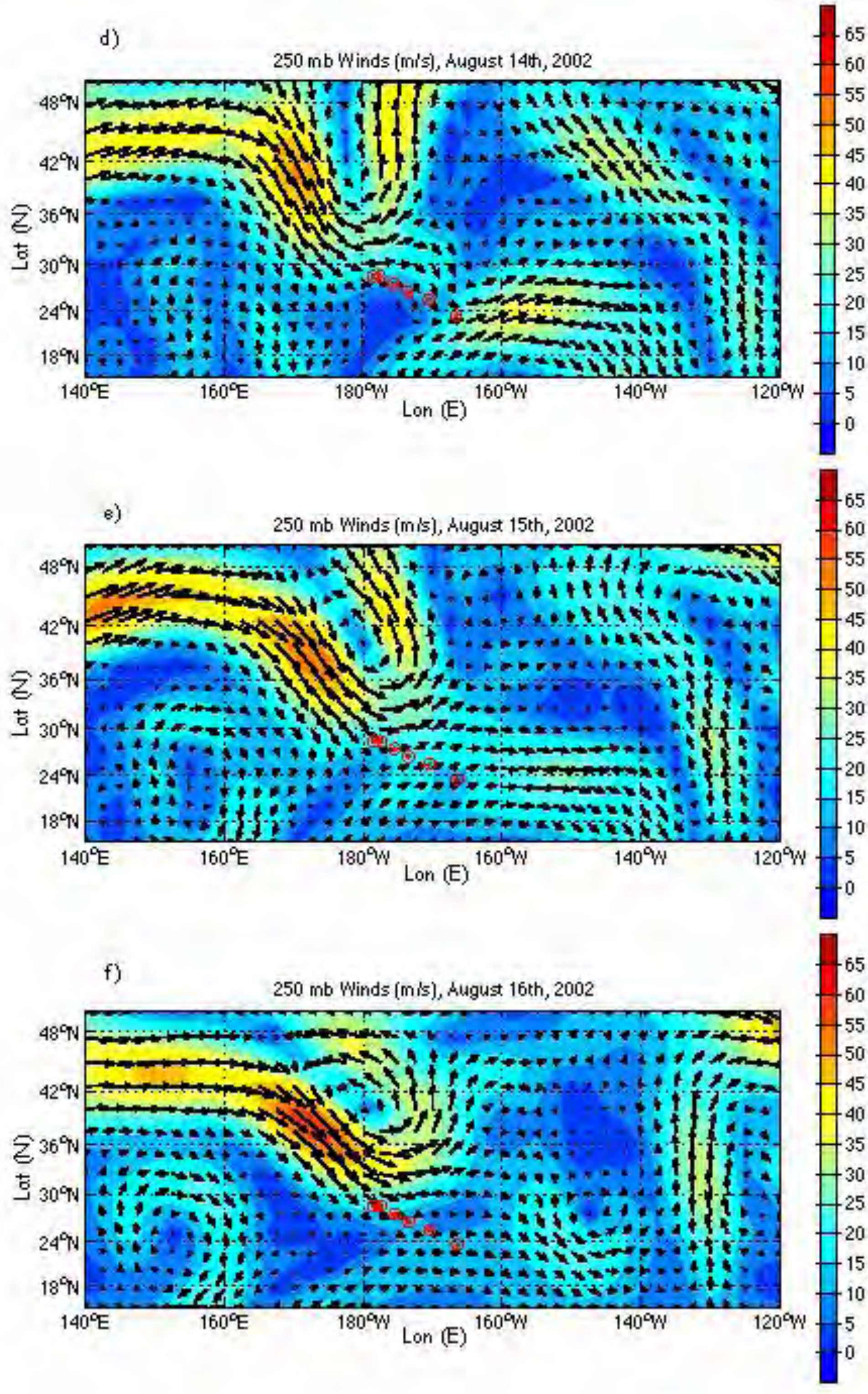
d)
250 mb Winds (m/s), August 14th, 2002
48°N
42°N
36°N
30°N
24°N
18°N
Lat (N)
140°E
160°E
180°W
160°W
140°W
120°W
Lon (E)
65
60
55
50
45
40
35
30
25
20
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10
5
0
e)
250 mb Winds (m/s), August 15th, 2002
48°N
42°N
36°N
30°N
24°N
18°N
Lat (N)
140°E
160°E
180°W
160°W
140°W
120°W
Lon (E)
65
60
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40
35
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250 mb Winds (m/s), August 16th, 2002
48°N
42°N
36°N
30°N
24°N
18°N
Lat (N)
140°E
160°E
180°W
160°W
140°W
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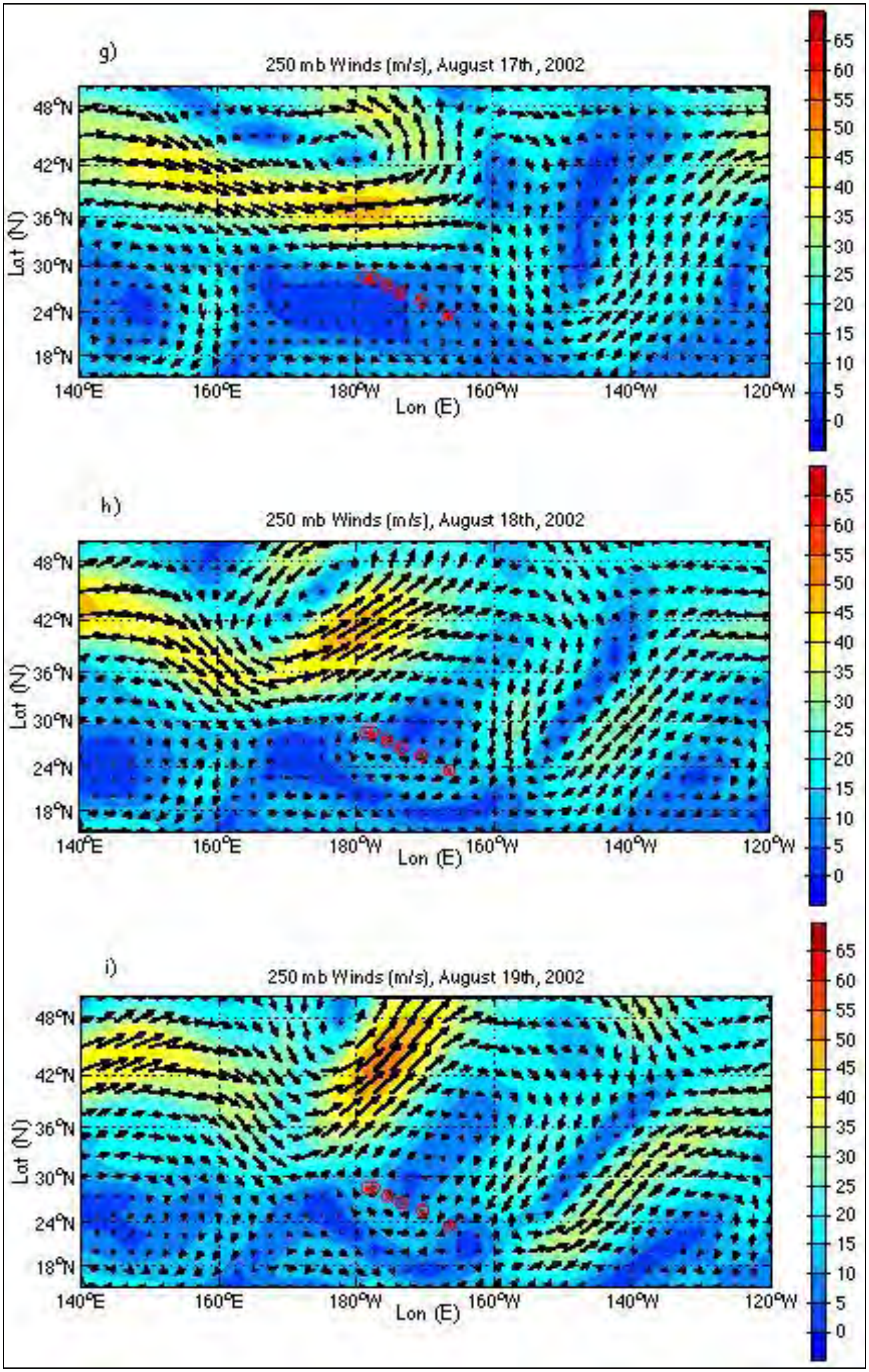

Figure 18 (a to i). Upper Level (250 mb) Winds over the NWHI Region (August 11th-August 19th).

In addition to the wind influence, cloudless skies can promote greater surface heating through enhanced short-wave solar irradiance at the sea surface. Looking at Geostationary Operational Environmental Satellite (GOES) visible, infrared and water vapor content band images from summer 2002, available at the National Climatic Data Centers Historical GOES Browser Server (http://cdo.ncdc.noaa.gov/GOESBrowser), although not conclusive, some evidence suggest fairly clear sky conditions during summer 2002.

Summary and Discussion

The 2002 coral bleaching event at the NWHI region coincides with the highest sea surface temperatures (>28°C for much of July and August) recorded in this region over the past 22 years (based on Reynolds SST, in situ data were not available). The warm area was limited to the northernmost atolls; atolls below Lisianski Island and Maro Reef, including the main Hawaiian Islands, were not as affected by this event. The evidence supports the common belief that elevated water temperature is the primary stress factor in this natural bleaching event.

The heat content of the ocean surface layer depends on a wide variety of factors, including surface heat flux, horizontal advection, and vertical mixing. In addition, the balance becomes more complicated near land where upwelling, wave action, and tidal mixing all play a role. Although the details of this balance are beyond the scope of this study, we do find a correlation between wind speed and SST, such that wind relaxations correspond to warm SSTs. Slack winds may cause surface warming due to reduced evaporation and latent heat flux, and weaker mixed layer turbulence and vertical mixing. Considering August 2002, the positive SST anomalies during July and August 2002 seem to be related with anomalously low wind speeds in the area. This synoptic anomaly appears to be on a small scale. All of this suggests that the summer 2002 NWHI coral bleaching event resulted from a synoptic scale, mid-latitude atmospheric feature that happened to occur concurrently with high seasonal SST. Stable, low cloud conditions may also have contributed to the high SSTs through enhanced solar radiation.

Interestingly, the intensity of the summer 2002 bleaching event appears to be relatively weak if we refer to the values we obtained for our accumulated thermal stress. Our values, based on weekly Reynolds SST, reached 20 DHDs, whereas NOAA's Coral Reef Watch Program estimates that 28 DHDs are needed for coral bleaching to occur. This may be due to the use of the Reynolds SST product, which neglects high frequency temperature variations that are significant in the NWHI, particularly on daily time scales.

It is important to remember that the satellite SST used to evaluate the temperature fluctuations in this remote region represent open ocean conditions. Although we attempted to show that Reynolds SST is a reasonable measure of in situ conditions at the atolls (section 4.2), the differences between weekly averages could be ~ 1°C (standard deviation). The restricted water circulation within the coral reefs could lead to significantly higher temperatures on time scales shorter than the weekly sampling period of the Reynolds SST. Local-scale oceanographic features (enclosed embayments, shallow coastal waters) have resulted in warmer and more variable SST regimes on some inshore fringing reefs compared with offshore reefs and between neighboring coastal waters (Berkelmans, 2002). In the case of the NWHI, the effects of the strong diurnal heating cycle observed at most of the atolls require further study. In addition, it would be useful to have more in situ data during the warmest summer months for comparison with Reynolds SST and, in particular, in situ data during a known bleaching event. The NOWRAMP project will address these issues as data becomes available.

In this study, we evaluate the accumulated heat stress using a degree-heating-days index (DHD). As noted by Berkelmans (2002), it is not known whether this is appropriate measure of stress on corals. For example, 20 degree-days can correspond to 6-7 days at 3°C above thermal threshold, or to 40 days at 0.5°C above thermal threshold. It is not clear if both situations have the same impact on coral bleaching. More studies of coral response to accumulated thermal stress are needed for NWHI species.

In other regions, large-scale bleaching events and increased SSTs have been related to recent El Nino events (Wilkinson et al., 1999), but the NWHI region has not experienced anomalous summer warming associated with any of the major El Ninos of the past 22 years (e.g., 1982-83, 1997-98). This supports the idea that the 2002 coral bleaching event was a weather, rather than a climate, induced event. There also is no indication of more frequent bleaching events associated with global warming, although the record examined here is too short for conclusive statements. While increasing SSTs may increase the frequency of temperature-induced stress on existing coral reefs over the long term, a critical question is the degree to which corals can tolerate and adapt to temperature increases in the short term (Brown et al., 1996).

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APPENDIX I
IKONOS satellite image of the major Northwestern Hawaiian Atolls with the exact locations of the STRs (NCCOS, 2004)

* Surface Temperature Recorder (STR)

Figure 1. French Frigate Shoals

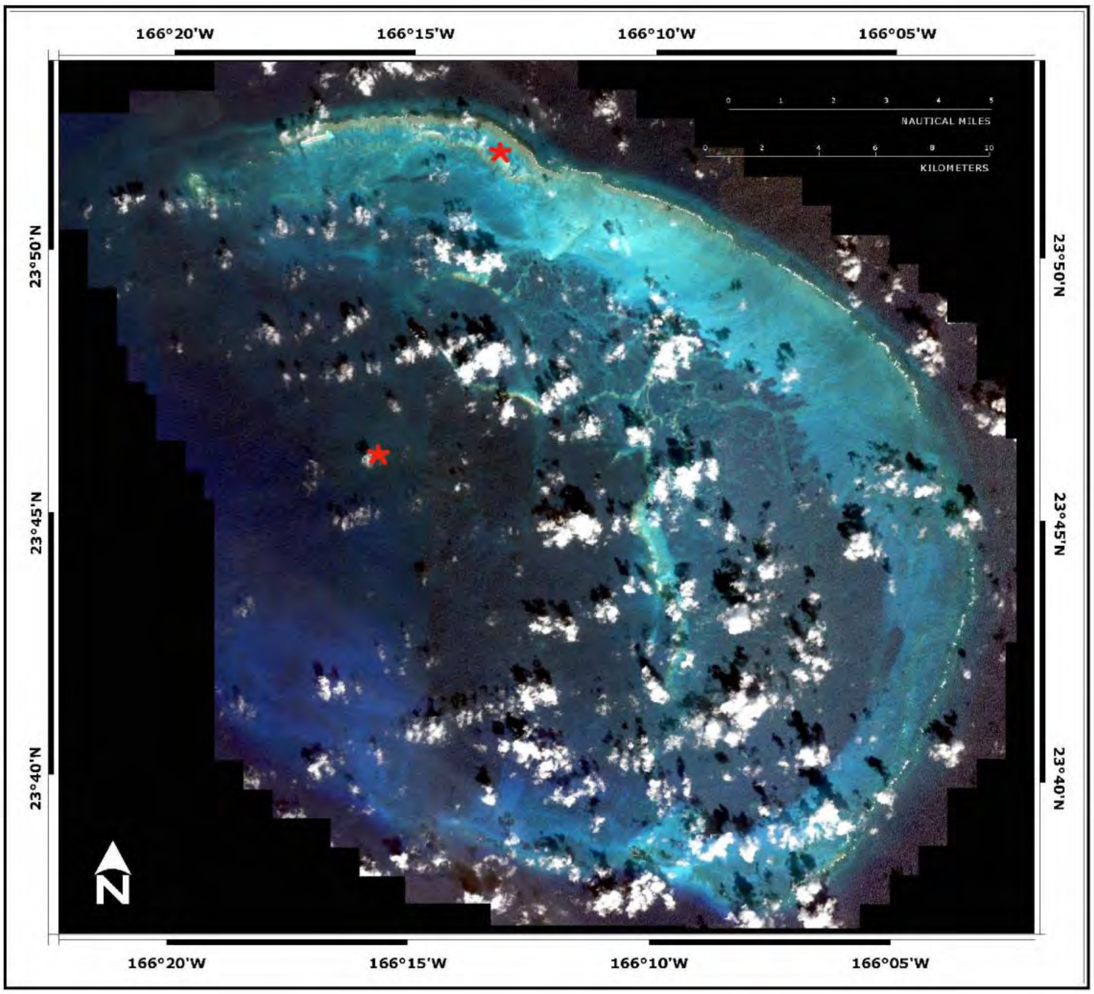


Figure 2. Maro Reef

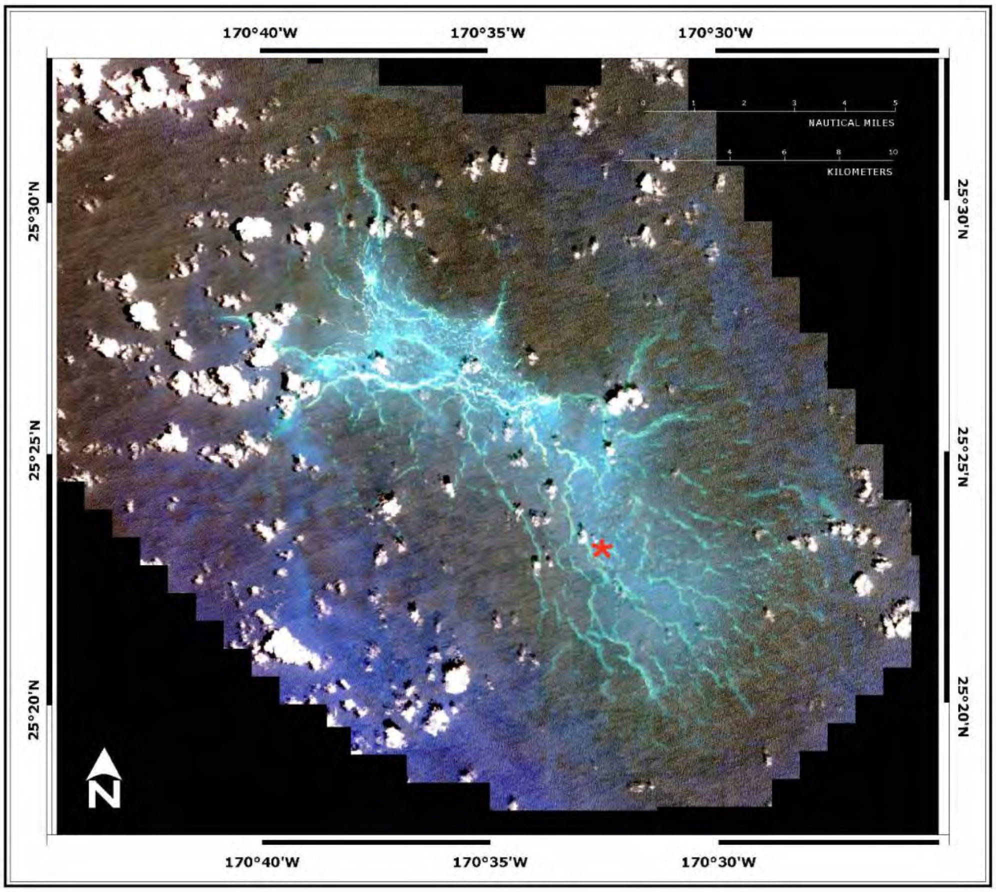


Figure 3. Lisianski Island

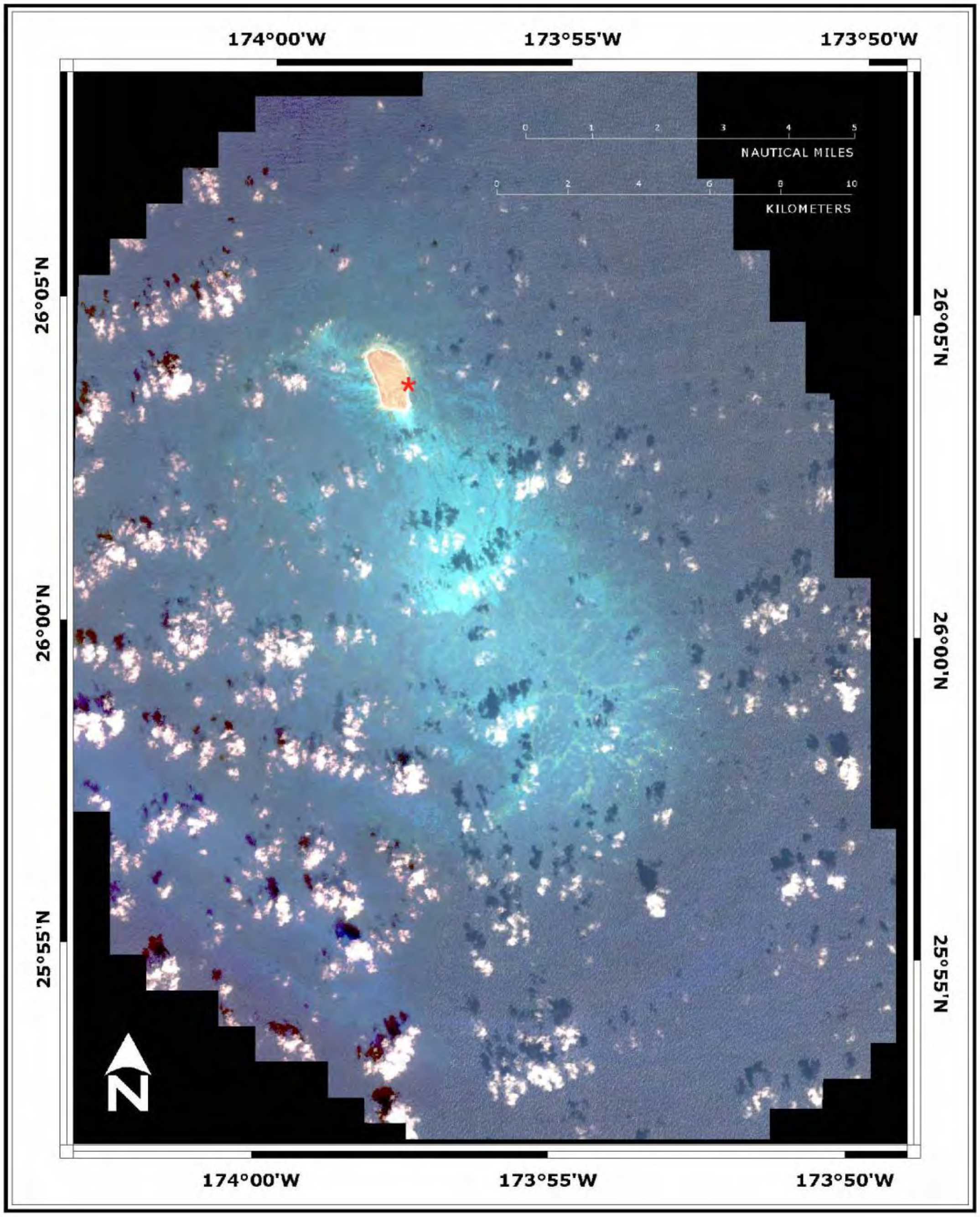


Figure 4. Pearl and Hermes Atoll

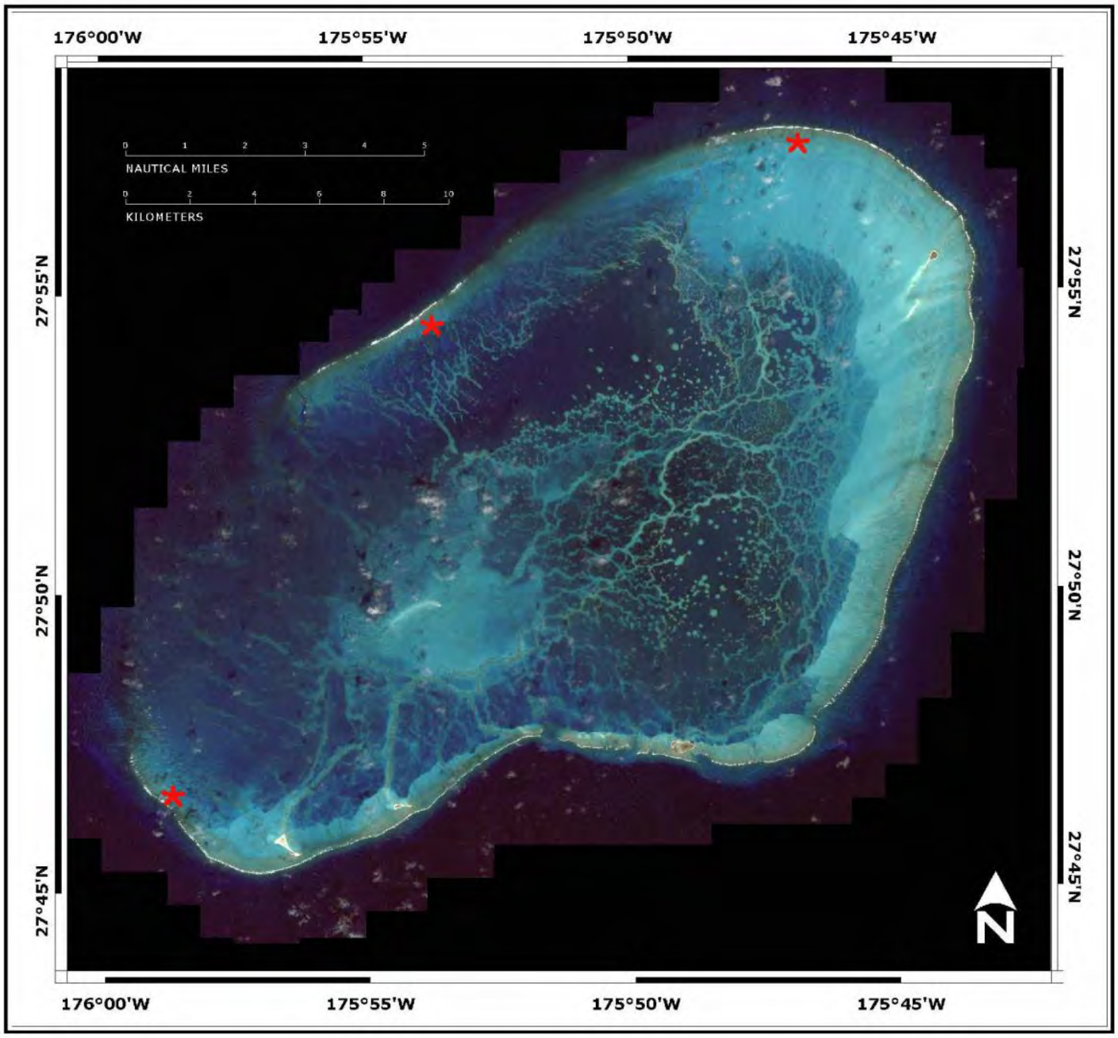


Figure 5. Midway Atoll

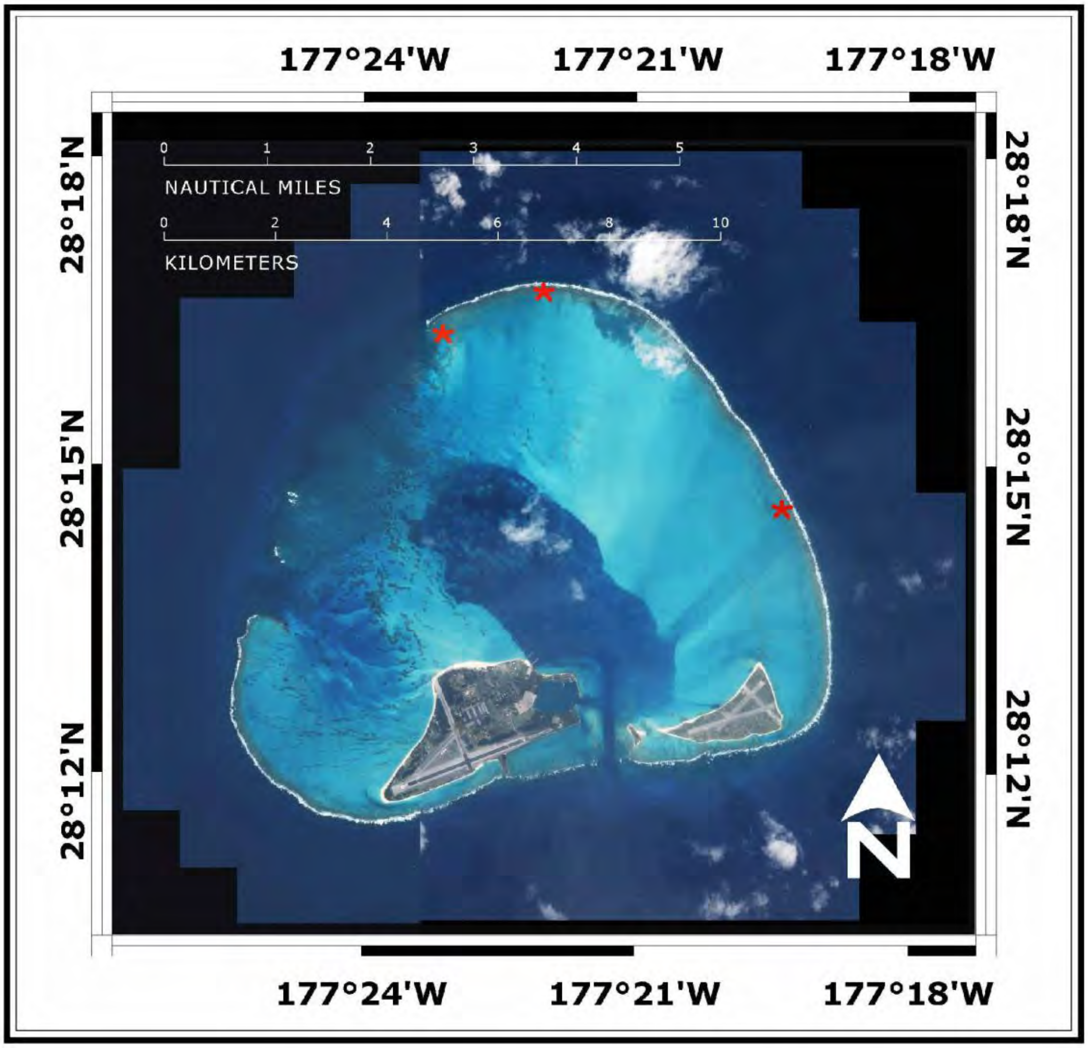
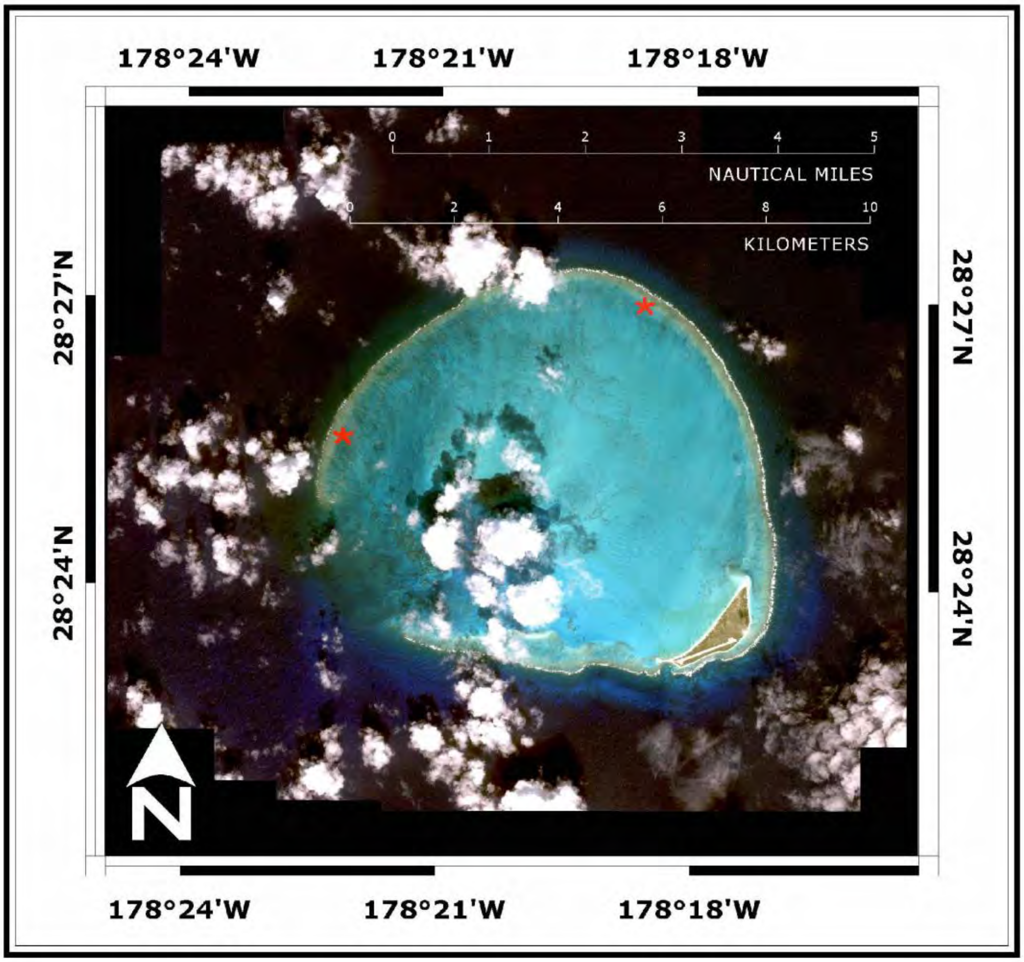


Figure 6. Kure Atoll



APPENDIX II.
IKONOS mosaic detailed habitat image of the major Northwestern Hawaiian Atolls (NCCOS, 2004)

Figure 1. Color Chart

1100	Sand
1121	Patchy macroalgae on sand (10- <50% cover)
1122	Dense macroalgae on sand (50-100% cover)
1300	Rubble
1400	Sand and Rubble
2100	Linear Reef
2120	Linear Reef, uncolonized
2121	Linear Reef, uncolonized + sparse algae
2130	Linear Reef, crustose coralline algae
2300	Spur and Groove
2400	Patch Reef
2430	Patch Reef, crustose coralline algae
2610	Scattered coral/rock, coral colonized
2700	Pavement
2702	Pavement + dense algae
2710	Pavement, >10% live coral
2720	Pavement, uncolonized
2730	Pavement, crustose coralline algae
2800	Pavement with sand channels
2810	Pavement with sand channels, coral colonized
3010	Deep water
3100	Land
	Cloud/Shadow/Surf/No data
3300	Unclassified

Figure 2. French Frigate Shoals

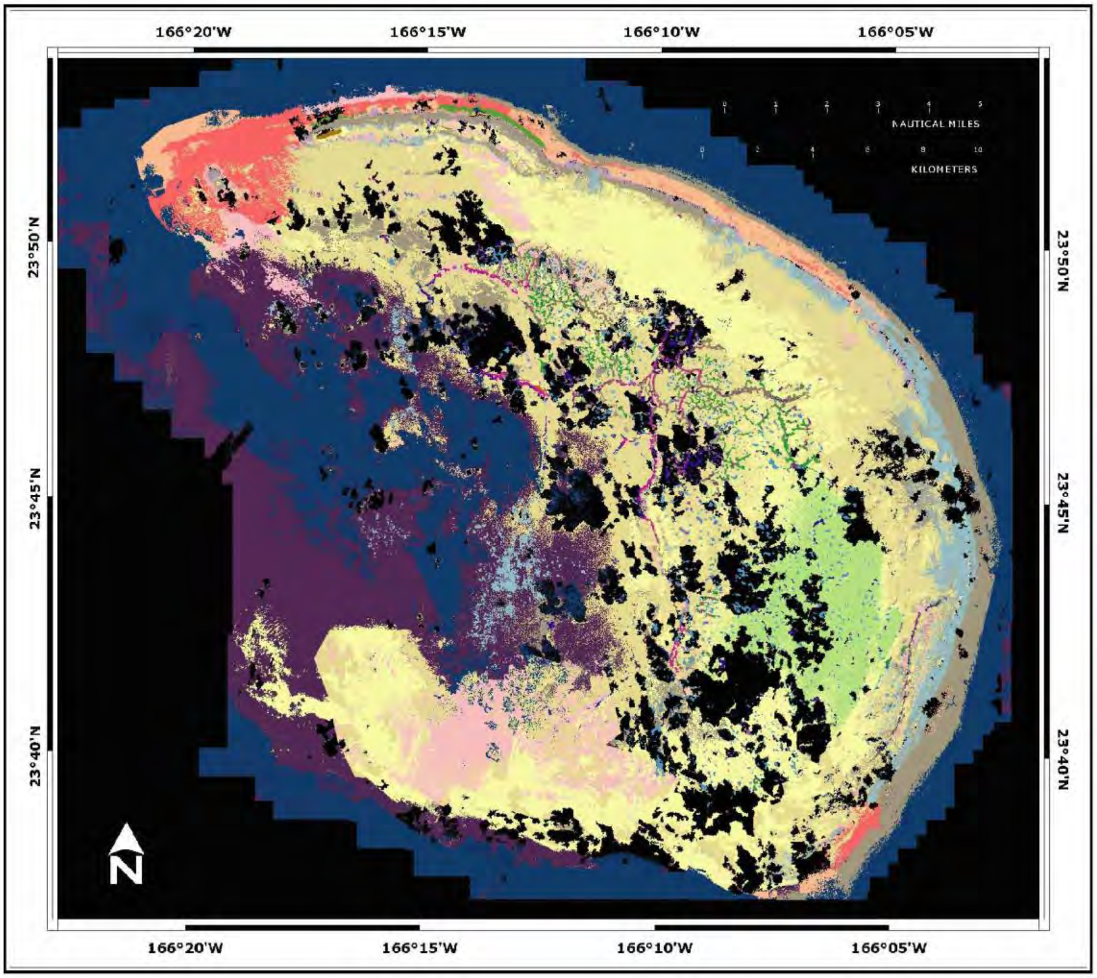


Figure 3. Maro Reef

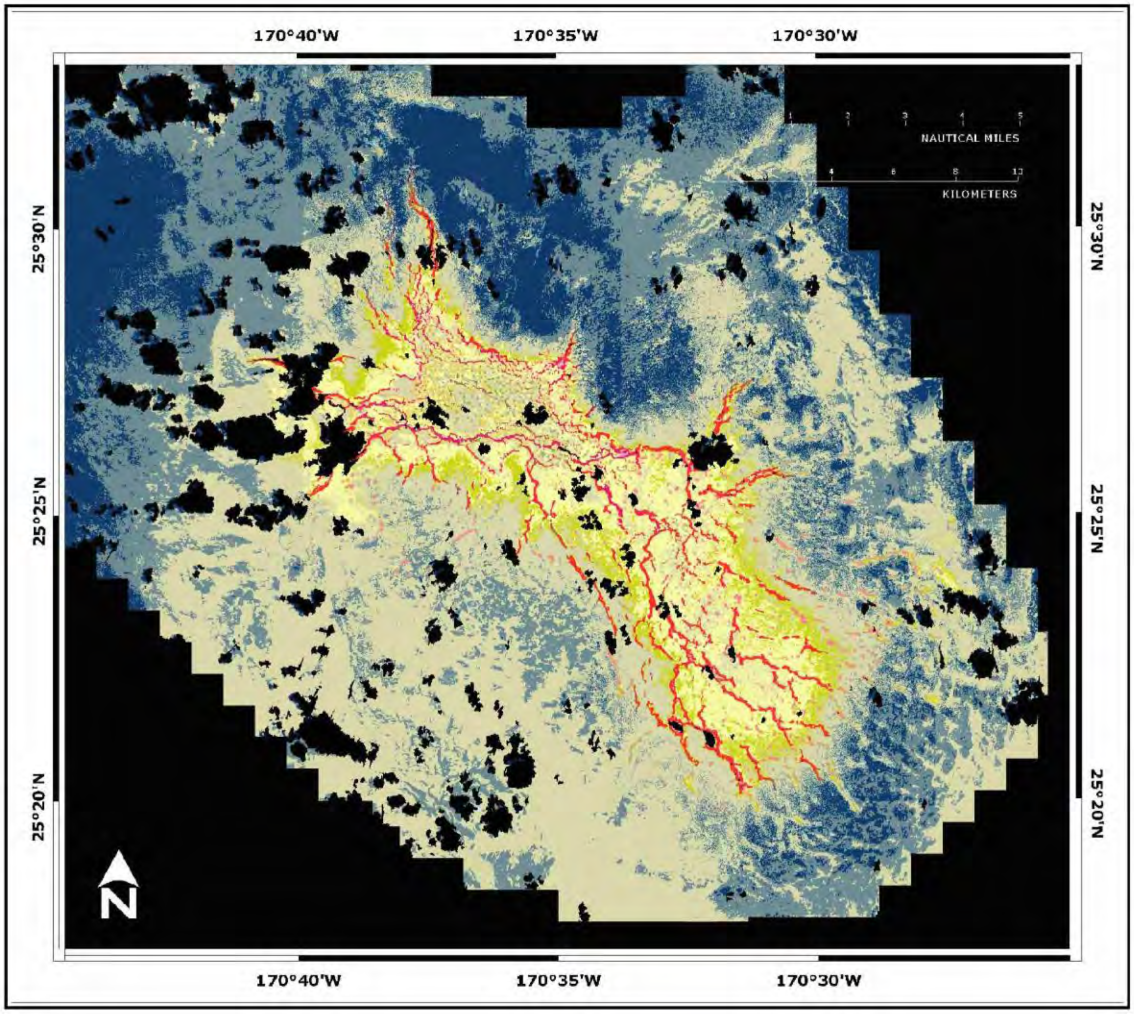


Figure 4. Lisianski Island

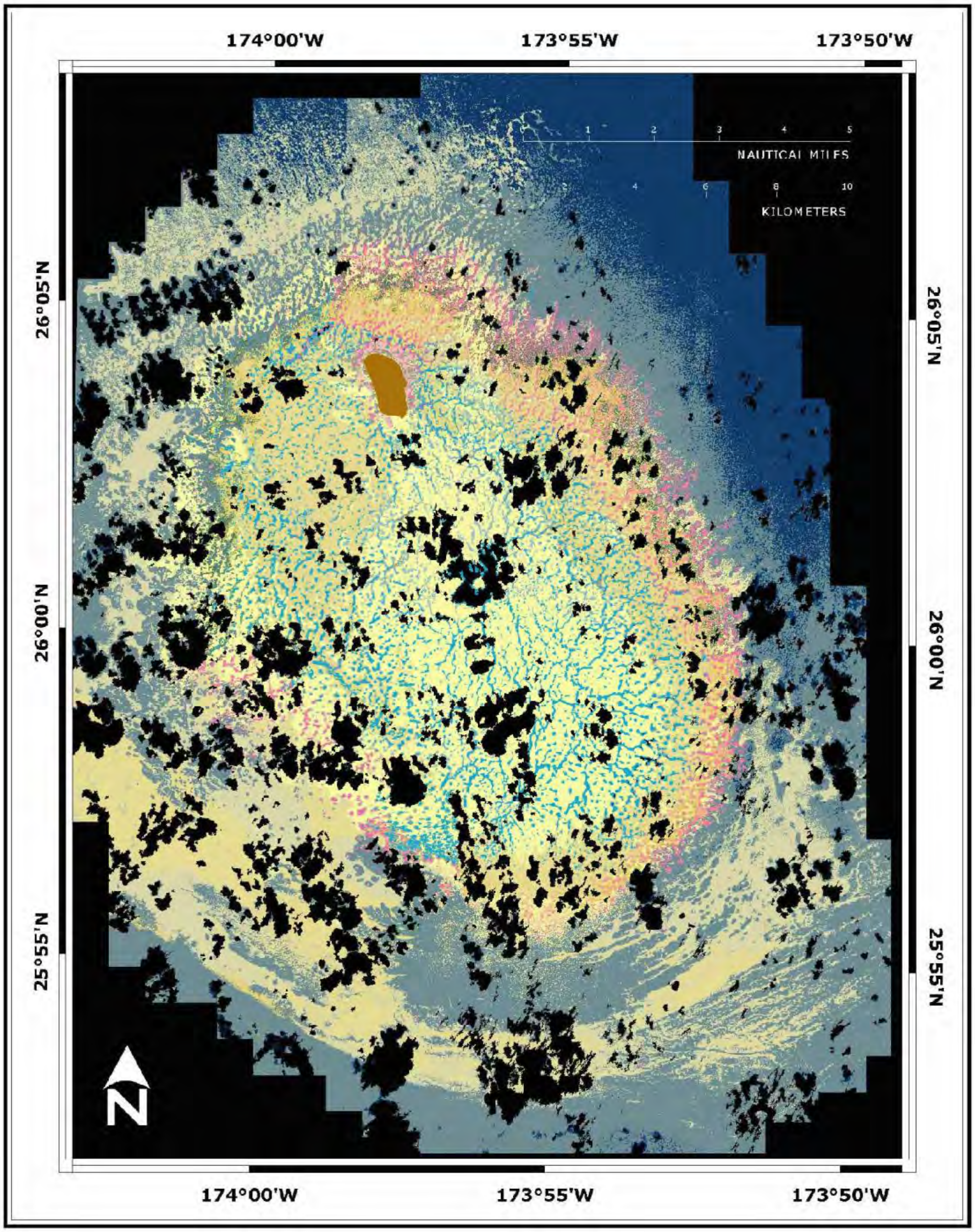


Figure 5. Pearl and Hermes Atoll

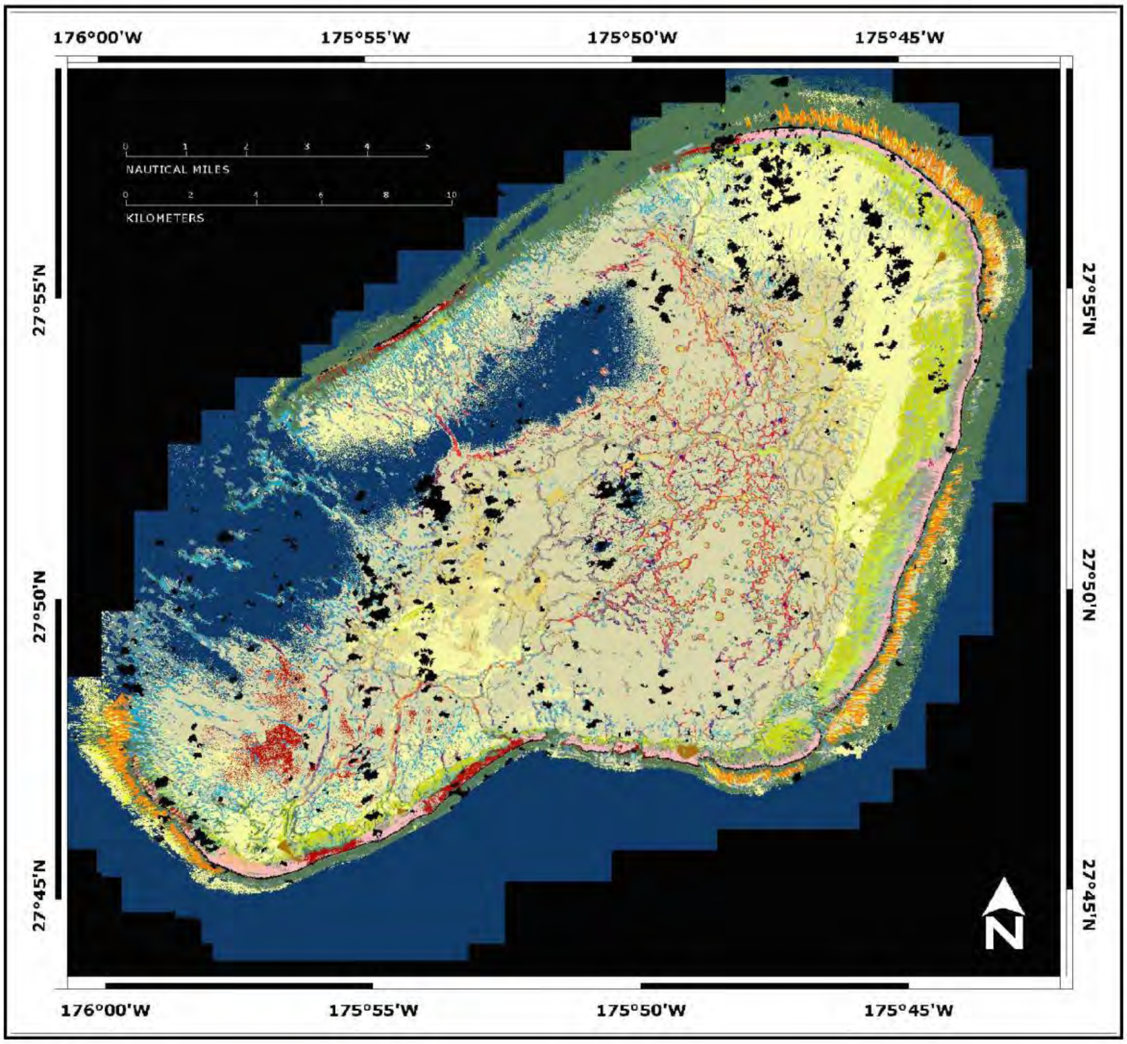


Figure 6. Midway Atoll

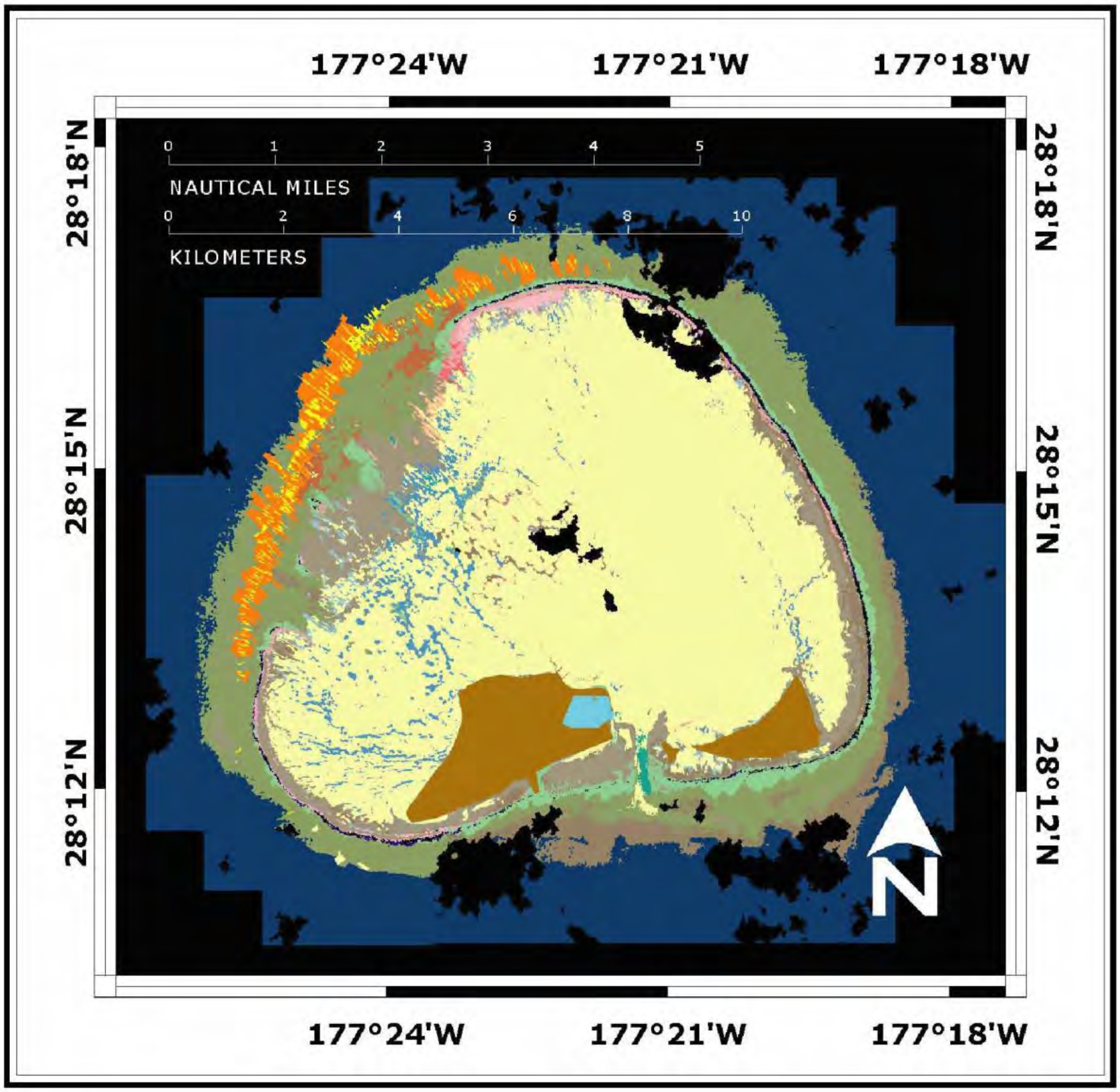
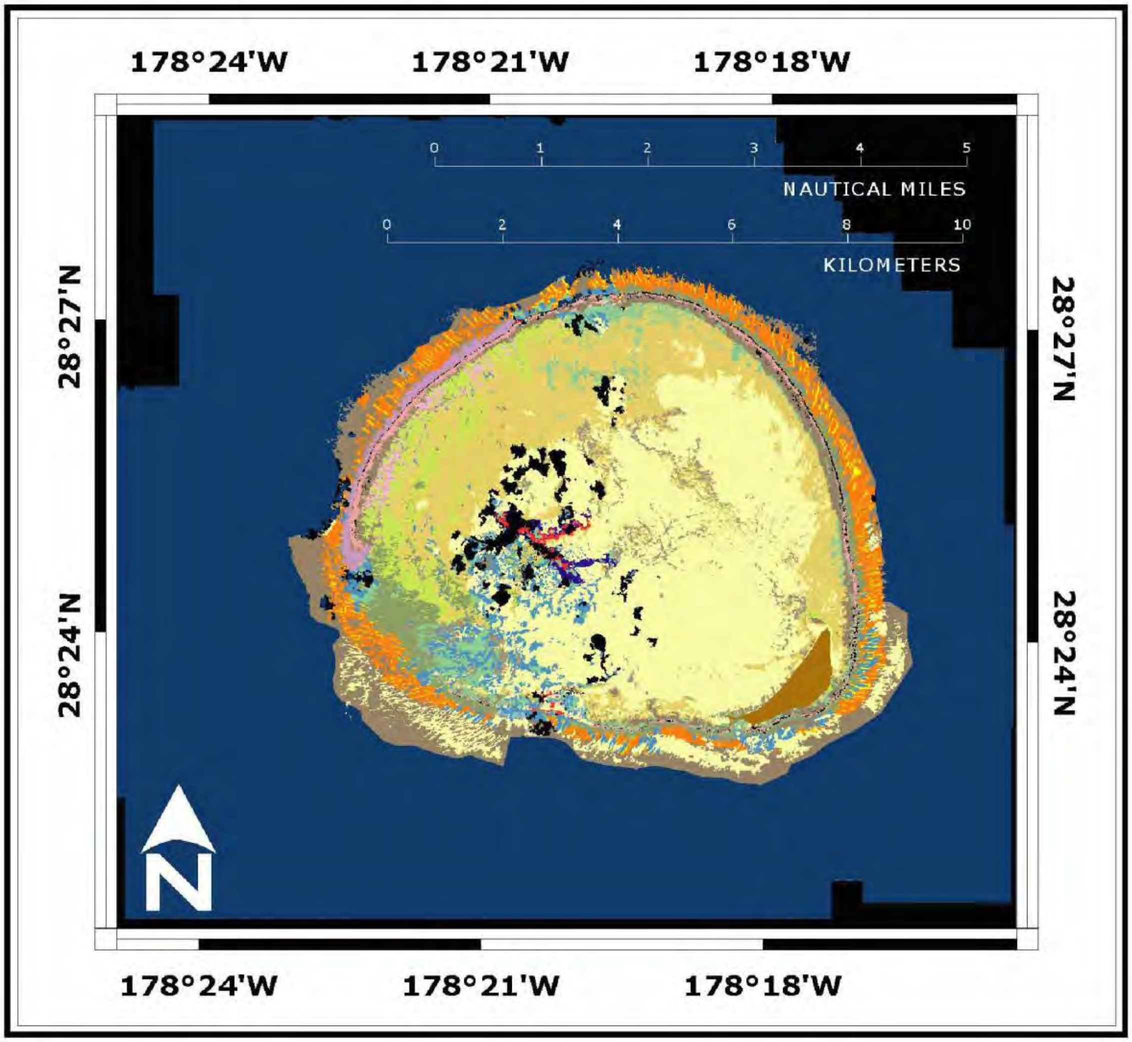
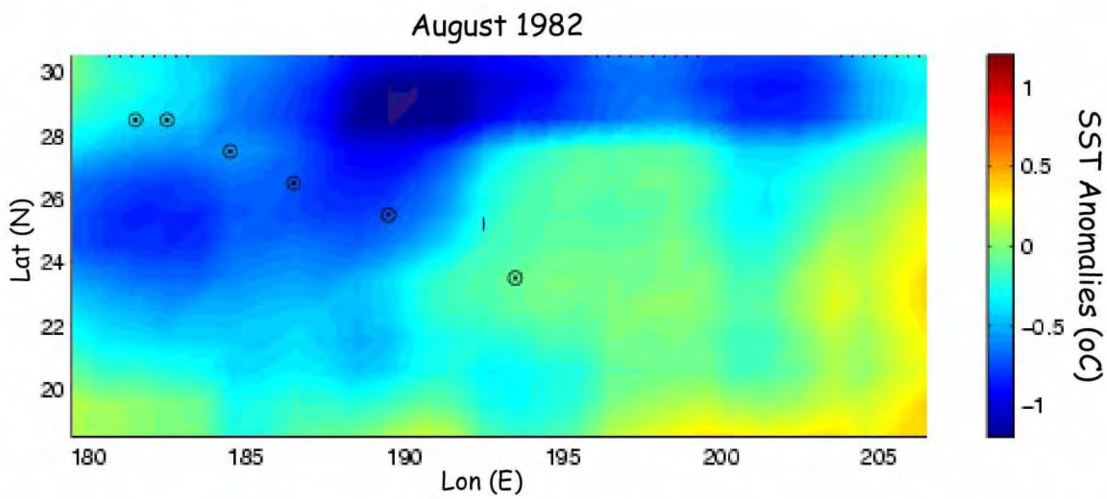
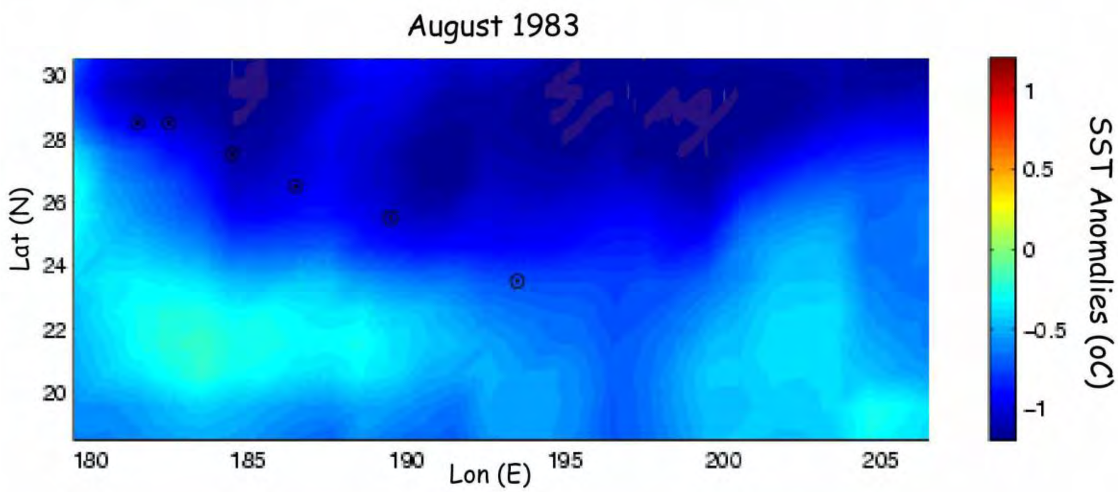


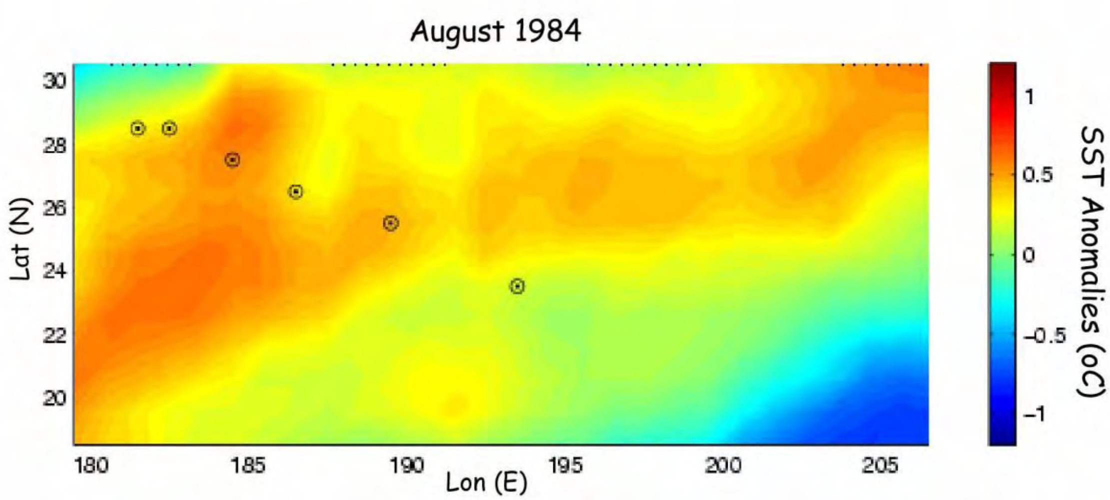
Figure 7. Kure Atoll

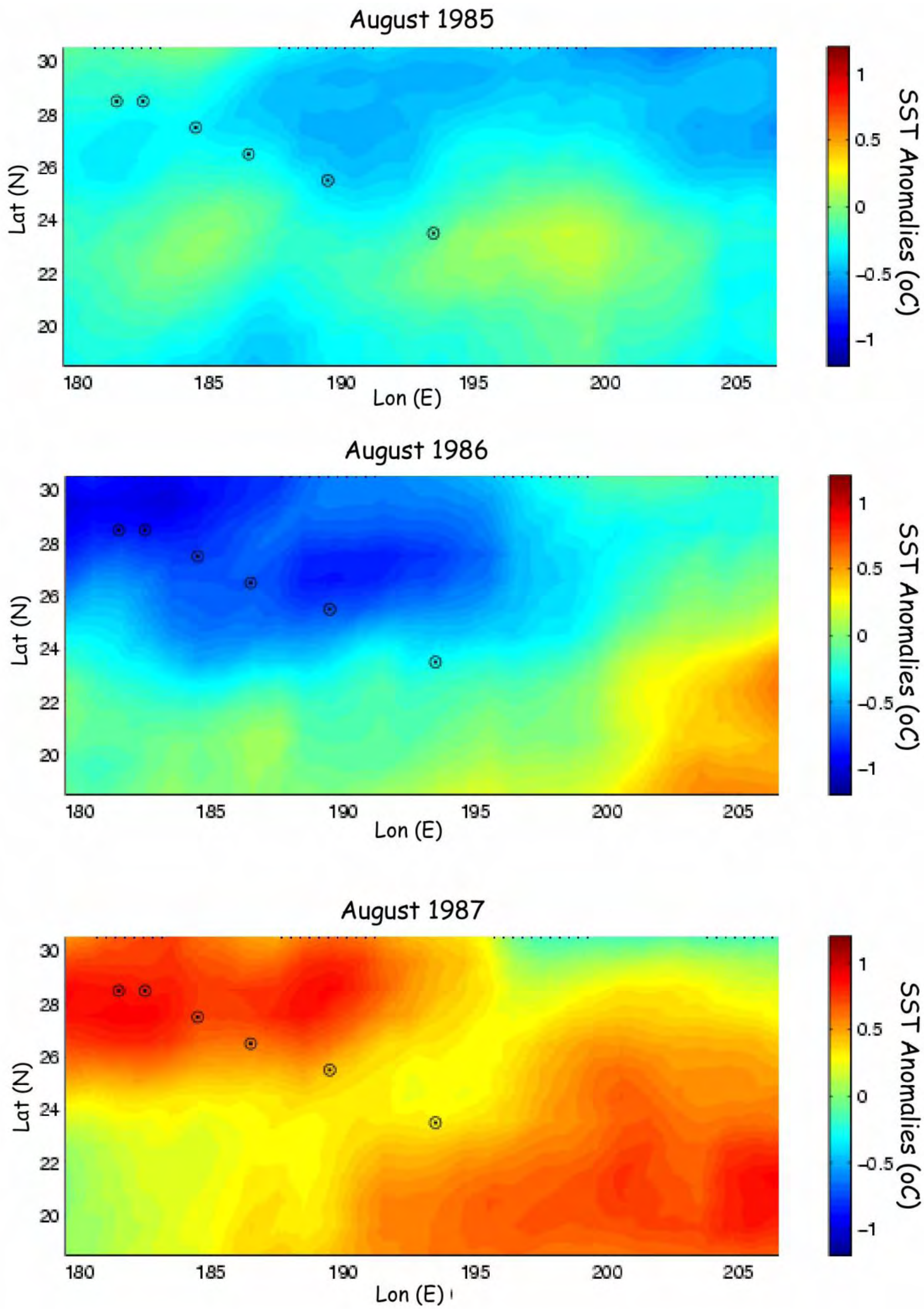


APPENDIX III
August Reynold's SST Anomalies in the NWHI Region
1982-2003

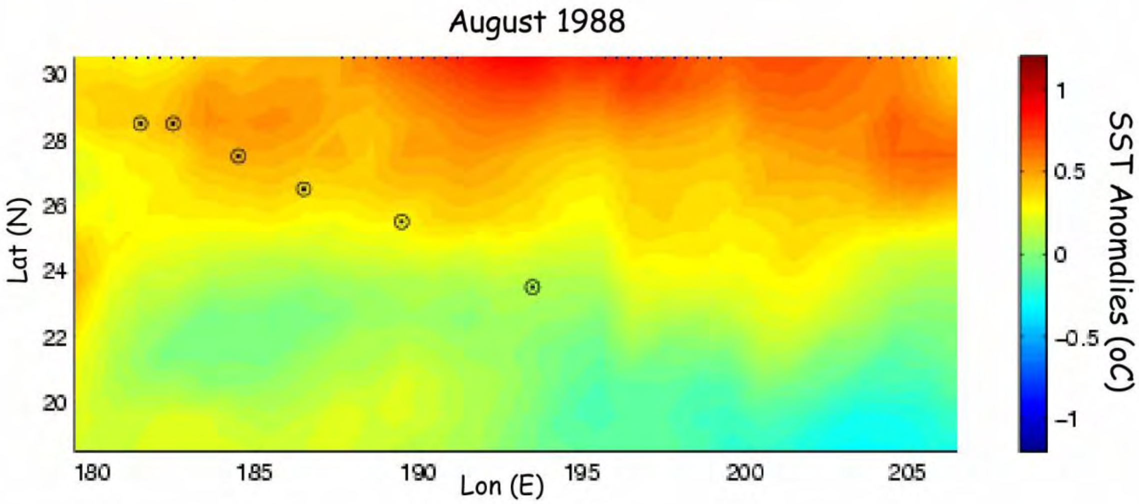




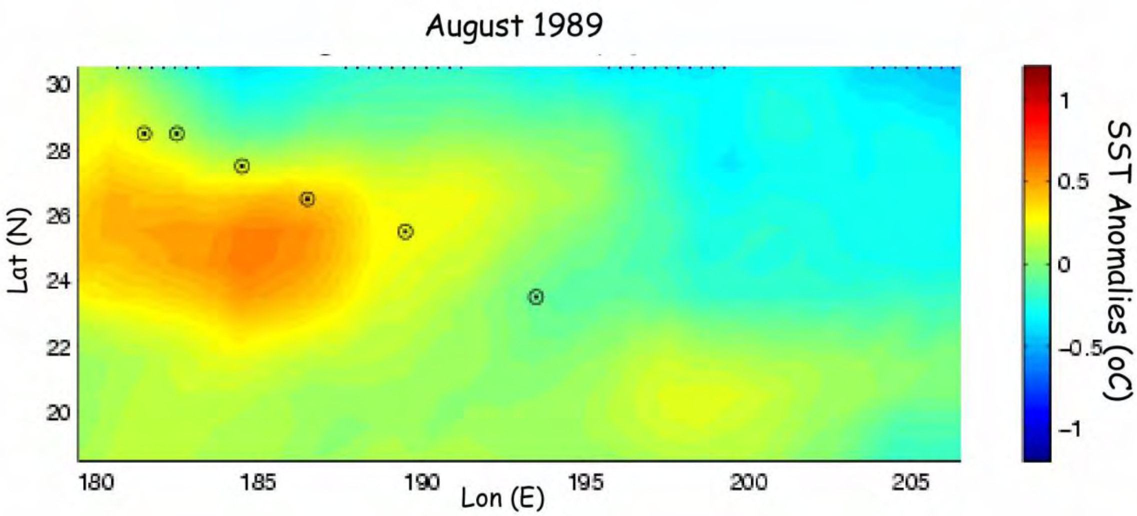




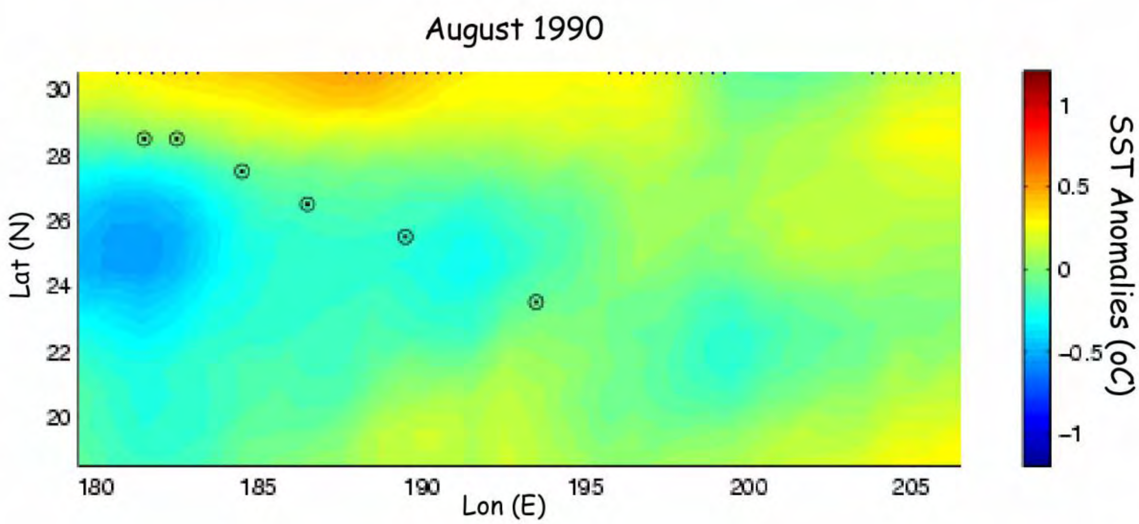
August 1985
Lat (N)
Lon (E)
SST Anomalies (oC)
August 1986
Lat (N)
Lon (E)
SST Anomalies (oC)
August 1987
Lat (N)
Lon (E)
SST Anomalies (oC)



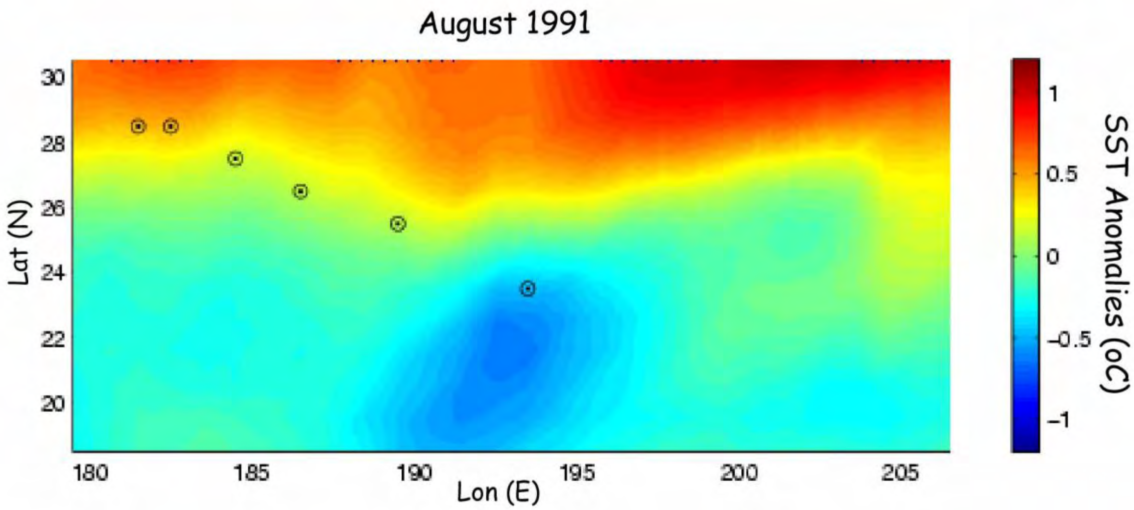
August 1988
Lat (N)
30
28
26
24
22
20
Lon (E)
180
185
190
195
200
205
SST Anomalies (oC)
1
0.5
0
−0.5
−1

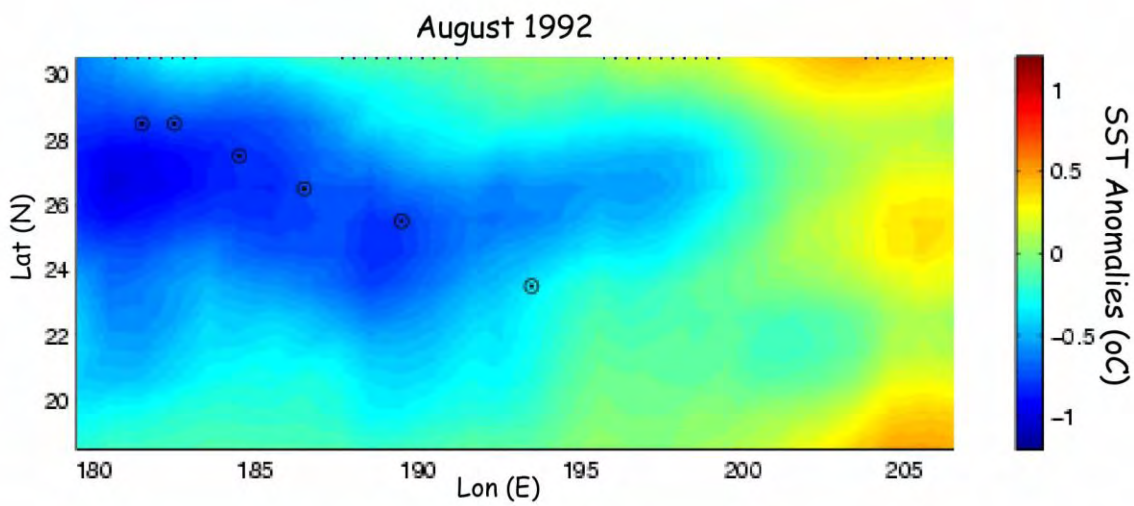


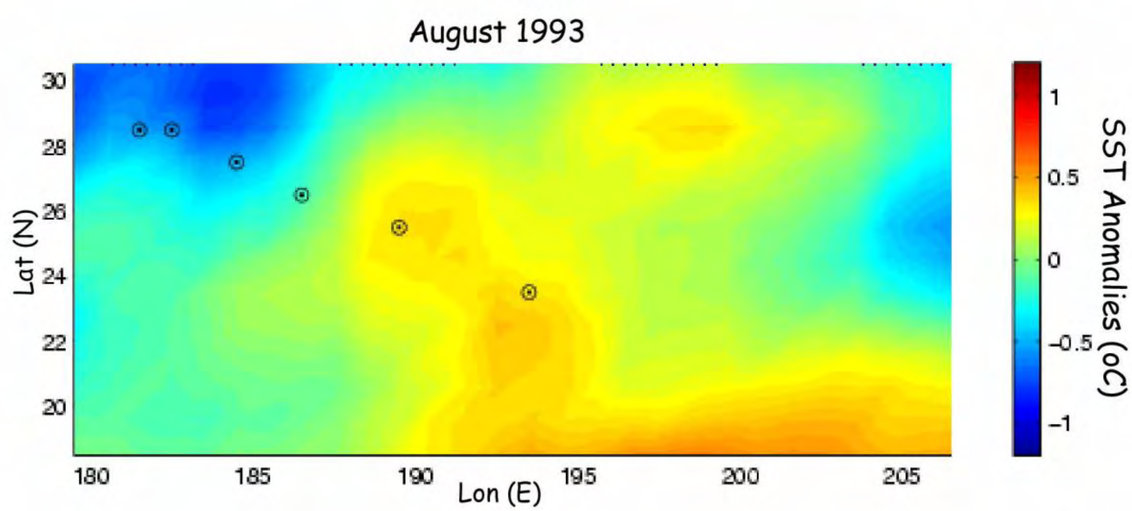
August 1989
Lat (N)
30
28
26
24
22
20
Lon (E)
180
185
190
195
200
205
SST Anomalies (oC)
1
0.5
0
−0.5
−1



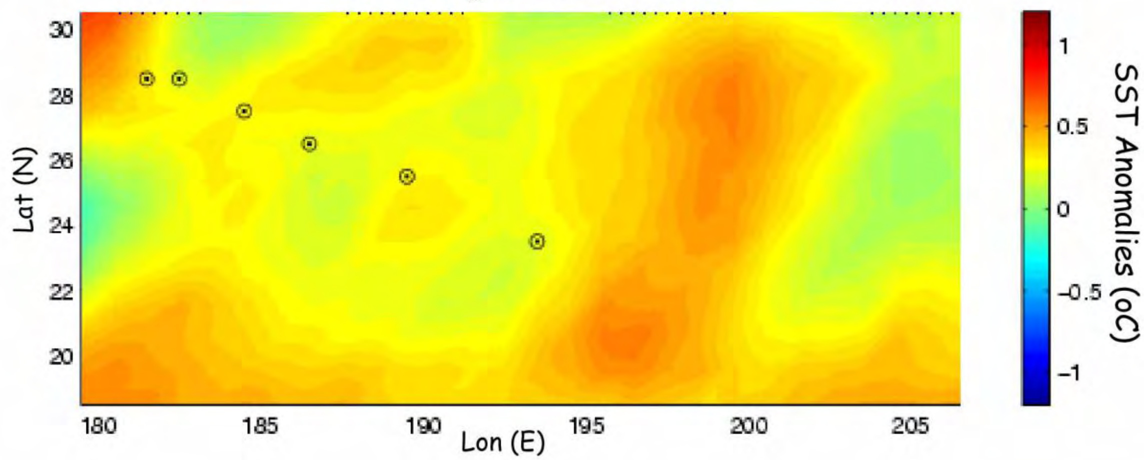
August 1990
Lat (N)
30
28
26
24
22
20
Lon (E)
180
185
190
195
200
205
SST Anomalies (oC)
1
0.5
0
−0.5
−1


August 1991
Lat (N)
Lon (E)
SST Anomalies (oC)
30
28
26
24
22
20
180
185
190
195
200
205
1
0.5
0
-0.5
-1

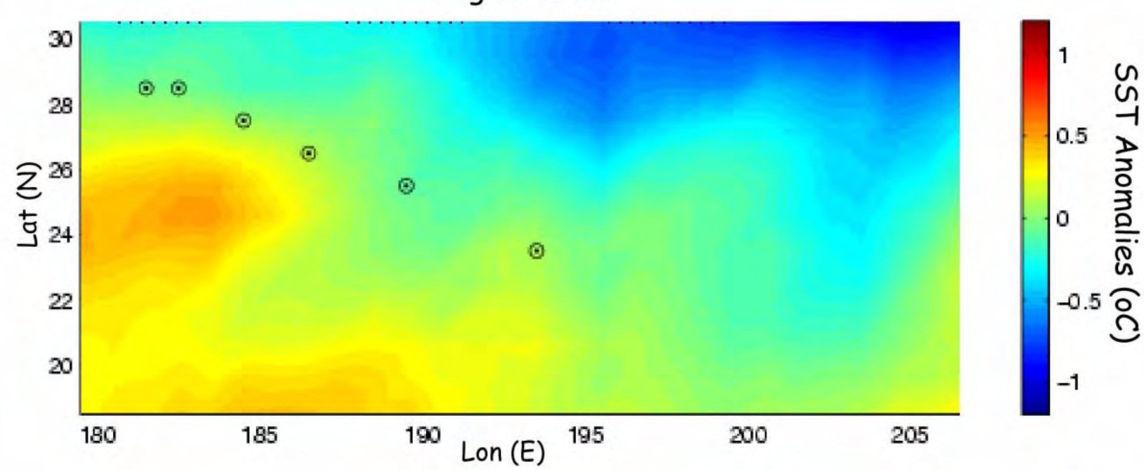

August 1992
Lat (N)
Lon (E)
SST Anomalies (oC)
30
28
26
24
22
20
180
185
190
195
200
205
1
0.5
0
-0.5
-1


August 1993
Lat (N)
Lon (E)
SST Anomalies (oC)
30
28
26
24
22
20
180
185
190
195
200
205
1
0.5
0
-0.5
-1

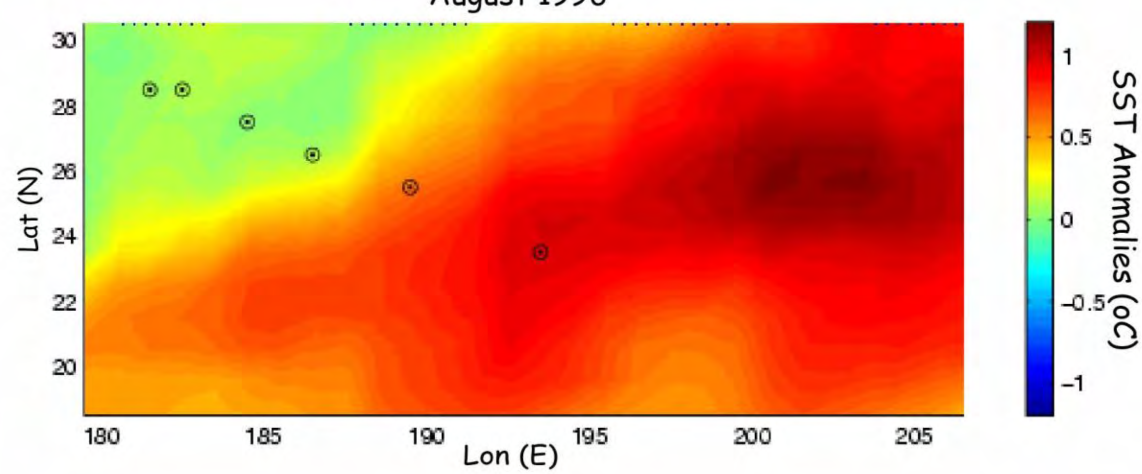
August 1994

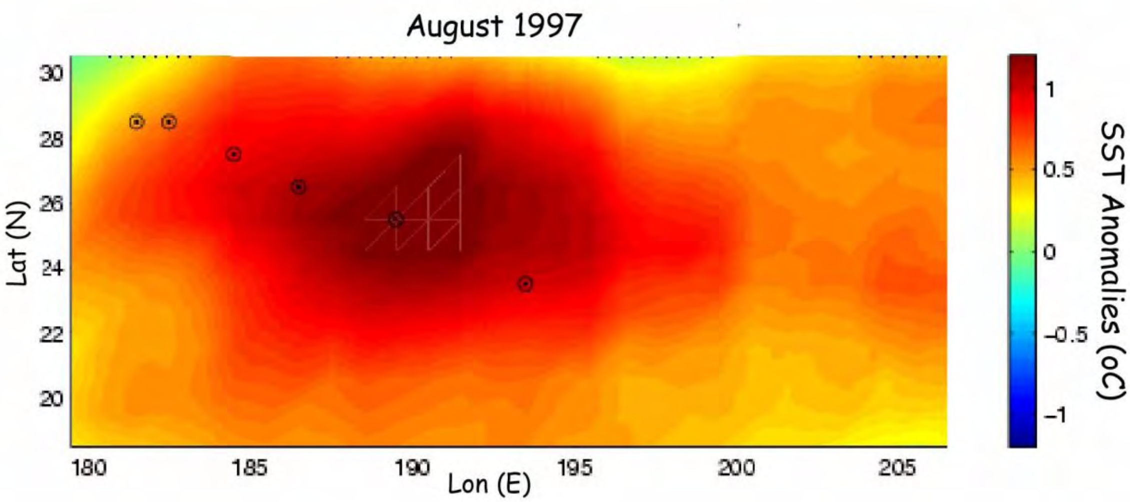


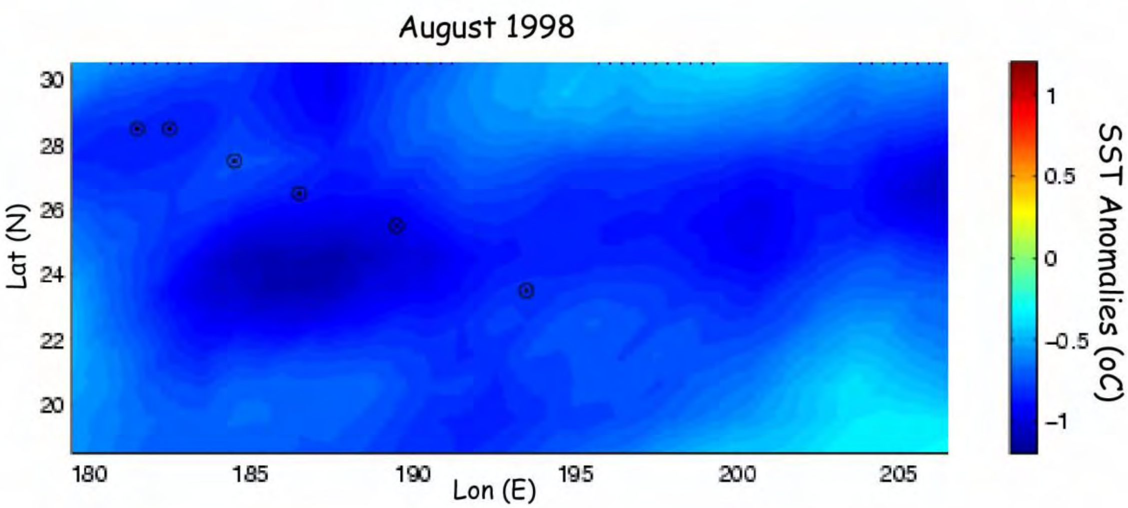
August 1995



August 1996




August 1997
Lat (N)
30
28
26
24
22
20
180
185
190
195
200
205
Lon (E)
1
0.5
0
-0.5
-1
SST Anomalies (oC)


August 1998
Lat (N)
30
28
26
24
22
20
180
185
190
195
200
205
Lon (E)
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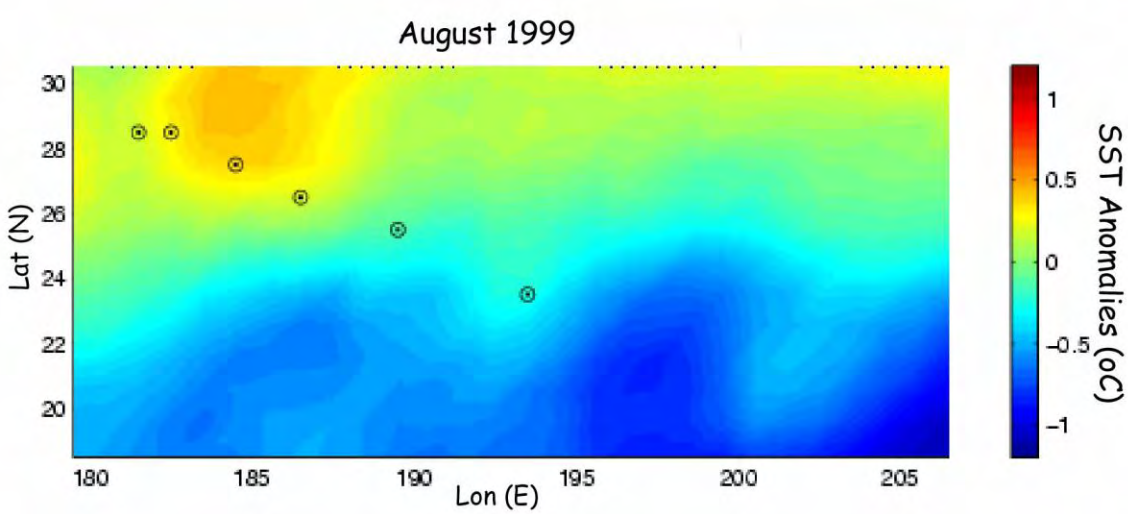
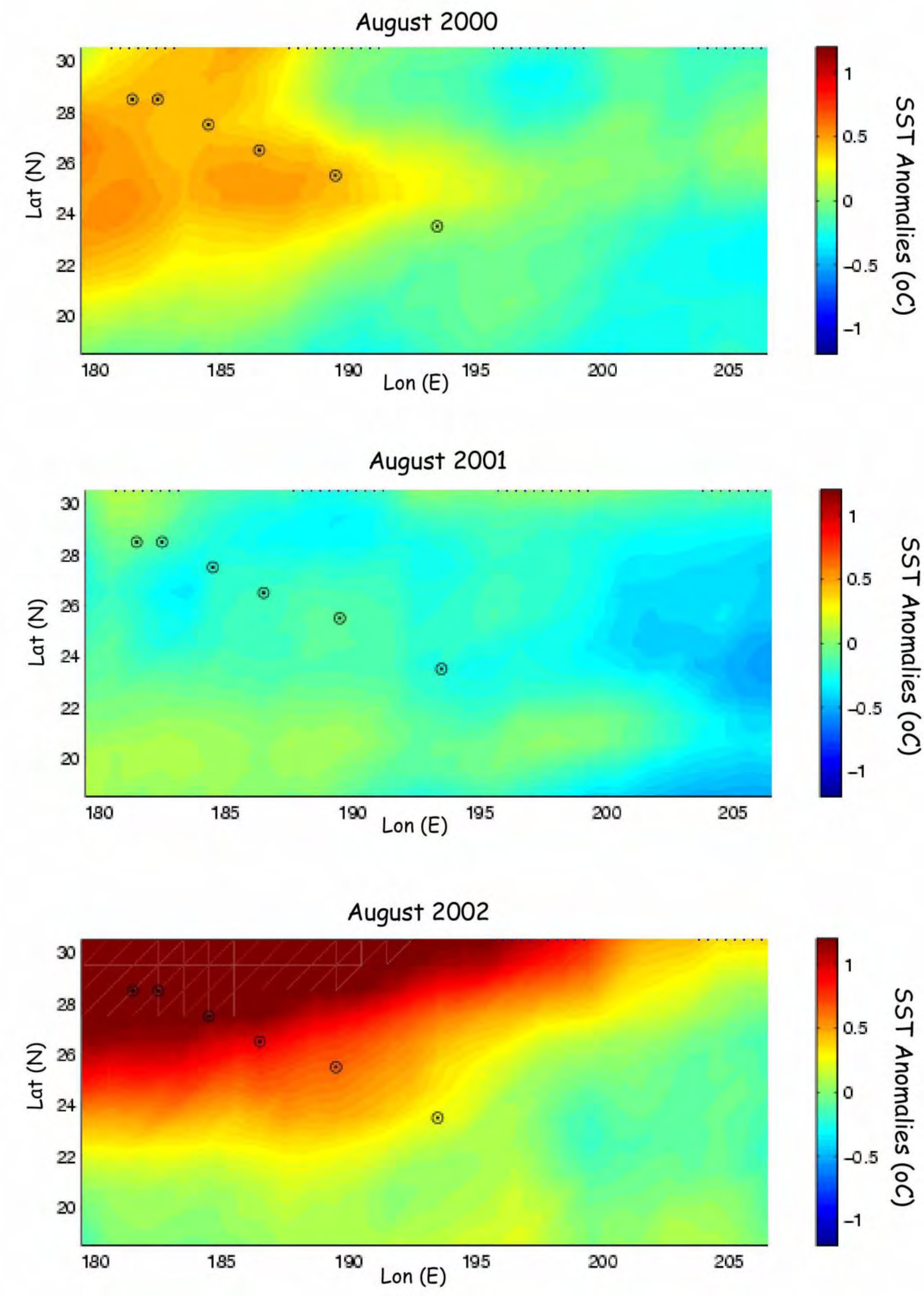
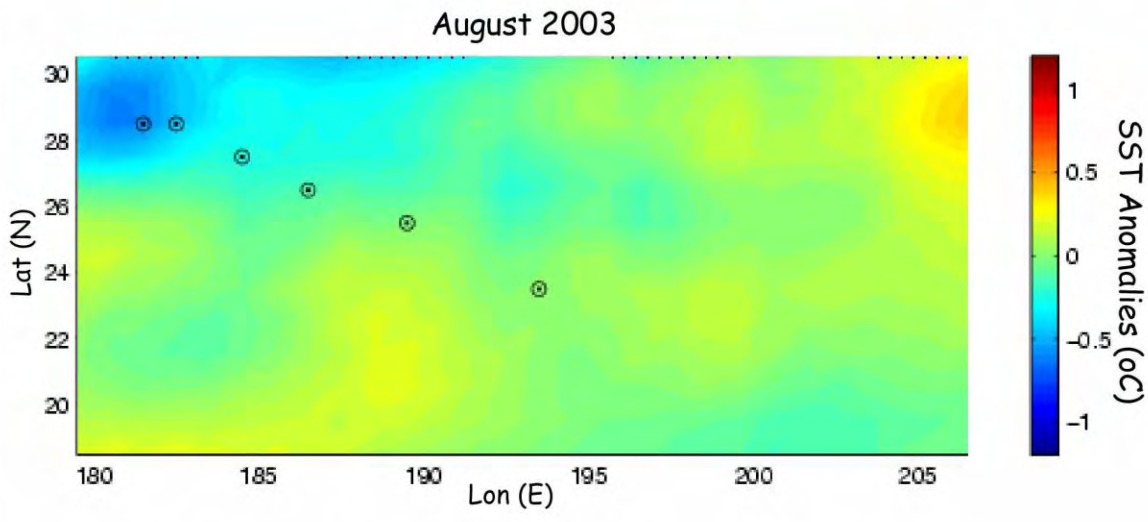
0.5
0
-0.5
-1
SST Anomalies (oC)

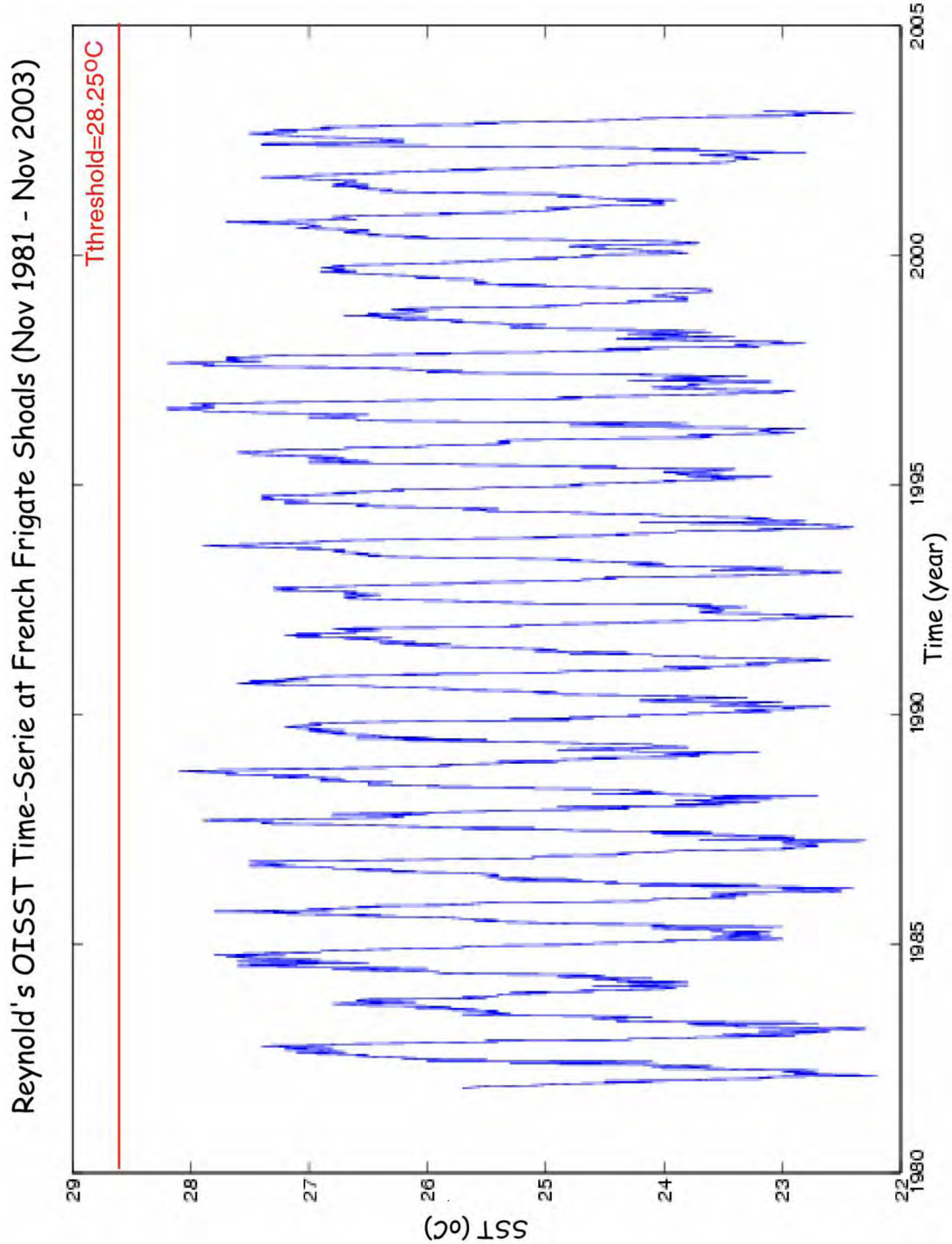

August 1999
Lat (N)
30
28
26
24
22
20
180
185
190
195
200
205
Lon (E)
1
0.5
0
-0.5
-1
SST Anomalies (oC)

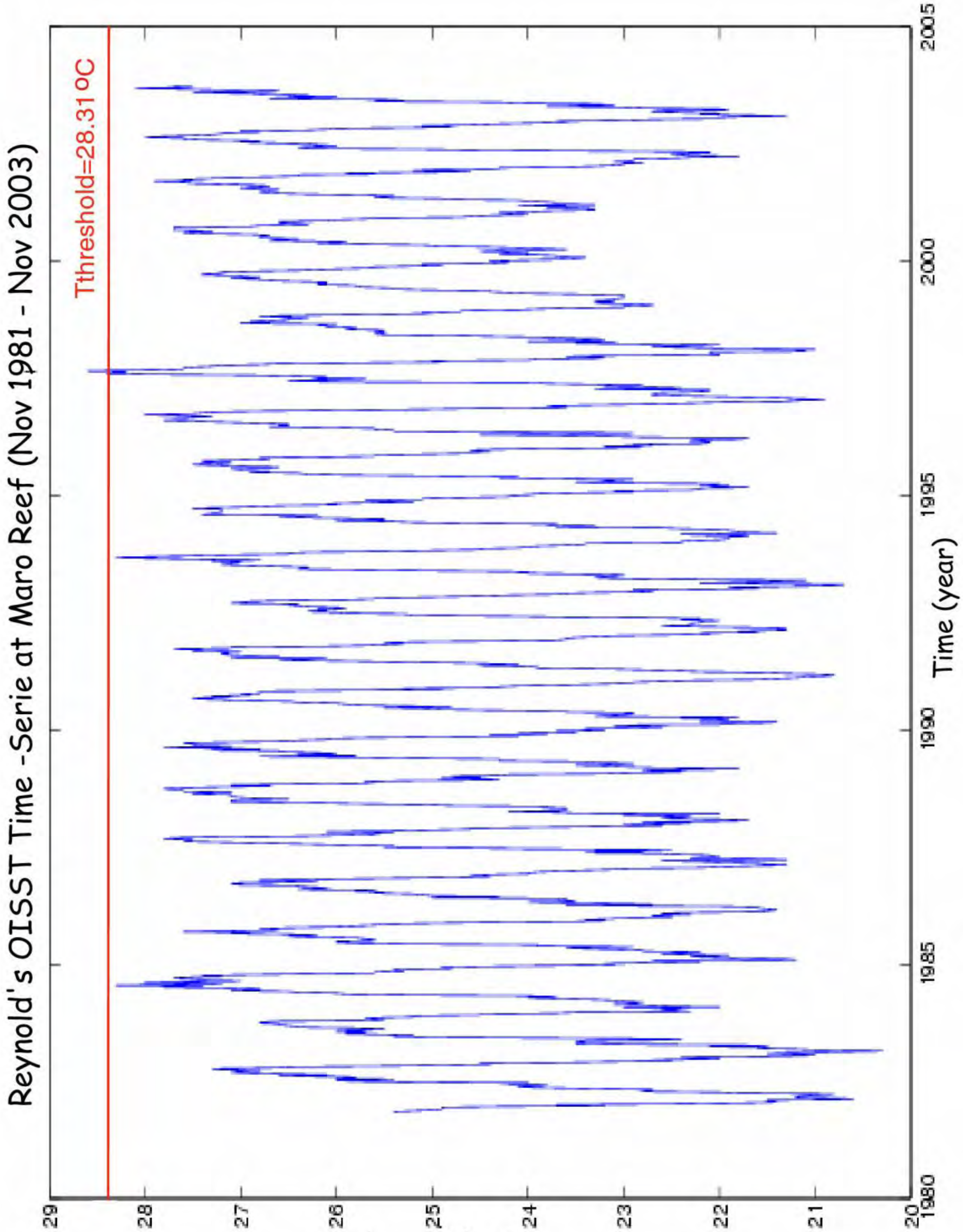

August 2000
Lat (N)
30
28
26
24
22
20
180
185
190
195
200
205
Lon (E)
SST Anomalies (oC)
1
0.5
0
−0.5
−1
August 2001
Lat (N)
30
28
26
24
22
20
180
185
190
195
200
205
Lon (E)
SST Anomalies (oC)
1
0.5
0
−0.5
−1
August 2002
Lat (N)
30
28
26
24
22
20
180
185
190
195
200
205
Lon (E)
SST Anomalies (oC)
1
0.5
0
−0.5
−1

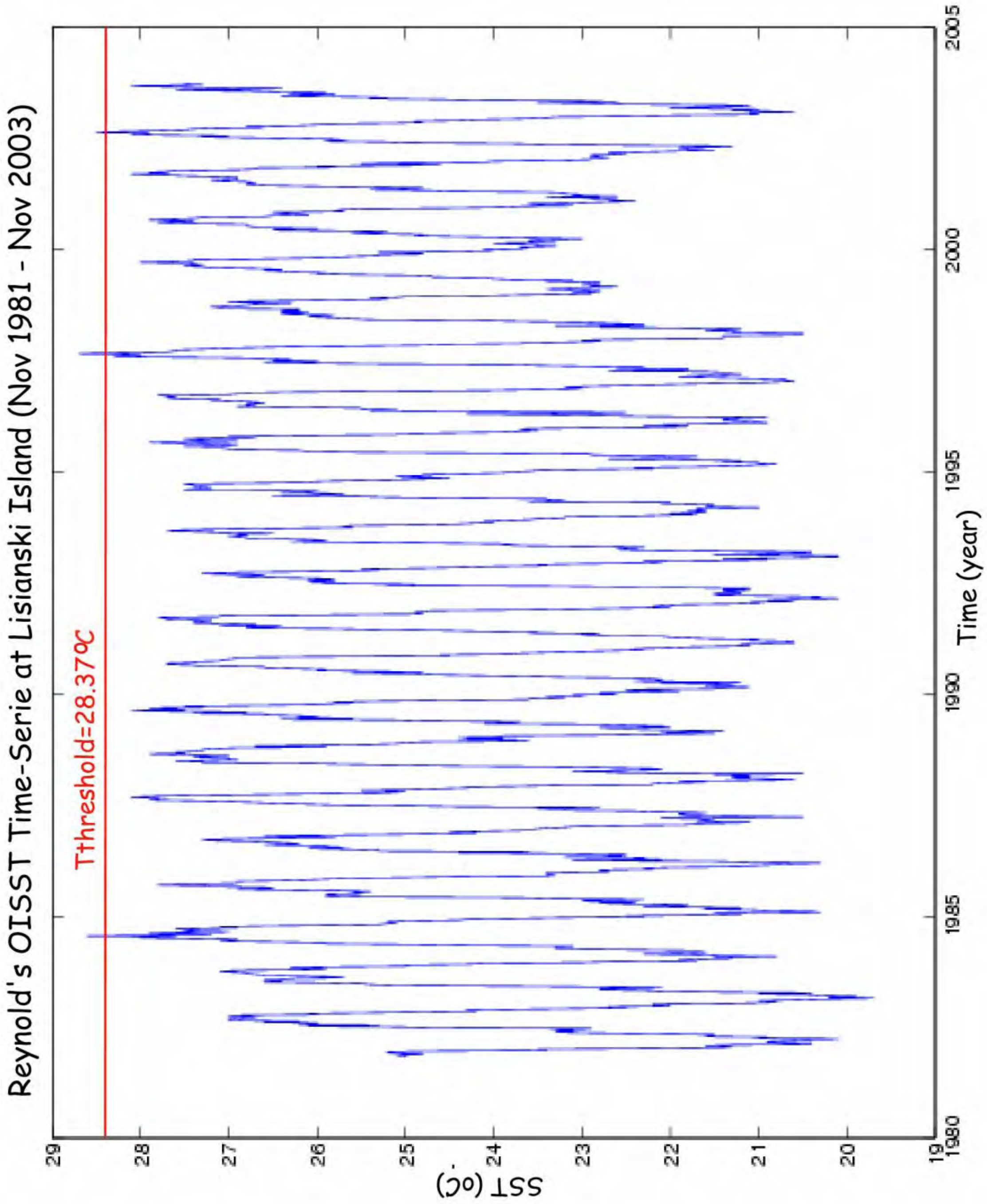


August 2003
30
28
26
24
22
20
Lat (N)
180
185
190
195
200
205
Lon (E)
1
0.5
0
−0.5
−1
SST Anomalies (oC)

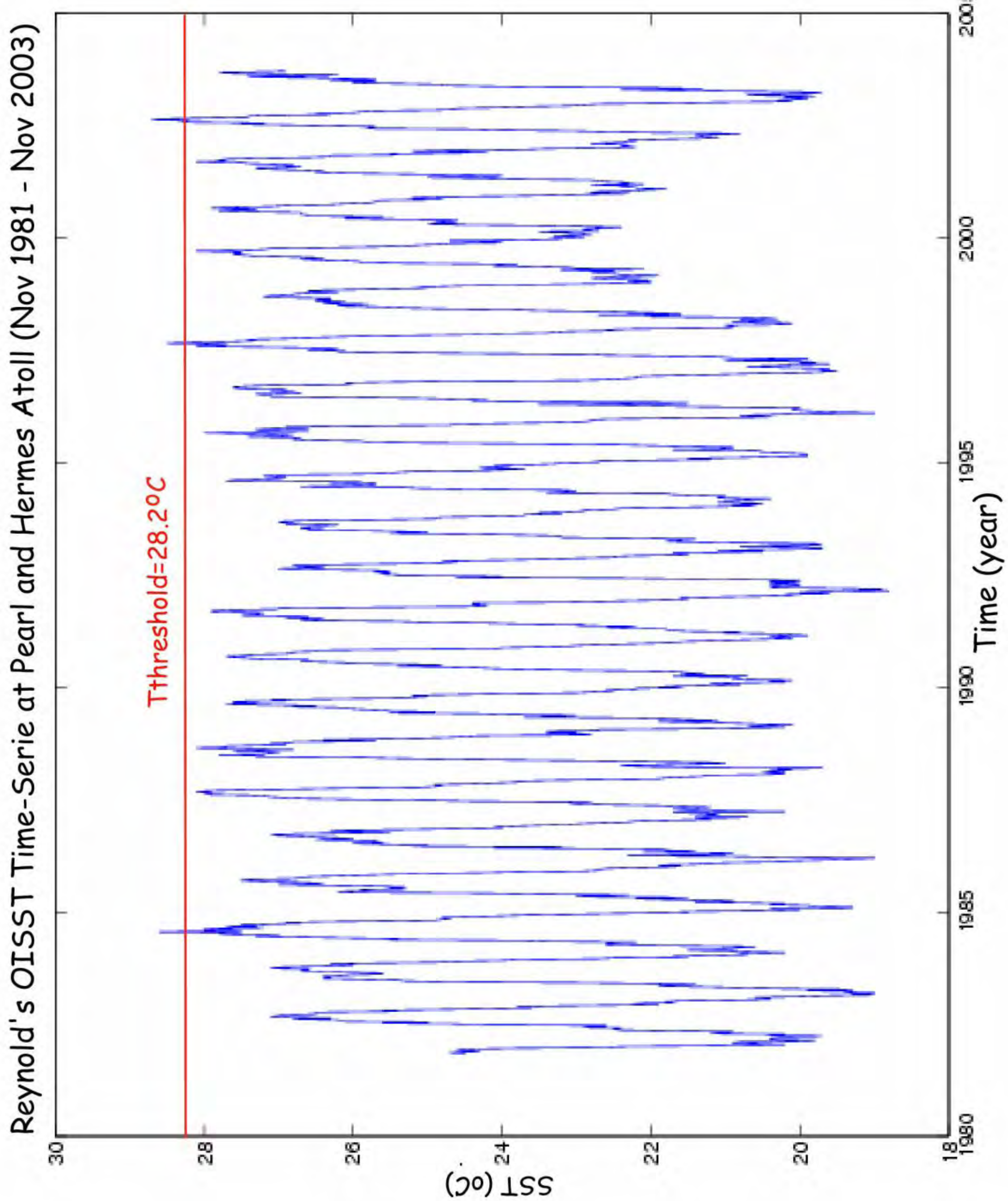
APPENDIX IV
Reynold's OISST Time-Series at every Location with red lines marking the corresponding Thermal Threshold

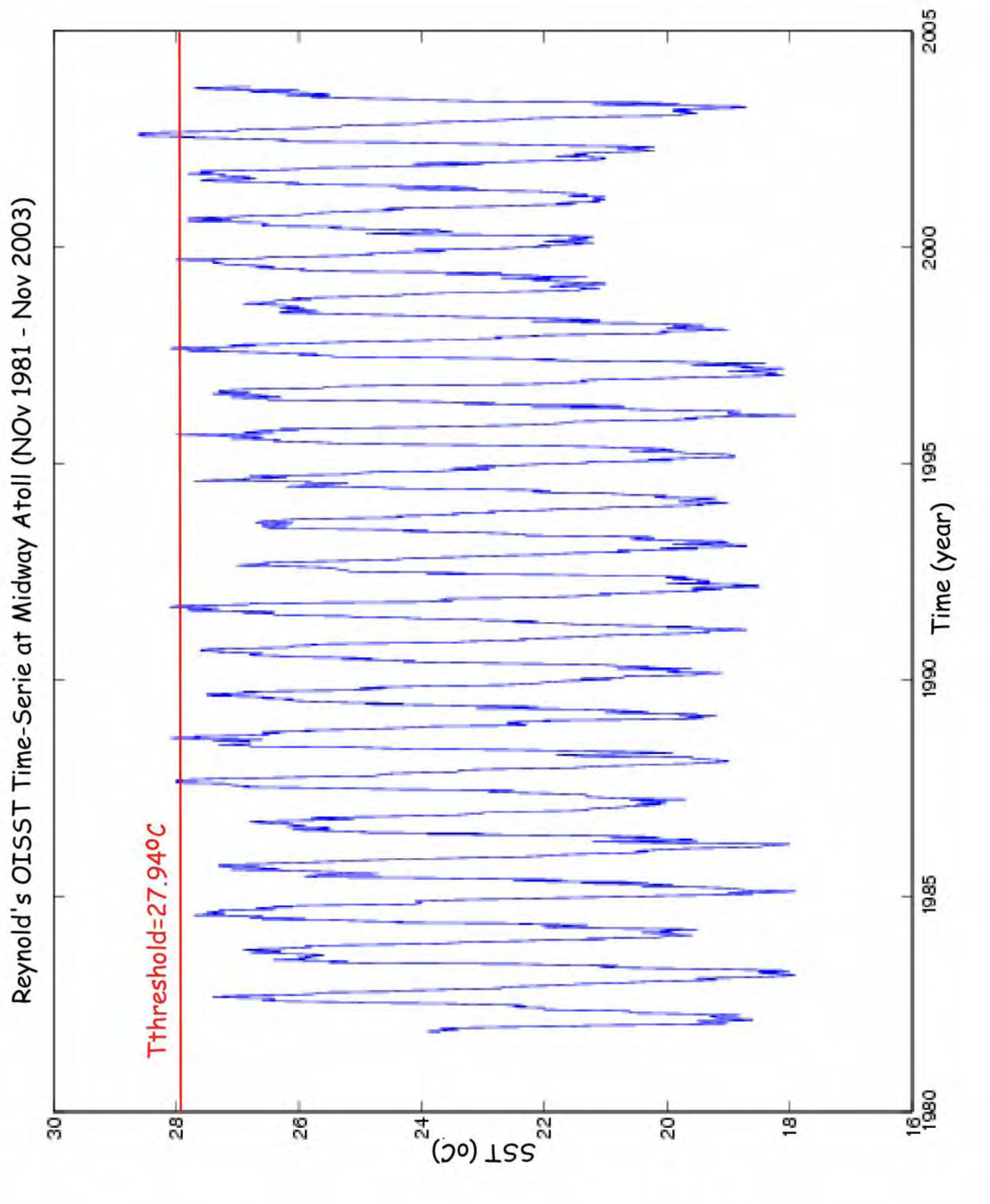



Reynold's OISST Time -Serie at Maro Reef (Nov 1981 - Nov 2003)
Tthreshold=28.31 ºC
SST (oC)
Time (year)
20
21
22
23
24
25
26
27
28
29
1980
1985
1990
1995
2000
2005

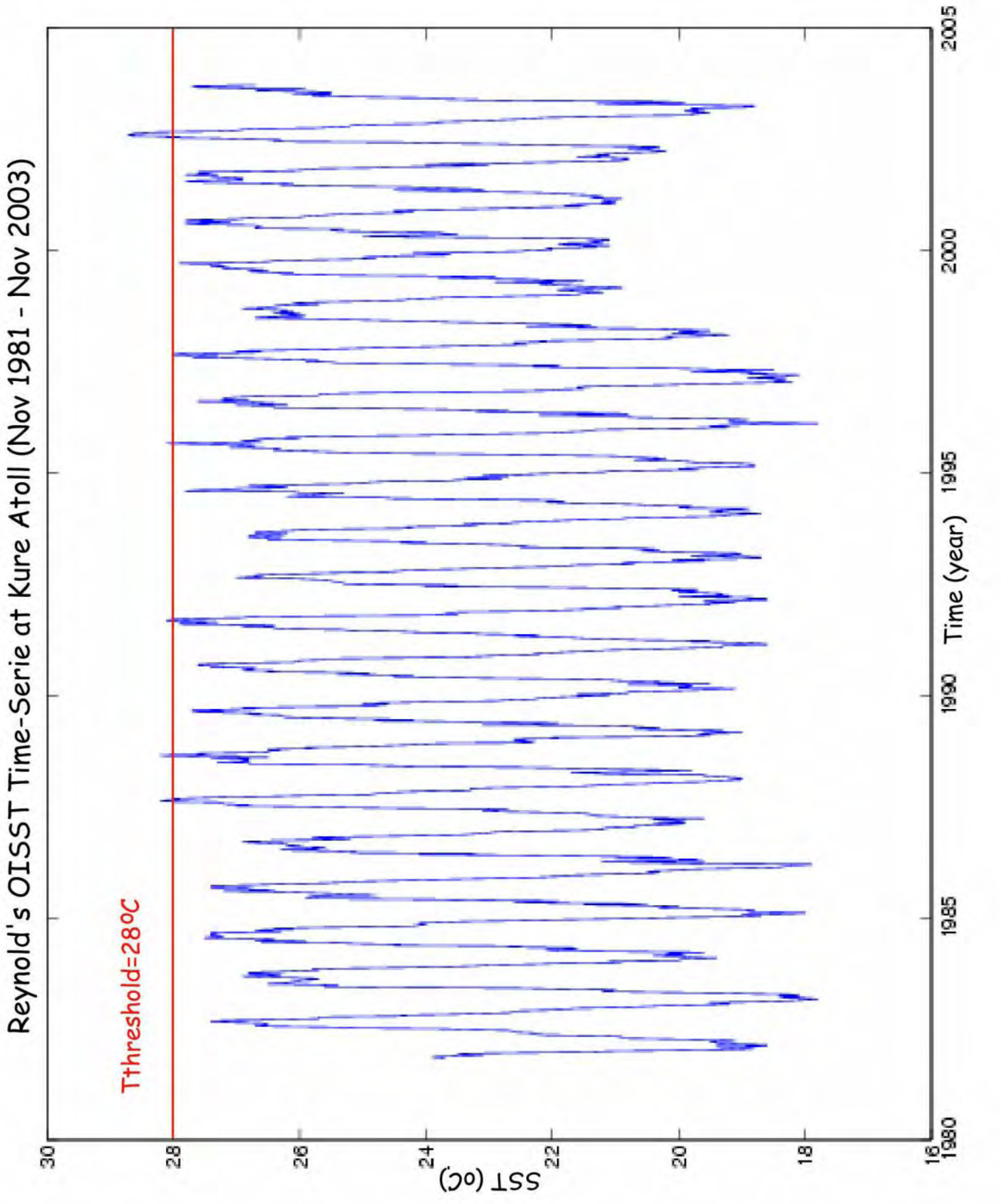


Reynold's OISST Time-Serie at Lisianski Island (Nov 1981 - Nov 2003)
Tthreshold=28.37°C
SST (oC)
Time (year)
19
20
21
22
23
24
25
26
27
28
29
1980
1985
1990
1995
2000
2005


Reynold's OISST Time-Serie at Pearl and Hermes Atoll (Nov 1981 - Nov 2003)
Tthreshold=28.2°C
SST (oC)
Time (year)
18
20
22
24
26
28
30
1980
1985
1990
1995
2000
2005



Reynold's OISST Time-Serie at Midway Atoll (NOv 1981 - Nov 2003)
Tthreshold=27.94oC
SST (oC)
30
28
26
24
22
20
18
16
1980
1985
1990
1995
2000
2005
Time (year)



Reynold's OISST Time-Serie at Kure Atoll (Nov 1981 - Nov 2003)
Tthreshold=28°C
SST (oC)
Time (year)
30
28
26
24
22
20
18
16
1980
1985
1990
1995
2000
2005

APPENDIX V
Accumulated Thermal Stress (DHDs) at every Location

Figure 1. Accumulated Thermal Stress at Maro Reef

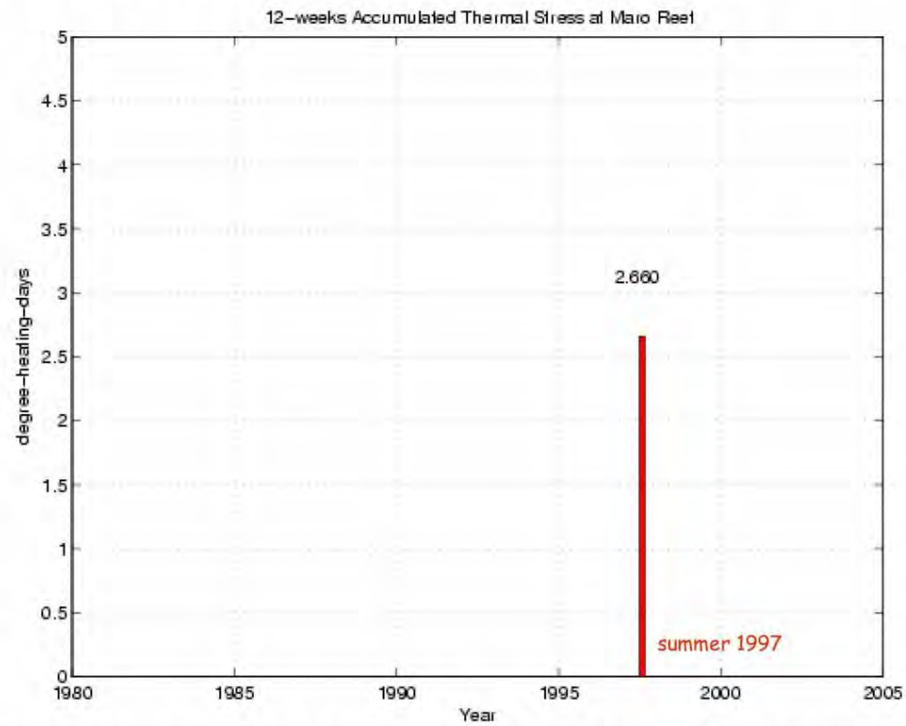


Figure 2. Accumulated Thermal Stress at Lisianski Island

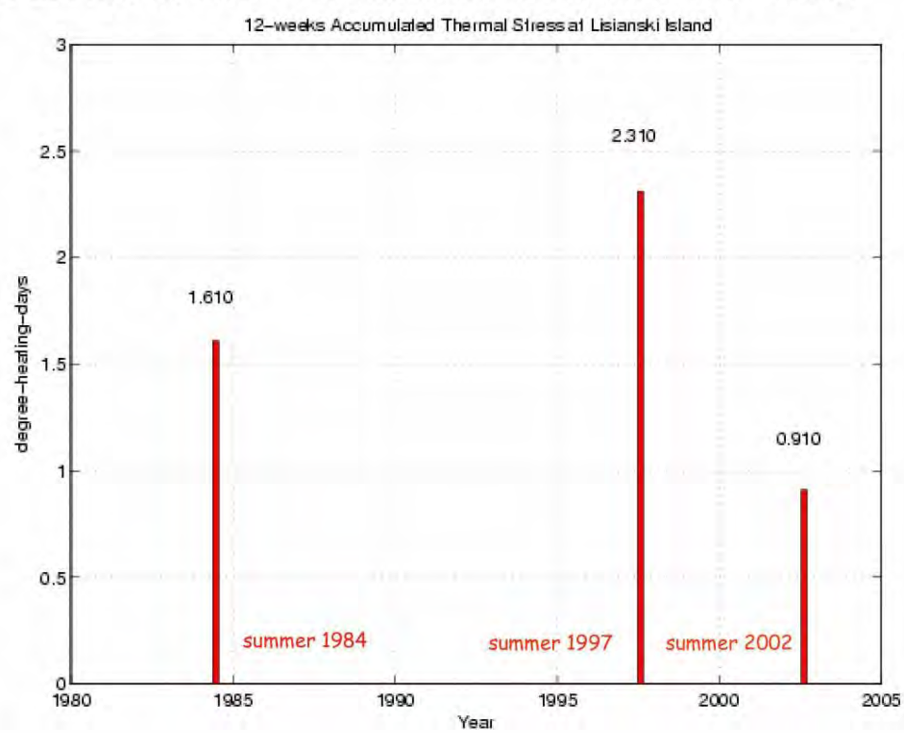


Figure 3. Accumulated Thermal Stress at Pearl and Hermes Atoll

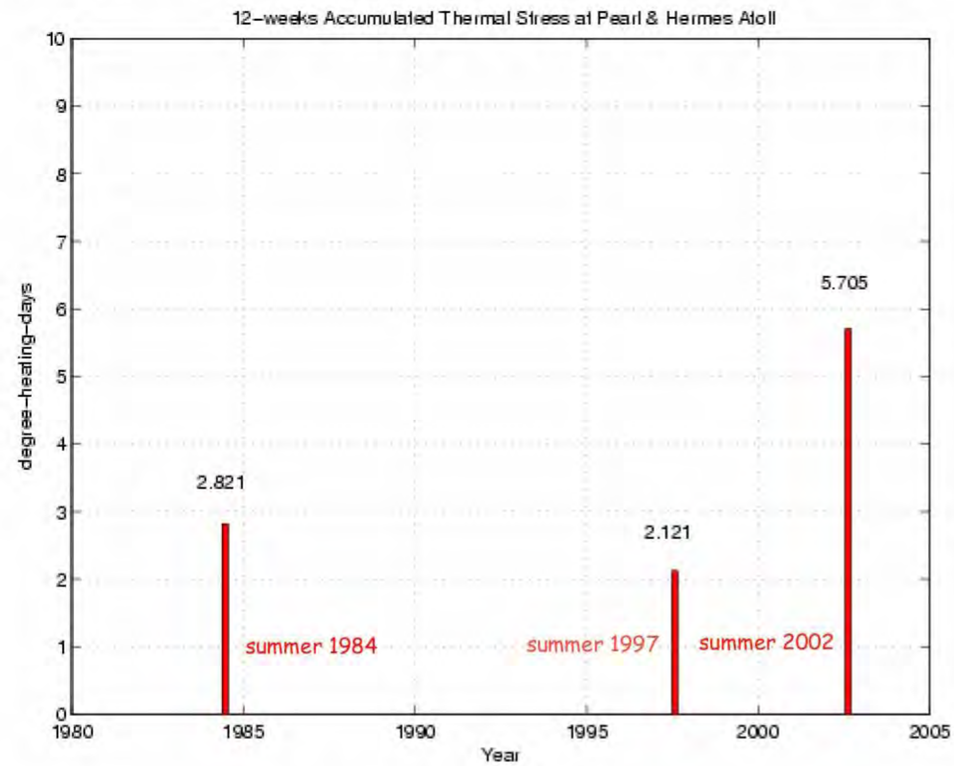


Figure 4. Accumulated Thermal Stress at Midway Atoll

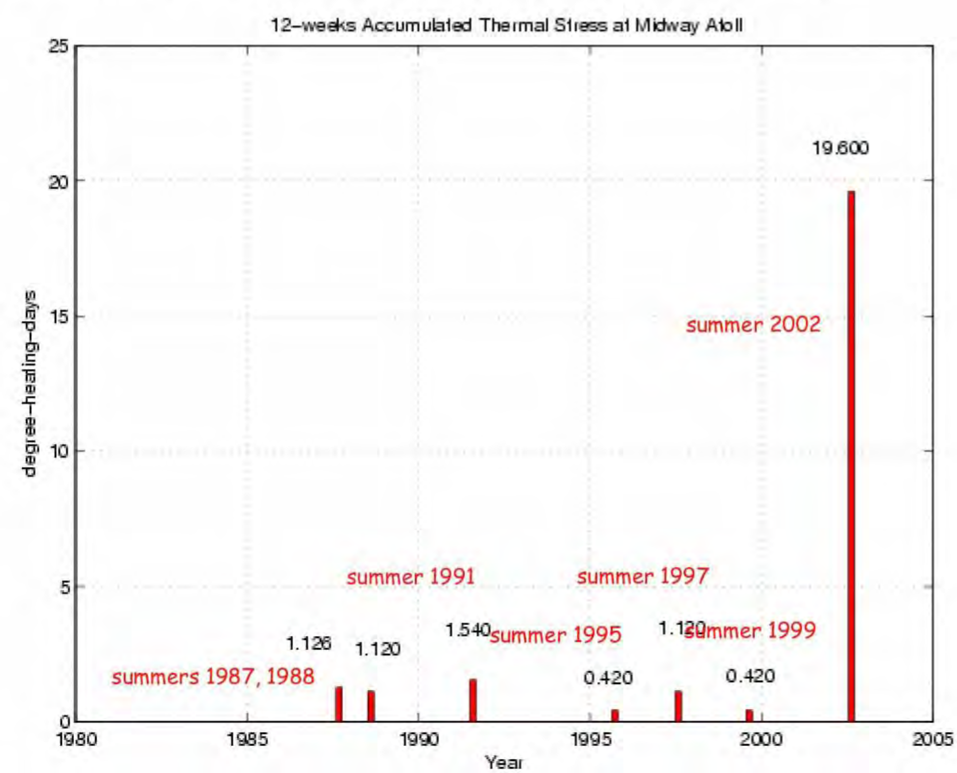
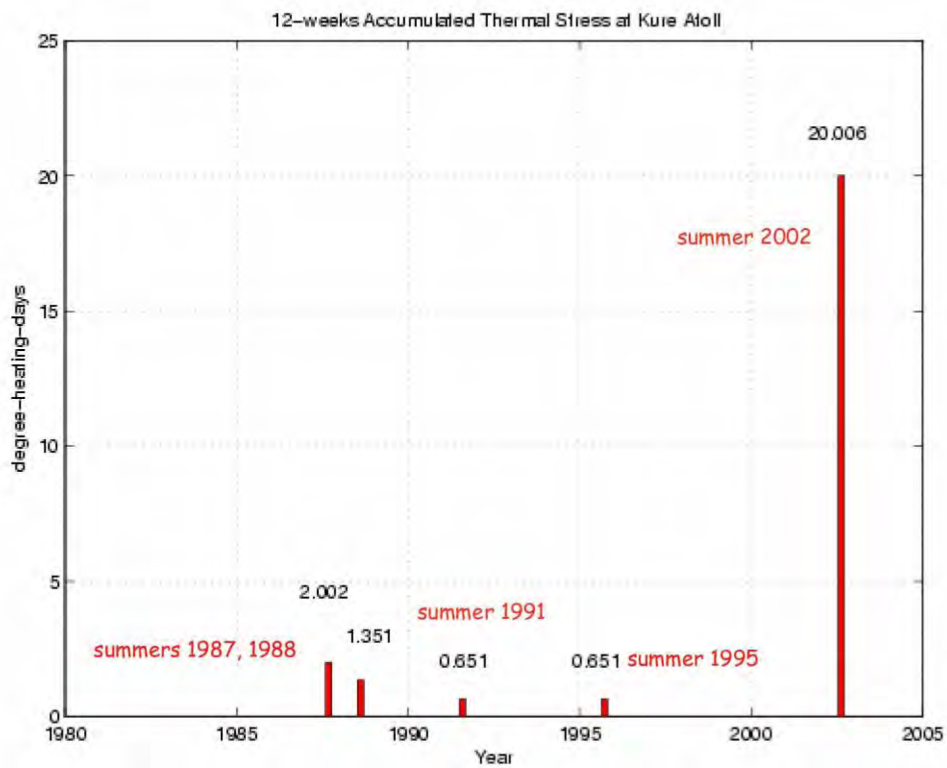
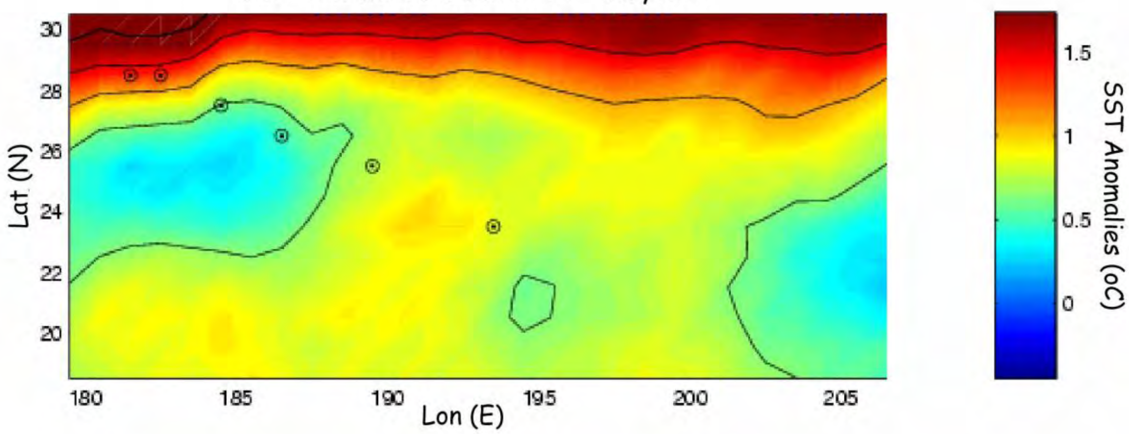


Figure 5. Accumulated Thermal Stress at Kure Atoll

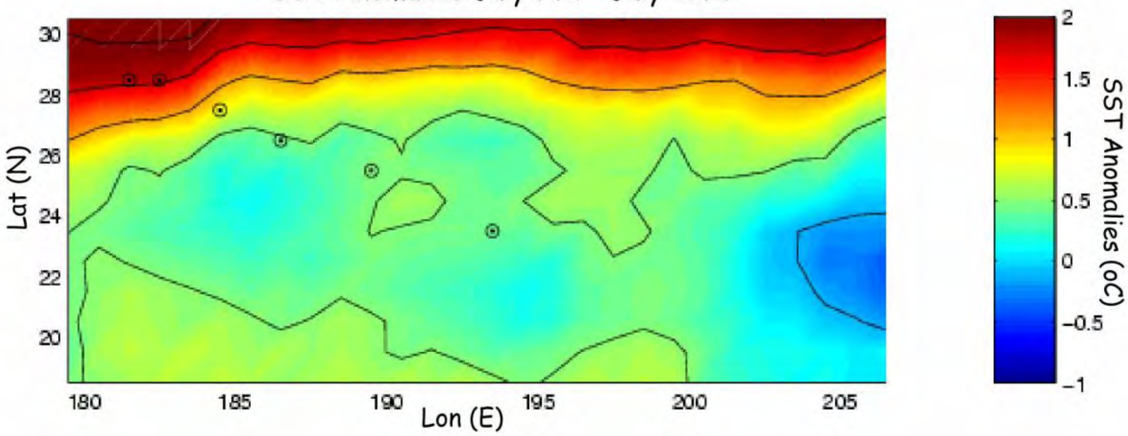


APPENDIX VI
Summer 2002 Reynold's Weekly SST Anomalies over the NWHI Region

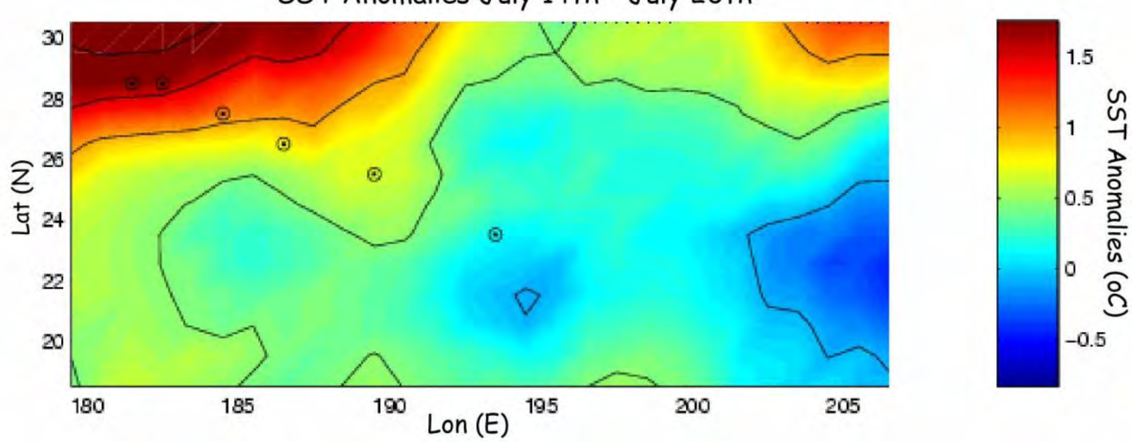
SST Anomalies June 30th - July 6th

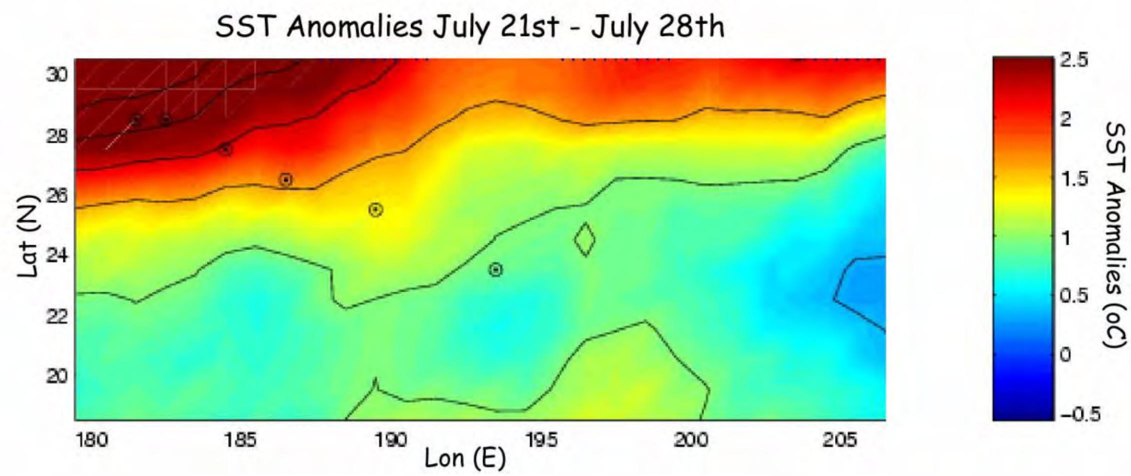


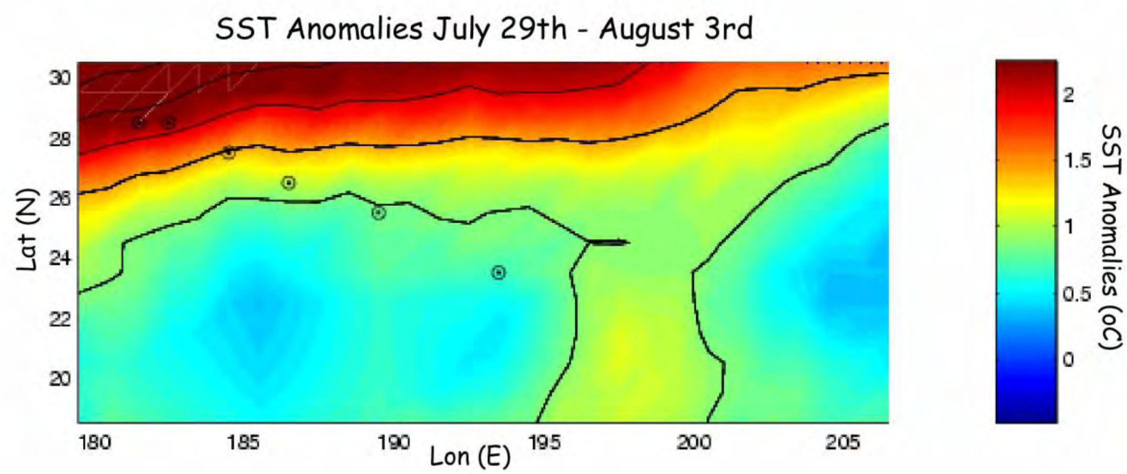
SST Anomalies July 7th - July 13th

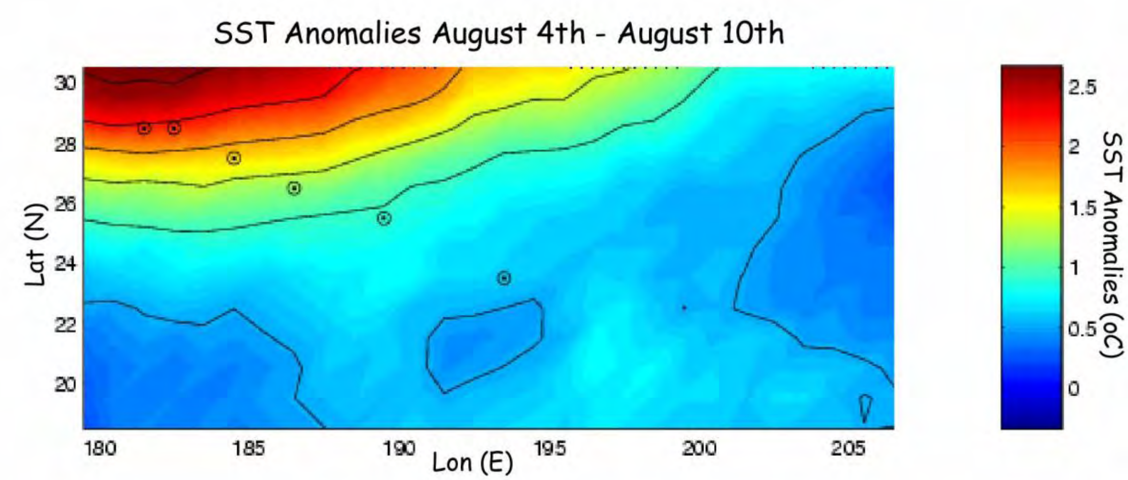


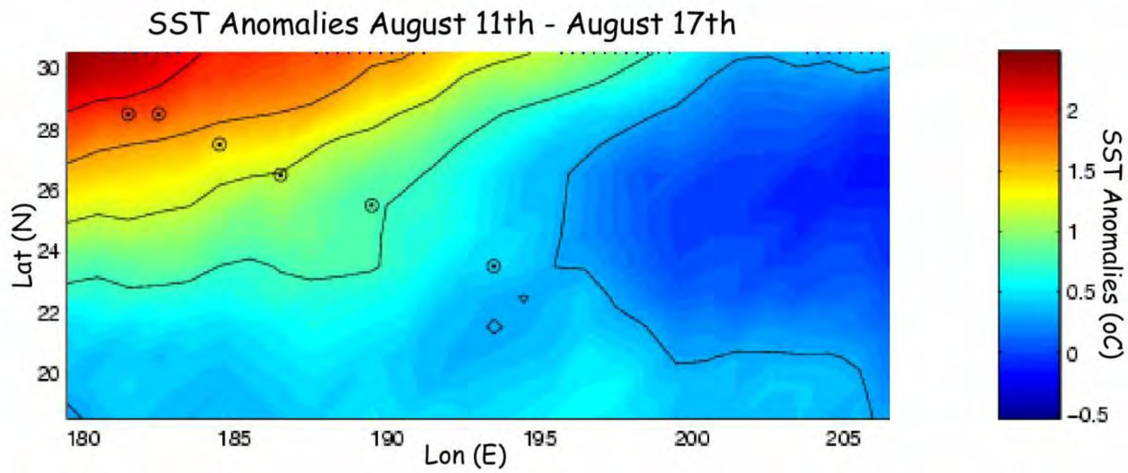
SST Anomalies July 14th - July 20th

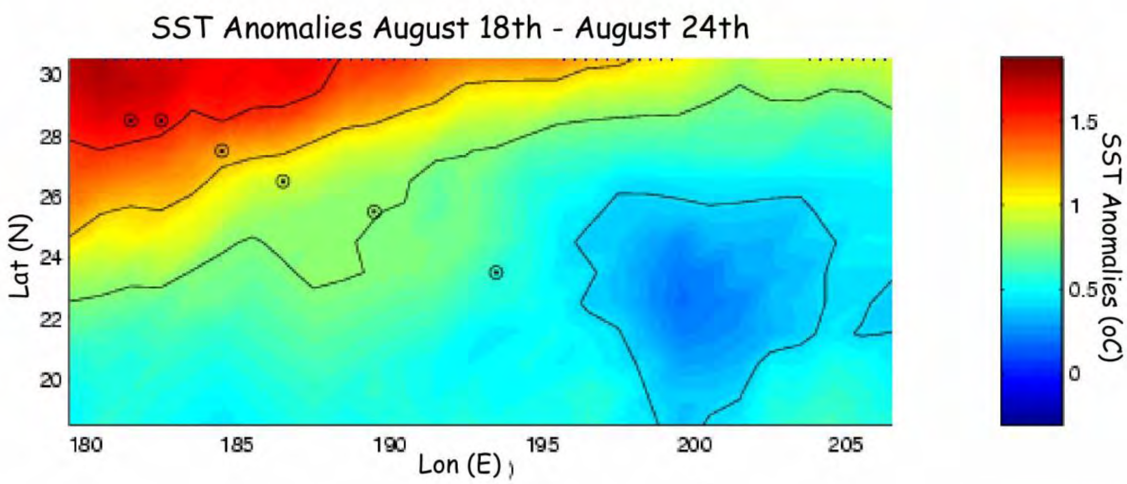


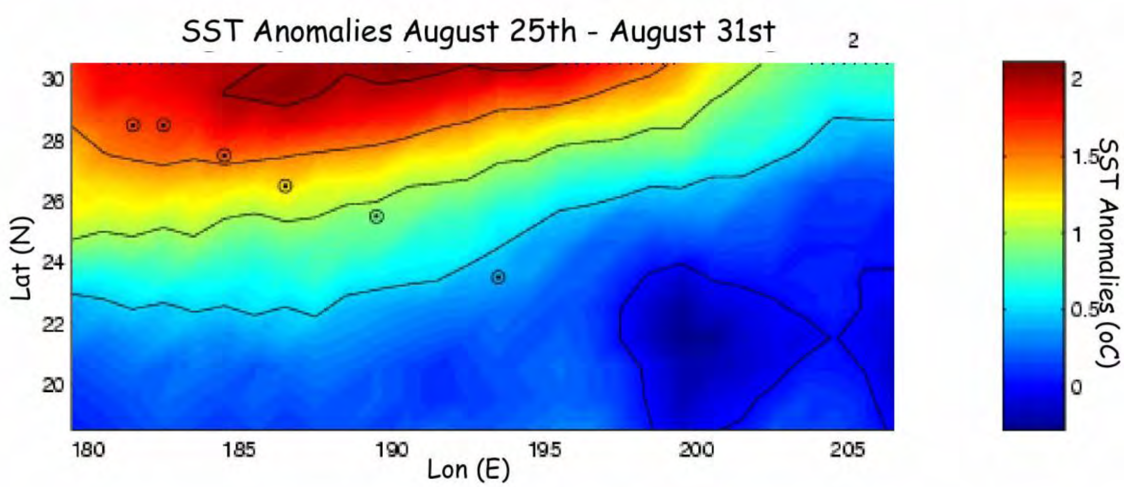

SST Anomalies July 21st - July 28th
Lat (N)
Lon (E)
SST Anomalies (oC)
30
28
26
24
22
20
180
185
190
195
200
205
2.5
2
1.5
1
0.5
0
-0.5

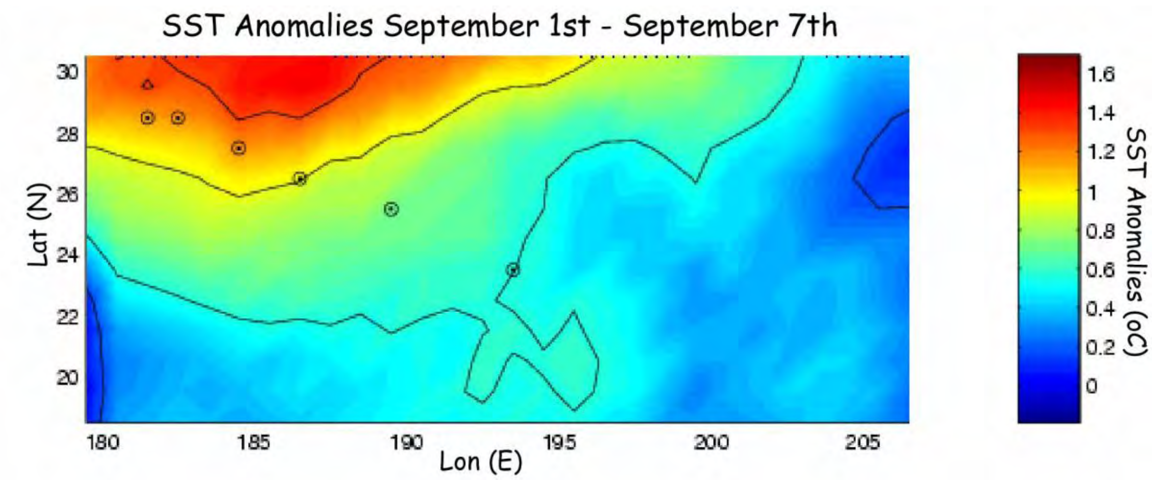

SST Anomalies July 29th - August 3rd
Lat (N)
Lon (E)
SST Anomalies (oC)
30
28
26
24
22
20
180
185
190
195
200
205
2
1.5
1
0.5
0

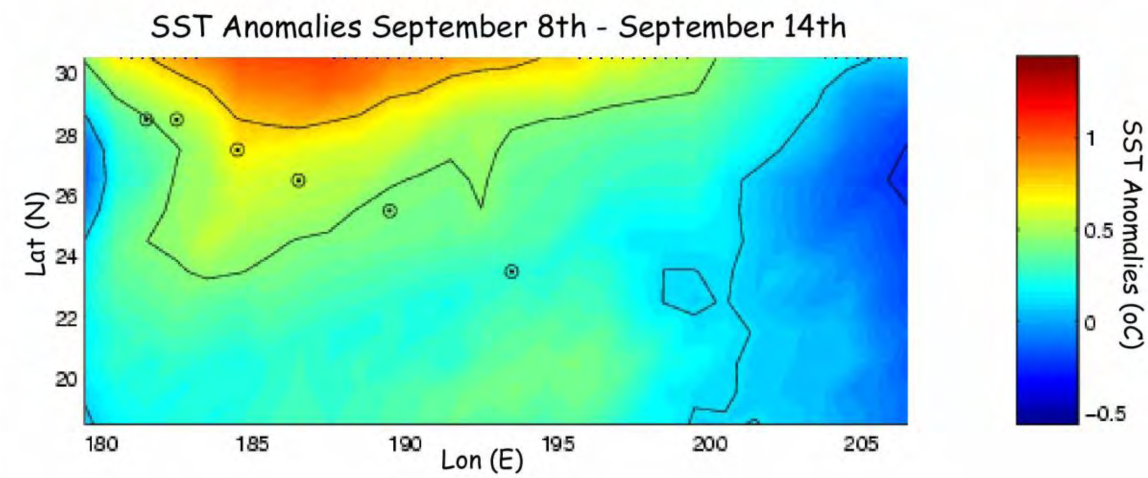

SST Anomalies August 4th - August 10th
Lat (N)
Lon (E)
SST Anomalies (oC)
30
28
26
24
22
20
180
185
190
195
200
205
2.5
2
1.5
1
0.5
0


SST Anomalies August 11th - August 17th
Lat (N)
Lon (E)
SST Anomalies (oC)
30
28
26
24
22
20
180
185
190
195
200
205
2
1.5
1
0.5
0
−0.5


SST Anomalies August 18th - August 24th
Lat (N)
Lon (E)
SST Anomalies (oC)
30
28
26
24
22
20
180
185
190
195
200
205
1.5
1
0.5
0


SST Anomalies August 25th - August 31st
Lat (N)
Lon (E)
SST Anomalies (oC)
30
28
26
24
22
20
180
185
190
195
200
205
2
1.5
1
0.5
0


SST Anomalies September 1st - September 7th
Lat (N)
Lon (E)
SST Anomalies (oC)


SST Anomalies September 8th - September 14th
Lat (N)
Lon (E)
SST Anomalies (oC)