World Resource Review Vol. 17 No. 3

REGIONAL PATTERNS OF SEA SURFACE TEMPERATURE RISE: IMPLICATIONS FOR GLOBAL OCEAN CIRCULATION CHANGE AND THE FUTURE OF CORAL REEFS AND FISHERIES

Thomas J. Goreau
President, Global Coral Reef Alliance, Cambridge, MA USA

Raymond L. Hayes
Professor Emeritus, Howard University, Washington DC USA

Don McAlllister
Formerly President of Ocean Voice International, Ottawa CANADA,
posthumously

ABSTRACT

Since the 1980s, corals have undergone unprecedented high temperature mass bleaching and mortality. Locations, intensity, and severity of bleaching are predictable by the sea surface temperature (SST) "HotSpot" method (Goreau & Hayes, 1994). HotSpot patterns over the last 2 decades show strong regional trends: SST increases are many times average rates in some regions, but lower in others. The regional spatial HotSpot patterns suggest that ocean circulation is being systematically altered by world-wide changes in winds, ocean currents, and upwelling. The data suggest that: 1) intensities of all warm currents are increasing; 2) intensities of all cold currents are decreasing; 3) coastal upwelling is being reduced at all major sites; 4) open-ocean upwelling is increasing in the interiors of all ocean basins; 5) wind driven upwelling is increasing all around Antarctica; and 6) flow from the Pacific to the Indian Ocean through Indonesia is increasing. Because of their magnitude, these changes will have much greater effects on regional climatic extremes and ecosystem alterations than mean global warming rates. The most rapidly warming areas are potential sites of regional coral reef ecosystem collapse. Corals may survive in areas where warming is slowest due to increased upwelling. However they will persist in marginal coral communities, not constructional coral reefs, due to increased competition from algae and filter feeders. These changes have strong implications for future patterns of global warming, ocean-atmosphere CO_2 fluxes, marine biodiversity, fisheries catches, and primary productivity. Pelagic fisheries should be displaced from intense coastal upwelling zones to less productive open-ocean upwelling areas, with

important economic consequences. The trends indicated by the measured temperature data in this paper suggest that negative effects on coral reef ecosystems will be much more imminent than predicted by current models of climate change.

INTRODUCTION

Large scale bleaching and mortality of corals caused by high temperatures have become worse with time since first observed in the early 1980s (Glynn, 1990, 1991; Jokiel & Coles, 1990, Williams & Bunkley-Williams, 1990). Although at first the phenomenon was regarded as linked to El Nino Southern Oscillation (ENSO) events (Glynn, 1990), bleaching has been known since the early 1990s to be correlated in near real time with anomalously high satellite-derived sea surface temperature (SST) (Goreau et al., 1993; Goreau & Hayes, 1994a; Goreau & Hayes, 1995; Goreau, Hayes, & Strong, 1997; Goreau et al. 2000; Goreau & Hayes, 2004a,b). Global rises in SST are closely coupled to changes in atmosphere temperatures (Karl & Trenberth, 2003).

We use the global satellite SST record provided by the infrared data from the NOAA Advanced Very High Resolution Radiometer (AVHRR) that has provided global coverage since 1982. Detailed analysis of this data set shows that it is highly consistent and has only minor differences with the oceanographic data base (Reynolds & Smith, 1994; Strong et al., 2000). Large scale coral bleaching follows high temperature extremes in which monthly average SST values reach 1.0 degrees Celsius above normal maximum monthly averages ("HotSpots", as defined by Goreau & Hayes, 1994a). Coral bleaching as well as mortality follows periods of 2 or more degrees Celsius above the normal for at least a month, or periods of one degree C above monthly averages for two months or more. The critical parameters for coral bleaching and mortality are the degree of the temperature anomaly and the duration of exposure. However, other stresses, such as intense sunlight, sediment loading or pollution, may exacerbate the loss of symbionts, delay the recovery, and promote coral tissue death. The coral bleaching response is an additive or gradient effect, not a threshold effect that influences coral species differentially.

Under all global warming scenarios HotSpots should become more frequent, persistent and severe (Goreau, 1990; Goreau and Hayes, 1994a). However it is not known if such anomalies are statistically independent climatic "noise" events, taking place at random locations and times, or if there are predictable regional changes in which some areas are systematically warming at higher or lower rates than other areas. Climate change models show irregular areas with patchy warmer temperatures (Hansen et al., 1988), but these are thought to reflect local fluctuations in weather rather than systematic regional patterns.

Hansen et al. (1999) have shown a long-term increase in air temperatures over the ocean, but did not discuss the effects on ocean circulation. Levitus et al. (2000) have shown a marked long term increase in the integrated heat content of the upper 3000 meters in all oceans from oceanographic data, but did not evaluate changes in ocean surface circulation patterns. Strong et al. (2000) have shown a latitudinal pattern in SST increases, with greater warming in the northern hemisphere than the southern, but did not examine systematic regional patterns of change, the focus of this paper. The zonal patterns shown by Strong et al. (2000) from a global SST database are virtually identical to those derived from analysis of SST data in coral reef regions alone (Goreau & Hayes, 2004b). This indicates that although coral reefs are not uniformly distributed in all parts of the oceans, they provide a data set that is large enough and well dispersed enough to come up with essentially the same results as a complete ocean study (except for polar regions).

As in those studies, we have used the complete global satellite SST record from 1982-1998, but we have eliminated data from those years in which El Nino events took place. Those events could bias the values slightly upwards. We have also eliminated data following the large volcanic eruptions of El Chichon (1982) and Mount Pinatubo (1991) that injected high sulfate aerosols in the stratosphere, reflecting sunlight back to space, and biasing the SST measurements to low values. This leaves 14 years of data over a span of two decades. Because warming associated with the El Nino years has been eliminated from our averaging, the rates of warming shown are biased to low values wherever temperatures are positively correlated with the ENSO. If El Ninos get more intense and longer lasting with global warming, as suggested by global climate change models (Fedorov & Philander, 2000; A. Bush, personal communication) then the effects could become even greater than estimated here. Our data indicate that consistent regional differences in warming have taken place in the last two decades, with profound implications for global ocean circulation, regional climate change, and the future of coral reefs and fisheries.

SST HOTSPOT PATTERNS

HotSpot spatial patterns are very variable year by year (see color graphs of annual HotSpots at www.globalcoral.org Instantaneous HotSpot maps are available at http://www.osdpd.noaa.gov/PSB/EPS/SST/climo&hot.html, but those reflect very short term fluctuations which must be integrated for a month to be HotSpot in the sense of the definition by Goreau & Hayes, (1994). When averaged to form a composite HotSpot map these variations appear not to be random, and clear long term regional patterns become obvious (Figure 1, but see www.globalcoral.org for more information in color maps): some regions are warming up much more rapidly than the global average, while other regions are warming at a much slower rate. It is important to note that these are the trends in maximum monthly temperatures at each site, not in average annual temperatures.

Detailed examination of SST data from the Caribbean showed that while maximum monthly temperatures were increasing, the minimum monthly temperatures were increasing even faster, reducing the seasonal range (Goreau et al., 1993). As a result the trends in warmest months are likely to underestimate annual temperature trends. This is also seen in the expanded global database (Goreau and Hayes, 2004b, plus supplementary data at www.globalcoral.org). A further underestimate of warming in our estimates is due to the fact that El Nino years, which tend to be warmer than normal, have been excluded from the database used to calculate trends. In addition, calibration of satellite derived SST against in-situ measured values show that while the satellite values are generally within 0.2 degrees of the measured value, they increasingly underestimate in site values as temperature rises, presumably because of increased sub-pixel size cloud contamination of the signals measured by satellite AVHRR infrared SST sensors (Goreau & Hayes, 2004a).

Regions that are getting warmer faster than the average must have systematically more heat entering the area than is leaving. This buildup of heat is most likely due to changes in ocean currents and winds or changes in sun hours (insolation). Local warming could be explained by changes in cloudiness, winds, wave breaking, ocean currents, depth to the thermocline, and/or rates of upwelling, as well as global warming.

Altered currents, upwelling, and/or vertical mixing caused by changing currents and winds would account for much larger changes in regional surface temperature than global average trends. Changes in SST due to altered ocean currents would depend on whether cold or warm currents are modified. Warming would result from areas that are receiving more water transport from warm currents or reduced water transport from cold currents, and cooling would result from increased cold water current flow or decreased input from warm currents. Areas with decreasing cloudiness would get warmer, while areas with increasing cloud cover would get cooler. Areas of increased wind velocity would have increased mixing depths and increased wind-driven upwelling and would get cooler, while areas of reduced wind velocity would show warming. Changes in the depth of the thermocline would affect surface water temperatures if the warm surface layer were confined to a narrower depth range. This would cause warming at the surface even at fixed total heat content, while increased depth of mixing would cause surface cooling. Decreased upwelling raises surface temperature, and increased upwelling lowers surface temperature.

Those regions worldwide where rates of maximum monthly SST change are markedly different than the average are discussed individually in the following text, along with the possible changes in ocean and wind circulation that would account for the SST changes. These have been identified in Figure 1 and on separate maps of higher than average and lower than average warming (color maps at www.globalcoral.org). Anomalous areas are numbered or marked in the center of each area. Anomalous areas vary greatly in size, but show clear spatial patterns related to ocean circulation, which are discussed individually below.

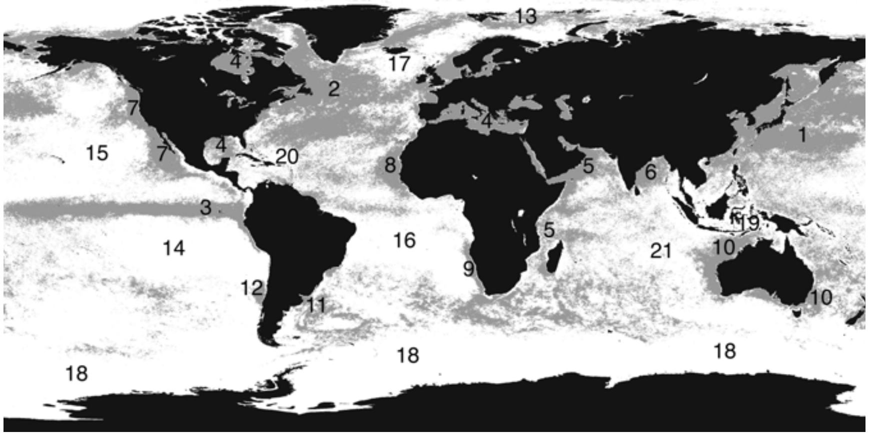

Figure 1 Map of average HotSpot values in the edited data set (non-El Nino years and non-volcano years from 1982-1997). Regions of the world ocean whose average maximum temperatures were consistently at HotSpot levels are shaded. The numbers on the map refer to the regions of greater than average and less than average warming discussed in the text. Much more detail, including quantitative values, is seen in the color figures posted on the web (link and captions below).

COLOR FIGURES ON THE WEB AT www.globalcoral.org

FIGURE A Map showing mean hot spot intensities of edited data series, showing regions warming more rapidly than average.

FIGURE B Map showing mean hot spot intensities of edited data series, showing regions warming more slowly than average.

AREAS OF GREATER THAN AVERAGE WARMING

1. Northwest Pacific

   Intense HotSpots regularly line up along the axis of the Kuroshio Current and the areas immediately down-current from it as far as Alaska. This accelerates the velocity of heat transport into the northwest Pacific from the western tropical Pacific, affecting climate of western North America. Since the Kuroshio is the world's strongest current in terms of heat flow, these changes have significant implications for increasing global heat fluxes from the tropics to the temperate zone and for driving climate change in North America. Such changes also are consistent with an increased strength of typhoons in the North Pacific (Emmanuel, 1987).

2. Northwest Atlantic

   Intense HotSpots regularly line up along the axis of the Gulf Stream Current and the areas immediately down-current from it as far as Europe. This implies that the velocity and total heat transport into the northwest Atlantic from the Caribbean has accelerated. The Gulf Stream, the world's second strongest current in terms of heat flow, appears to be strongly increasing the flow of heat into the north Atlantic and adjacent European shores.

3. Pacific and Atlantic Equatorial Zones

   A zone of consistently warmer water lies along the equator across the entire breadth of the Pacific Ocean from Ecuador to Borneo, with the strongest warming in the east. This suggests that upwelling from the Equatorial divergence and the Equatorial Counter Current might be declining, as is the upwelling in the core of the Eastern Pacific El Nino region, or since El Nino years are excluded, that the strength of La Ninas are increasing. A similar, but weaker, warm zone marks the equatorial Atlantic and the Guiana Current. Such a feature is not found in the Indian Ocean, probably because it is over-ridden by seasonally reversing Monsoonal circulation patterns.

4. Enclosed Seas

   Enclosed seas (Gulf of Mexico, Western Caribbean, Hudson Bay, Baltic, Mediterranean, Black Sea, Caspian, Red Sea, Persian Gulf, Sea of Japan, East China Sea, South China Sea, Aral Sea, North Sea, and Baffin Bay), whether in hot or cold regions, show increases in maximum monthly temperatures. As these are areas of restricted circulation, heat must be building up in the surface layers, depressing the thermocline, and reducing rates of internal vertical exchange. Such change is in accord with predictions of increasing hurricane strength in the Western Caribbean (Emmanuel, 1987). The only semi-enclosed seas that do not follow this trend are the Indonesian Seas, which are dynamically very different and discussed separately below.

5. Western Indian Ocean

   The entire Western Indian Ocean shows higher than average warming, with the strongest effects in the northwest area that lies in the core of the Somali Current, where upwelling appears to have been reduced. The warm Agulhas Current area also appears to be increasing in heat transport.

6. Bay of Bengal

   The entire Bay of Bengal north of a line connecting Sri Lanka to the Andaman Islands is a focus of warming. This warming is likely to produce increasingly strong cyclones as anticipated by Emmanuel (1987).

7. Western North America

   The entire western coast of North America shows increased warming. This would be expected from decreased flow of the cold Alaskan and California Currents, coupled with decreased upwelling.

8. Northwestern Africa

   A strong increase in temperature off Northwestern Africa lies in the core of the area normally affected by the Mauritanian upwelling system. This temperature increase may indicate decreased upwelling in this area.

9. Southwestern Africa

   The region normally affected by the cold Namibian Current and southwest Africa upwelling system is warming sharply, probably due to reduced influx of cold water by reduced cold current velocity or to a decrease in upwelling.

10. Australia and New Zealand

    A distinct composite HotSpot surrounds Australia and extends as far as New Zealand. This is consistent with increased warm current flow from the equatorial Pacific and Indian Oceans on the east and an increase in the warm Leeuwin current along the west coast of Australia.

11. Southwestern Atlantic

    A HotSpot lies off southeast South America from Cabo Frio to the Malvinas (Falklands). Cold water flow northwards from Antarctica may be diminishing westerly wind-driven upwelling off Patagonia. Also a change in velocity of the warm Brazil Current may be reducing local upwelling around Cabo Frio.

12. Western South America

    Distinct warming is found along most of the western coast of South America. This implies that the strength of the world's largest shelf edge upwelling area is decreasing, and that the strength of the cold Humboldt Current is decreasing.

13. Arctic margins

    Distinct warming is seen around all the margins of the Arctic Ocean, with strong HotSpots frequently found north of Iceland and around Spitsbergen and Novaya Zemlya.

AREAS OF LESS THAN AVERAGE WARMING

14. Southeast Pacific

    A distinctly cooler area marks the interior of the Southeast Pacific. The area affected is the interior of the ocean, and does not extend to the coast of South America. An increase in wind driven upwelling by the Southeast trades would account for this change, presumably because of increased wind speed in the ocean interior.

15. Northeast Pacific

    A distinctly cooler area marks the interior of the Northeast Pacific. The area affected is the interior of the ocean, and does not extend to the coast of North America. Wind driven upwelling by the Northeast trades is apparently increasing due to increased wind speed in the ocean interior.

16. Southeast Atlantic

    A distinctly cooler area marks the interior of the Southeast Atlantic. The area affected is the interior of the ocean, and does not extend to the coast of Africa. Wind driven upwelling by the Southeast trades is increasing, due to increased wind speed in the ocean interior.

17. Northeast Atlantic

    An oddly-shaped cold water spot lies south of Iceland, extending northeast into the Barents Sea. This could be caused by wind-driven upwelling caused by strong westerly winds in the North Atlantic. The open ocean cooler patch in the North Atlantic is distinctly smaller than in other oceans, because it is reduced by the influence of the large Gulf Stream HotSpot.

18. Antarctic Divergence

    A circum-Antarctic band of relative cooling fills the southern oceans. This could be due to increased wind driven upwelling if the Westerlies are increasing in speed.

19. Indonesia

    The waters around Indonesia are anomalously cooler compared to all other Equatorial regions. Indonesia is where the major flow of surface water from the Pacific to the Indian Ocean takes place. If the velocity of the Indonesian throughflow from the Pacific to the Indian Oceans were increased there would be increased concomitant entrainment of deep basin waters, and localized cooling would be expected.

20. Eastern Caribbean

    Eastern Caribbean waters are warming at a slightly cooler rate than surrounding waters. The increased flow of warm water out of the Caribbean into the Gulf Stream has caused increased entrainment of colder water from below or from deeper waters of the open Atlantic. This may be the reason why the Caribbean, while having numerous severe bleaching events since 1987, has experienced less coral mortality than that seen in severe Indo-Pacific bleaching events, and increased upwelling would explain part of the increase of algae in some remote reef areas.

21. Indian Ocean

    A distinctly cooler region is found in the southeast Indian Ocean. This appears to be analogous to the cooler areas found in the Trade Wind belts of the North Pacific, South Pacific , South Atlantic, and North Atlantic.

GLOBAL SST CHANGES AND ATMOSPHERIC CLOUD, WIND, AND SOLAR RADIATION PATTERNS

Ocean circulation is a major driving force behind global climate change (Rahmstorf, 2002), and strongly affects climate on adjacent continents (Seager et al., 2002). However there are surprisingly few direct measurements of global ocean surface circulation change at the present time due to the limited number of long term ocean current measurements. SST data are shown here to provide a unique global data set that can be used to evaluate such changes. Most of the areas of greater than average warming are in the Northern Hemisphere, and most areas of less than average warming are in the Southern Hemisphere (Table 1), implying a net transfer of heat from south to north across the Equator.

Global SST changes are similar to surface atmospheric trends, but differ from them due to changes in ocean circulation. It should be noted that the entire data set examined here postdates a large global jump in atmospheric surface temperatures that took place in the late 1970s. Had global satellite SST data been available for the previous decade, larger trends might have been shown, with greater insights into possible changes in ocean circulation. These surface trends in turn follow similar trends towards increases in the heat content of the ocean shown by oceanographic databases (Levitus et al., 2000) and in the entire troposphere (Santer et al., 2003a; Vinnikov & Grody, 2003), along with an increase in the height of the tropopause (Santer et al., 2003b).

These patterns of SST change coincide with global trends in wind, cloud, and humidity. Tropical humidity and winds have shown strong increases as the earth warms, causing an increase in tropical atmospheric heat, moisture, wind, and energy circulation (Flohn & Kappala, 1989; Flohn et al., 1990). Since water vapor is the major atmospheric greenhouse gas, absorbing much more heat than carbon dioxide, these increases act as a positive feedback mechanism amplifying global warming from fossil fuel combustion and other anthropogenic sources. Global changes in wind patterns, measured by direct measurements (Cardone et al., 1990) and by radar scattering signals from surface waves measured by satellites, show increases in open ocean winds, especially all around Antarctica and in the North Atlantic, but decreases along the continental margins where shelf edge upwelling takes place (S. Caires et al. 2003). The areas of highest input of wind kinetic energy into the surface ocean (Alford, 2003) are the areas of slower than average warming. Increasing wind speeds in the high stress areas implies more energy input into internal waves, and greater internal mixing in remote ocean basins due to breaking of internal waves. The local increase in upwelling suggested by the reduced rate of warming in circum-Antarctic waters is supported by increased wind velocity in this area caused by changes in the solar radiation caused by the expansion of the Antarctic ozone hole (Thompson & Solomon, 2002; Gillett and Thompson, 2003). Small scale temperature gradients related to ocean currents generate persistent wind features with strong implications for weather patterns and heat and gas fluxes across the air-sea interface (Chelton et al., 2004).

Global cloudiness shows a decrease in cloudiness over land, especially in the temperate zone of the northern hemisphere, but little change in the oceans or the tropics (D. P. Wylie, et al., 2002). Although global cloud area shows a small but clear decrease, there is strong evidence from decreasing global rates of pan evaporation (Peterson et al., 1995; Golubev et al., 2001; Roderick & Farquhar, 2002) and direct measurements (Russak, 1994; Gilgen et al., 1998) that solar irradiance at the earth's land surface is decreasing, indicating more absorption of sunlight by clouds. This is also linked to a decrease in the diurnal temperature range (Roderick and Farquhar, 2002). A decrease in cloudiness in the Amazon basin is linked to a global increase in net terrestrial primary productivity (Nemani et al., 2003).

The apparent contradiction of decreasing land evaporation with decreasing land cloudiness is neatly explained by a strong global pattern of lowering of the bases of clouds and raising of the cloud tops, making the clouds thicker (Chermykh et al., 2001)). Thicker clouds are more light absorbent, and contain increased aerosol content per unit surface area. These global trends suggest that the changes in SST HotSpots shown here should be affected by global changes in velocity, heat, and moisture content of oceanic winds and local cloud density.

Ocean freshening from ice melting is a major contributor to global sea level rise (Munk, 2003). Increased melting of polar ice (Laxon, Peacock, & Smith, 2003) also has a strong positive feedback on global warming due to changes in surface albedo (light reflectance). Increased tropical evaporation, and increased melting of ice caps in polar regions, due to global warming, are causing a change in density of the surface ocean (Curry, Dixon, & Yashayaev, 2003) which is acting to reduce the rate of deep water turnover. This in turn will provide a positive feedback on global warming, as heat accumulates at the surface instead of being carried into deep waters.

IMPLICATIONS FOR OCEAN CIRCULATION AND REGIONAL CLIMATE CHANGE

Table 1 shows dramatic changes in the global patterns of SST change when classified by ocean currents and upwelling regimes. The HotSpot patterns strongly suggest that: all major warm currents in the northern and southern hemisphere are increasing their rate of heat transport from the tropics poleward, and that heat is flowing out of the tropics at an increasing rate, with a net transfer from south to north. At the same time all major cold currents appear to be reducing their flow of cold surface water from the polar regions towards the tropics. This has been directly shown from long term measurements showing warming in the area affected by the cold California current (Roemmich, 1992). Also, all enclosed seas are undergoing increased stratification and getting warmer.

Table 1 Classification of warming rates by ocean circulation regions or habitats.

OCEAN HABITAT	FASTER WARMING	SLOWER WARMING
Mid ocean gyres	0	6
Equatorial currents	3	0
Antarctic Ocean	0	3
Warm coastal currents	5	0
Cold coastal currrents	4	0
Coastal upwelling zones	5	0
Marginal seas	10	0
Northern Hemisphere	20	3
Southern Hemisphere	9	6

Rates of shelf edge upwelling appear to be decreasing at all major coastal upwelling sites (Table 1), causing local warming in these areas. These include the major upwelling systems off Peru, Namibia, Mauritania, Somalia, and California as well as smaller ones like Cabo Frio in Brazil.

Rates of upwelling in ocean interiors appear to be increasing, presumably because of higher wind velocities. The rate of entrainment of deep water into the Indonesian Pacific-Indian Ocean throughflow appears to be increasing. This could be because the velocity is increasing or simply an effect of the extremely strong tidal mixing in Indonesian seas (Ffield & Gordon, 1996; Gordon, Susanto, & Vranes, 2003). This area plays a critical regulatory role for global climate because it is the major location through which surface water flows from the northern to the southern hemisphere and from the Pacific to Indian Oceans (Gordon & Fine, 1996; Visser et al., 2003).

Because all ocean basins contain areas of both greater than average and less than average warming, the internal temperature gradients within them are increasing. This implies greater variances in atmospheric pressure gradients and wind velocities, as well as increasing variance of extreme climatic events. The North Atlantic may be the least affected because of the very small area of relative cooling compared to all other ocean basins. The strongest effects should be seen in the South Pacific, North Pacific, and South Atlantic. These patterns are affected by global changes in sea surface pressure, with increasing atmospheric pressure over Europe, North Africa, and South Asia, and decreasing pressure in the North Pacific and Polar regions (Gillett et al., 2003). East-west gradients in temperature and pressure across the equatorial Pacific strongly influence the magnitude of ENSO events (Cobb et al., 2003).

Small regional variations in air temperatures (Hansen et al., 1999) and local ocean circulation can have much larger effects on local temperatures than does global warming. Therefore, models of climate change that do not include regional changes in ocean circulation will increasingly underestimate the ecological effects of extreme weather patterns. These changes in marine circulation should increase the incidence of extreme heat and precipitation events (Karl, 1996; Hoerling and Kumar, 2003). Their biotic consequences are significant for ecosystem vitality and for human health, in coastal regions of North America, Europe, Asia, Australia, and Africa, with smaller effects in South America.

Because deep ocean mixing is largely driven by surface currents and winds and tides (Munk & Wunsch, 1998; Wunsch, 2001; Wunsch, 2002; Papparella & Young, 2002; Rahmstorf, 2003: Garrett, 2003), deep ocean circulation could also be affected by the changes seen in SST distributions, especially where they correlate with changes in wind velocity. Ocean circulation models suggest that global warming and polar ice cap melting would cause increased vertical stratification, causing surface water in the North Atlantic to become too fresh to sink to the bottom, cutting off the deep sea circulation (Manabe & Stouffer, 1995, 1999; Vellinga & Wood, 2002)), but increases in wind velocity could counteract such stratification to some degree.

Carbon dioxide gas is less soluble in warmer waters than cooler waters, and so is released from the warmest areas to the atmosphere and dissolves in cooler surface waters (Takahashi et al., 2002). Increased thermal gradients between relatively warmer and relatively cooler spots within every ocean imply increased internal recycling of carbon dioxide within the ocean and between ocean and atmosphere. Even the cooler areas are largely warming, though at a slower rate than average, rather than actually getting cooler (although a few areas are doing so, primarily in the Southeast Pacific and Northern Atlantic). The net trend is an increasing release of carbon dioxide from oceans to atmosphere, providing a positive feedback that amplifies global warming. And changes in carbon dioxide fluxes have corresponding changes in oxygen fluxes between ocean and atmosphere (Karl et al., 2003)

These positive feedbacks could be further amplified if increased ocean stratification reduces the supply of deep water nutrients that drive phytoplankton primary production and export of particulate carbon to the ocean floor (Falkowski, Barber, & Smetacek, 1998). Intense upwelling of cold waters along continental shelves provides an important mechanism for bringing not only nutrients but carbon dioxide from deep cold waters into warmer surface waters where it can be released to the atmosphere, with globally significant climatic effects (Palmer and Pearson, 2003). The global decreases of intense coastal upwelling suggested here by SST data and its substitution by diffuse open ocean upwelling imply a decrease in the rate of release of ocean carbon dioxide from the deep ocean to the surface, and conversely in its transport from surface waters to the deep sea, which acts to slow down the rate of warming at the Earth's surface.

This study has used global satellite SST data sets to infer changes in global patterns of ocean surface circulation that could only be directly measured with long-term deployment of expensive long-term arrays of current meters worldwide. However, long term spatially dense current meter data and/or acoustic tomography may prove essential for verifying detailed inferences about ocean circulation suggested here from SST data alone.

DEEP WATER EFFECTS OF SEA SURFACE TEMPERATURE ELEVATION

Other studies using global climate models indicate that global warming can also account for elevated temperatures in the deep ocean to depths as great as 10,000 feet or 3,000 meters (Levitus et al., 2001; Barnett et al., 2001). While important for the assessment of changes in the ocean realm, our focus upon sea surface temperature anomalies in this study is necessary to establish the direct impact of warming of the near shore and shallow water column upon tropical coral reef ecosystems. Physical characteristics of surface ocean waters have been sufficient to disturb the vitality and relationships among reef dwelling organisms, and in turn threaten the persistence of ecosystem services and the survival of associated ecosystems that are dependent upon the integrity of structure and function of the coral reef. Changes in surface ocean conditions can differentially change species abundances, altering the flow of particulate carbon that nourishes deep water ecosystems.

Although warming of ocean waters depends on heat transfer from the sun and seasonally from the atmosphere, the temperature of sub-surface water is influenced by wind friction at the air-ocean interface (Longhurst, 1998). In the tropics, the trade winds generate surface current transport. Continental land masses deflect the flow into littoral currents that run northerly above the equator and southerly below the equator. At higher latitudes within the Atlantic and Pacific Oceans, gyres circulate in the opposite direction because flow in temperate latitudes is in the opposite direction as the trade winds, although in the Indian Ocean, winds reverse with the Monsoon seasons and water currents follow. These currents are deflected by the Coriolis forces of the Earth's rotation. In the northern hemisphere, deflection is to the right, and in the southern hemisphere to the left. Surface waters in subtropical gyres are deflected inward toward the center of the gyre, and warm surface waters depress the thermocline and raise the sea level. Deeper waters, containing nutrients, are kept low in the water column by the resultant downwelling. Tropical storms lift the deep cooler water to the surface as they traverse the ocean.

Equatorial and coastal Kelvin or boundary waves are gravity-sensitive and are driven by changes in wind. Coastal Kelvin waves propagate in the northern hemisphere along the coastline in a counter clockwise direction; in the southern hemisphere, they propagate clockwise. Wind anomalies change Ekman transport and push water toward the equator. This causes warm surface water to pile up near the equator, thereby downwelling and depressing the thermocline. Major zones of strong upwelling normally occur off the coasts of Chile. Peru, West Morrocco, Namibia, Somalia, and the Pacific coast of the United States, with smaller ones elsewhere. This coastal upwelling occurs where surface winds around subtropical anticylonic gyres blow parallel to the coastline or offshore. Through these complex interactions, modulated by oceanic dipole oscillations, changes in surface boundary conditions will affect deep ocean properties at varying rates in different locations. Our data refer only to surface changes, and full three dimensional models are needed to evaluate their long term impacts on the deep ocean.

IMPLICATIONS FOR THE FUTURE OF REEF-BUILDING CORALS AND CORAL REEFS

Predictions of coral reef vulnerability assume that the pattern of ocean circulation change that has taken place in the 1980s and 1990s will continue, which they thus far appear to be doing. It is of course risky to extrapolate current trends into the future because of possible long term climatic cycles and "noise" (Wunsch, 1999). Also non-linear thresholds in ocean and wind circulation patterns could be reached that qualitatively change the intensity and distribution of HotSpots in the future. Nevertheless these SST patterns suggest that the past 20 years have seen global changes in ocean circulation with profound implications for future climate change, fisheries, and coral reefs world-wide.

Coral reefs around the world lie very close to their upper thermal limits and have been repeatedly pushed over them in the last two decades (Glynn, 1991; Goreau et al.; 1993; Goreau & Hayes, 1994a; Goreau et al. 2000). Yet all reefs are not equally vulnerable, as they would be if global warming were uniform. While most coral reef regions have been repeatedly bleached, a few reefs have yet to be seriously affected. The composite HotSpot pattern provides insight into which areas are most vulnerable to coral reef extinction and which are least likely to be affected.

Coral reefs that are most vulnerable to HotSpots, if current trends continue, are those that lie in the areas affected by increasing heat transport in warm currents (such as the South China Sea, the East China Sea, The Ryukyu Islands, Australia, the Equatorial Pacific, the Western Indian Ocean, the western Pacific, Bermuda, Florida, the Northern Bahamas), and Australia, along with those in semi-enclosed seas (such as the Persian Gulf, the Red Sea, the Gulf of Mexico, and the Caribbean). These regions are the most vulnerable to losing coral reef ecosystems and their species from severe bleaching events if current regional warming patterns and trends continue.

Coral reef areas with the least vulnerability, if current trends continue, are far fewer: Indonesia, Brazil, central and eastern Micronesia. Areas of localized upwelling induced around oceanic islands, for example in the Indian and Pacific Oceans (Goreau et al., 2000), will likewise be protected. While there are regions where increased upwelling of cool water to the surface will protect corals from bleaching, it should be noted that this is a double-edged sword, because increased upwelling not only brings lower temperatures but also higher nutrients, promoting the growth of algae and filter feeding sponges, tunicates, bivalves, and worms that smother coral tissue or bore into coral skeletons and greatly reduce coral's ability to compete for space. Thus while the Indonesian global coral reef biodiversity maximum is being relatively protected from extinction by high temperatures by high tidal mixing or from increased regional upwelling, corals that survive increased cold water upwelling will increasingly be a smaller component of the fauna, being found more and more in marginal coral communities rather than in constructional coral reefs. Indonesia has the largest concentration of shallow water endemic species in the world (Roberts et al, 2002).

Where SST HotSpots are coincident with biodiversity maxima, the risks for significant mortality, loss of biodiversity, and reduced speciation in coral reefs would be elevated. The product of the rate of increase of temperature in the hottest month and the reef biodiversity, especially of endemic species, would provide an index of extinction probability due to global warming. While many coral species could survive in areas of increased local upwelling, the live coral cover and reef species diversity would decrease, and the coral reef ecosystems themselves will be increasingly threatened: by bleaching in areas of anomalously rapid warming, while by being out-competed by nutrient loving food-chains in areas of increased upwelling. So even if coral species survive in marginal refuges, the richest coral-dominated reef ecosystems may go extinct.

In 1998, the hottest year in world history, most reef-building corals died in the Indian Ocean, and severe mortality also took place in the West Pacific and Caribbean (Goreau et al., 2000). This spatial distribution is consistent with global warming and not with the well-known El Nino pattern, in which the eastern Pacific warms up, the west Pacific cools, and effects elsewhere are minor (Trenberth, 1989). This normally causes cold waters, low evaporation and rain, droughts, and forest fires in Indonesia and Australia during El Nino years, but instead of surface waters cooling in the western Pacific during the 1998 El Nino, there was hot water and severe bleaching. During 2002, the second hottest year in history, and not an El Nino year, most corals in much of the southern Pacific appear to have died, with HotSpot areas stretching the entire width of the Pacific from the Great Barrier Reef to Colombia, and with the worst impacts in Australia, Fiji, Samoa, the Cook Islands, and New Caledonia. Systematic reports of the severe damage to coral reefs are only now starting to come in. If El Ninos get more intense and longer lasting with global warming, as suggested by global climate change models (Federov and Philander, 2000; Bush, personal communication), then the effects could become even greater than estimated here.

All the years in between these two extremes, 1999, 2000, and 2001, were barely tenths of degrees lower than these two record years. These spatial and temporal pattens do not fit the El Nino pattern as the dominant factor but do support global warming pattern. Nevertheless intense propaganda has been spread to blame all bleaching on El Ninos. The effect of this red herring is to suggest that bleaching is due to natural cycles beyond human control, not due to greenhouse gas buildup, and that they are temporary aberrations that may never recur. Another year like 1998 or 2002 could wipe out most of the surviving corals, and is statistically likely to take place within the next few years, given current global warming regional trends. Therefore the likely time scale for loss of most remaining corals is likely to be only years, not decades or centuries, as is widely assumed by policymakers.

We note that the SST data trends measured directly by satellites used in this paper show that reefs worldwide are likely to suffer much more dramatic damage from bleaching than those predicted using theoretical climate change models, which predict severe temperature impacts on coral reef ecosystems only on the scale of decades to centuries (Hoegh-Guldberg, 1999; Hughes et al., 2003, Sheppard, 2003), or claims that coral reefs are “resilient” to environmental stress (McClanahan, Polunin, & Done, 2002). Close examination of the climate change model-derived predicted temperature trends used in these papers show that they do not match either the current temperatures at each site nor their rates of change. By shifting each of the model’s locally predicted temperature curves (adding an arbitrary positive or negative constant to get the right value), the curves can be arbitrarily forced to fit the current data (Sheppard, 2003), but they still show a clear discontinuity in their slopes. This indicates that the models do not adequately describe current conditions, and therefore that the trends that they predict are not reliable except in a very crude qualitative sense. They further underestimate the time to severe bleaching impacts because they estimate the mean trends and do not account for natural variability or extreme events. Because of climatic variability ("weather") at each site, extreme positive temperature events with severe biological impacts (Schar et al., 2004) can be expected to occur much sooner than would be predicted by extrapolating trends of the average maximum temperatures.

While increases in atmospheric carbon dioxide will reduce ocean pH, thereby reducing the rate of coral skeleton formation, the buffering of seawater pH makes this a problem for coral reefs only on a multi-century time scale (Caldeira &Wickett, 2003), hundreds of times longer than the likely lethal effects of carbon dioxide-induced global warming.

IMPLICATIONS FOR MARINE BIODIVERSITY AND FISHERIES

The implications of regional SST increases for the biodiversity and productivity of all other marine ecosystems are also profound. An index of ecosystem vulnerability to climate change can be computed from the product of the mean HotSpot intensity with the species diversity at each point. As many marine organisms are widely distributed, a better measure of extinction probability would be the product of the mean HotSpot intensity with the number of local endemic species.

Primary productivity in coastal upwelling zones should be systematically decreasing, while there should be a corresponding, but smaller, increase of productivity in open ocean gyres. The distribution of global annual net primary productivity (NPP), expressed as grams of carbon per square meter per year (Field et al., 1998), is driven by upwelling zones which transport nutrients from the deep sea (Longhurst, 1998). These areas coincide with elevated SST Hot Spots in coastal zones. A long term 80% decline in zooplankon was reported in the California Upwelling System by Roemmich and McGowan (1995). This cannot be due to excessive predation as the area is severely overfished, and so must be due to a decline in primary production.

Ocean primary productivity and chlorophyll levels are highly sensitive to surface temperatures, and hence control the amounts and kinds of fish caught (Chavez et al., 2003). Analysis of global satellite chlorophyll data shows that there has been a global decline in oceanic chlorophyll levels, especially in the north Atlantic and north Pacific between 1979-1986 and 1997-2000 (Gregg & Conkright, 2002). This change is consistent with the global warming signal, as these are the most rapidly warming areas of ocean. However there have been increases in chlorophyll in the North Indian Ocean, Equatorial Indian Ocean, Northernmost Atlantic, Equatorial Atlantic, and around Antarctica (Gregg & Conkright, 2002). These changes are consistent with more nutrient transport to the surface in these areas, as suggested in this paper. Globally there has been a 6%

decrease in marine primary productivity since the 1980s (Gregg et al. 2003), with a decrease whose spatial pattern closely matches the areas of greatest warming shown in our data. Decreases in chlorophyll are locally reversed in areas of increased upwelling in the East Pacific during La Nina periods (Behrenfeld et al., 2001)

Although the fisheries crisis is generally regarded as a crisis of overfishing, deteriorating carrying capacity due to habitat degradation and global changes in the supply of new nutrients from the deep sea are likely to also be crucial factors. Pelagic food chains, driven by upwelling of new nutrients from below the thermocline, are likely to be displaced away from the more productive upwelling zones along continental shelves towards the less productive open ocean upwelling zones (Antoine et al., 1996). This should cause decreased pelagic fish catches per unit effort, due to shifts to areas of lower and more diffusely spread productivity, and their increased distance from land would cause increased travel times and transportation costs. Reef fisheries would also be strongly negatively impacted since reef fish populations are highly dependent on live coral cover. The global availability of fish is therefore likely to decrease, even if there were no overfishing (Pauly et al., 1998, 2000, 2003: Myers & Worm, 2003), or direct negative effects of high temperature on fish recruitment and survival (Beaugrand et al., 2003). Global warming is likely to exacerbate declining fish catch trends even if all fisheries were sustainably managed. Marine reserves and controls on fishing efforts and gear alone may be insufficient to stem the decline.

A wide variety of biological responses to global warming have been identified, including shifts in species ranges, and timing of flowering, fruiting, and nesting (Parmesan & Yohe, 2003; Root et al., 2003). These responses involve shifts of biological activity in time or space in response to temperature changes, basically involving migration away from the warmest areas into formerly cooler areas. These do not apply to equatorial ecosystems like coral reefs that occupy the warmest habitats and are going extinct because there is no place for organisms already adapted to warmer habitats to migrate from (Hayes & Goreau, 1991; Goreau and Hayes, 1994a).

Coral reefs could expand poleward, but existing reefs would die before new reefs can be established in areas that become warmer. Expansion would be limited because temperate waters are too eutrophic to permit healthy reef growth even if temperatures were adequate. Marine diseases that are temperature sensitive are increasing (Cervino et al., 2004, in press). Coral larvae have lower viability, survival, and dispersion at elevated temperatures (Bassim et al., 2002; Bassim & Sammarco, 2003). Global warming therefore poses imminent threats to coral reef ecosystems, many of which are at risk of extinction of their species and ecosystem services to over 100 countries, especially the island nations, and in particular low lying atolls.

ACKNOWLEDGEMENTS: We thank Alan Strong for providing data and for encouragement in the early stages of this work, and Maggie Toscano for providing maps used as the basis for some of the figures. We thank Carl Wunsch, Walter Munk, and Arnold Gordon for helpful comments and advice. We thank the late Henry Stommel for illuminating discussions while driving between Woods Hole and Cambridge for first opening our interest in ocean circulation changes and the effects of climate change and extreme events on them. This paper is dedicated to the memory of the late Don McAllister, a marine biologist who combined a broad scientific perspective with rare wisdom, and who played an important part in this paper.

REFERENCES

Alford, M.R., Redistribution of energy available for ocean mixing by long-range propagation of internal waves, *Nature*, **423,** 159-162 (2003).

Antoine, D., J.M. Andre and A. Morel, Oceanic primary production 2: Estimation at global scale from satellite (coastal zone scanner) chlorophyll, *Glob. Biogeochem. Cycles*, **10,** 57-69 (1996).

Barnett, T.P., D.W. Pierce and R. Schnur, Detection of anthropogenic climate change in the world's oceans, *Science,* **292,** 270-273 (2001).

Bassim, K.M., P.W. Sammarco and T. Snell. Effects of temperature on fertilization success and embryogenesis in Diploria strigosa (Coelenterata, Scleractinia). *Marine Biology,* **140**(3), 479 - 488 (2002).

Bassim, K.M. and P.W. Sammarco, Effects of temperature and ammonium on larval development and survivorship in a scleractinian coral, Diploria strigosa, *Marine Biology*, **142,** 241-252 (2003).

Beaugrand, G., K.M. Brander, J.A. Lindley, S. Souissi and P.C. Reid, Plankton effect on cod recruitment in the North Sea, *Nature*, **426,** 661-664 (2003).

Behrenfeld, M.J., J.T. Randerson, C.R. McClain, G.C. Feldman, S.O. Los, C.J. Tucker, P.G. Falkowski, C.B. Field, R. Frouin, W.E. Esaias, D.D. Kober and N.H. Pollack, Biospheric primary production during an ENSO transition, *Science*, **291,** 2594-2597 (2001).

Bush, A., personal communication (2004).

Caires, S., A. Sterl, G. Komen and V. Swail, Global *Wave Climatology Atlas*, Royal Netherlands Meteorological Institute (KNMI), http://www.knmi.nl/waveatlas (2003).

Caldeira, K. and M.E. Wickett, Anthropogenic carbon and ocean pH, *Nature*, **425,** 365 (2003).

Cardone, V.J., D.E. Hunter and M.A. Cane, On trends in historical marine wind data, *Journal of Climate,* **3,** 113-127 (1990).

Cervino, J., R.L. Hayes, S.W. Polson, S.C.Polson, T.J. Goreau, R.J. Martinez and G.W. Smith, Relation of Vibrio species infection and elevated temperatures to Yellow Blotch/Band Disease in Caribbean corals , *Applied and Environmental Biology*, **70**, 6855 (2004).

Chavez, F. P., J. Ryan, S. E. Lluch-Cota, and M. Niiquen C., From anchovies to sardines and back: multidecadal change in the Pacific Ocean, *Science*, **299,** 217-221 (2003).

Chelton, D.B., M.G. Schlax, M.H. Freilich and R.F. Milliff, Satellite measurements reveal persistent small-scale features in ocean winds, *Science*, **303,** 978-983 (2004).

Chermykh, I.V., O.A. Alduchov and R.E. Eskridge, Cloud top and bottom height, *Bull. Am. Meteorol. Soc.,* **82,** 1941-1947 (2001).

Cobb, K.M., C.D. Charles, H. Cheng and R.L. Edwards, El Nino/Southern Oscillation and tropical Pacific climate during the last millennium, *Nature*, **424,** 271-276 (2003).

Curry, R., B. Dixon and I. Yahayaev, A change in the freshwater balance of the Atlantic Ocean over the past four decades, *Nature*, **426,** 826-829 (2003).

Emmanuel, K., The dependence of hurricane intensity on climate, *Nature*, **326,** 483-485 (1987).

Falkowski, P.G., R.T. Barber and V. Smetacek, Biogeochemical controls and feedbacks on ocean primary production, *Science*, **281,** 200-206 (1998).

Fedorov, A.V. and S.G. Philander, Is El Nino changing?, *Science*, **288,** 1997-2001 (2000).

Field, A. and A.L. Gordon, Tidal mixing signatures in the Indonesian Seas, *Journal of Physical Oceanography,* **26,** 1924-1937 (1996).

Field, C.B., M.J. Behrenfield, J.T. Randerson and P. Falkowski, Primary production of the biosphere: Integrating terrestrial and oceanic components, *Science,* **281**, 237-240 (1998).

Flohn, H. and A. Kappala, Changes of tropical sea-air interaction processes over a 20 year period, *Nature,* **338,** 244-246 (1989).

Flohn, H., A. Kapala, H.R. Knoche and H. Machel, Recent changes of the tropical water and energy budget and of midlatitude circulations, *Climate Dynamics,* **4,** 237-252 (1990).

Garrett, C., Internal tides and ocean mixing, *Science*, **301,** 1858-1859 (2003).

Gilgen, H., M. Wild and A. Ohmura, Means and trends of shortwave irradiance at the surface estimated from global energy balance archive data, *Journal of Climate*, **11,** 2042-2061 (1998).

Gillett, N.P. and D.W.J. Thompson, Simulation of recent southern hemisphere climate change, *Science*, **302,** 273-275 (2003).

Gillett, N.P., F.W. Zwiers, A.J. Weaver and P.A. Stott, Detection of human influence on sea level pressure, *Nature*, **422,** 292-294 (2003).

Glynn, P.W., Coral mortality and disturbances to coral reefs in the tropical eastern Pacific, In *Global Ecological Consequences of the 1982-83 El Nino-Southern Oscillation,* Elsevier Oceanographic Series, P.W. Glynn (ed.), Elsevier, Amsterdam (1990).

Glynn, P.W., Coral reef bleaching in the 1980s and possible connections with global warming, *Trends in Ecology and Evolution*, **6,** 175-179 (1991).

Golubev, V.S., J.H. Lawrimore, P.Y. Groisman, N. Speranskaya, S.A. Zhuravin, M.J. Menne, T.C. Peterson and R.W. Malone, Evaporation changes over the contiguous United States and the former USSR: A reassessment, *Geophysical Research Letters*, **28,** 2665-2668 (2001).

Gordon, A.L. and R.A. Fine, Pathways of water between the Pacific and Indian Oceans in the Indonesian Seas, *Nature,* **279,** 146-149 (1996).

Gordon, A.L., R.D.Susanto and K.Vranes, Cool Indonesian throughflow as a consequence of restricted surface layer flow, *Nature*, **425,** 824-828 (2003).

Goreau, T.J., Coral bleaching in Jamaica, *Nature*, **343,** 417 (1990).

Goreau, T.J., R.L. Hayes, J.W. Clark, D.J. Basta and C.N. Robertson, Elevated sea surface temperatures correlate with Caribbean coral bleaching, p. 225-255 in R.A. Geyer (ed.), *A Global*

Warming Forum: Scientific, Economic, and Legal Aspects, CRC Press, Boca Raton, FL (1993).

Goreau, T.J. and R.L. Hayes, Coral reef bleaching and ocean Hot Spots, *Ambio*, **23,** 176-180 (1994a).

Goreau, T.J. and R.L. Hayes, Monitoring and calibrating sea surface temperature anomalies using satellite and in-situ data to study the effects of weather extremes and climate change on coral reefs, *Proceedings of the Conference for Remote Sensing and Environmental Monitoring for the Sustainable Development of the Americas,* San Juan, Puerto Rico (1994b).

Goreau, T.J. and R.L.Hayes, *A survey of coral reef bleaching in the South Central Pacific during 1994: Report to the International Coral Reef Initiative*, p. 201, Global Coral Reef Alliance website: www.globalcoral.org (1995).

Goreau, T.J., R.L. Hayes and A.C. Strong, Tracking South Pacific coral reef bleaching by satellite and field observations, *Proceedings 8th International Coral Reef Symposium*, **2,** 1491-1494 (1997).

Goreau, T.J. and R.L. Hayes, Monitoring and calibrating sea surface temperature anomalies using satellite and in-situ data to study the effects of weather extremes and climate changes on coral reefs, *World Resources Review* (this volume) (2005a).

Goreau, T.J. and R.L. Hayes, Global coral reef bleaching and sea surface temperature trends from satellite derived HotSpot analysis, *World Resources Review* (this volume) (2005b).

Goreau, T.J., T. McClanahan, R.L. Hayes and A.E. Strong, Conservation of coral reefs after the 1998 global bleaching event, *Conservation Biology*, **14,** 5-15 (2000).

Gregg, W.W. and M.E. Conkright, Decadal changes in global ocean chlorophyll, *Geophysical Research Letters,* **29,** 20-1-20-4 (2002).

Gregg, W.W., M.E. Conkright, P. Ginoux, J.E. O'Reily and N.W. Casey, Ocean primary production and climate: Global decadal changes, *Geophysical Research Letters,* **30,** 1809 (2003).

Hansen, J., I. Fung, A. Lacis, D. Rind, S. Lebedeff, R. Ruedy and G. Russell, Global climate changes as forecast by Goddard Institute for Space Studies three-dimensional model, *Journal of Geophysical Research*, **93,** 9341-9346 (1988).

Hansen, J., R. Ruedy, J. Glascoe and M.Sato, GISS analysis of surface temperature change, *Journal of Geophysical Research*, **104,** 30997-31022 (1999).

Hayes, R.L. and T.J. Goreau, The tropical coral reef ecosystem as a harbinger of global warming, *World Resources Review*, **3**(3), 306-322 (1991).

Hoegh-Guldberg, O., Climate change, coral bleaching, and the future of the world's coral reefs, *Marine and Freshwater Research*, **50,** 839-866 (1999).

Hoerling, M. and A. Kumar, The perfect ocean for drought, *Science*, **299,** 691-694 (2003).

Hughes, T P., A.H. Baird, D.R. Bellwood, M. Card, S.R. Connolly, C. Folke, R. Grosberg, O. Hoegh-Guldberg, J. Jackson, J. Kleypas, J.M. Lough, P. Marshall, M. Nystrom, S.R. Palumbi, J.M. Pandolfi, B. Rosen and J. Roughgarden, Climate change, human impacts, and the resilience of coral reefs, *Scienc,* **301,** 929-933 (2003).

Jokiel, P. and S.L. Coles, Response of Hawaiian and other Indo-Pacific corals to elevated temperatures, *Coral Reefs*, **8,** 155-162 (1990).

Karl, D.M., E.A. Laws, P. Morris, P.J.LeB. Williams and S. Emerson, Metabolic balance of the open sea, *Nature*, **426,** 32 (2003).

Karl, T., Indices of climate change for the United States, *Bulletin of the American Meteorological Society*, **77,** 279-292 (1996).

Karl, T.R. and K.E. Trenberth, Modern global climate change, *Science*, **302,** 1719-1723 (2003).

Klein, S.A., B.J. Soden and N.-C. Lau, Remote sea surface temperature variations during ENSO: Evidence for a tropical atmospheric bridge, *Journal of Climate*, **12,** 917-932 (1999).

Laxon, S., N. Peacock and D. Smith, High inter-annual variability of sea ice thickness in the Arctic region, *Nature,* **425,** 947-950 (2003).

Levitus, S., J.I. Antonov, T.P. Boyer and C. Stephens, Warming of the world ocean, *Science,* **287,** 225-229 (2000).

Levitus, S., J.I. Antonov, J. Wang, T.L. Delworth, K.W. Dixon and A.J. Broccoli, Anthropogenic warming of Earth's climate system, *Science,* **292,** 2167-270 (2001).

Longhurst, A.R., *Ecological Geography of the Sea*, Academic Press, New York (1998).

Manabe, S. and R. Stouffer, Stimulation of abrupt climate change induced by freshwater input to the North Atlantic Ocean, Nature 378:165-167 (1995).

Manabe, S. and R. Stouffer, Are two modes of thermohaline circulation stable?, *Tellus*, **51A,** 400-411 (1999).

McClanahan, T., N. Polunin and T. Done, Ecological states and the resilience of coral reefs, *Ecological Ecology*, **6(**18), 1-27 (2002).

Munk, W., Ocean freshening, sea level rising, *Science*, **300,** 2041-2043 (2003).

Munk, W. and C. Wunsch, Abyssal recipes II: Energetics of tidal and wind mixing, *Deep Sea Research*, **45,** 1976-2009 (1998).

Myers, R.A. and B. Worm, Rapid worldwide depletion of predatory fish communities, *Nature*, **423,** 280-283 (2003).

Nemani, R.R., C.D. Keeling, H. Hashimoto, W.M. Jolly, S.C. Piper, C.J. Tucker, R.B. Mymeni, and S.W. Running, Climate-driven increases in global terrestrial net primary production from 1982 to 1999, *Science*, **300,** 1560-1563 (2003).

Palmer, M.R. and P.N. Pearson, A 23,000-year record of surface water pH and PCO_2 in the Western Equatorial Pacific Ocean, *Science*, **300,** 480-482 (2003).

Papparella, F. and W.R. Young, Horizontal convection is non turbulent, *Journal of Fluid Mechanics*, **466,** 205-214 (2002).

Parmesan, C. and G. Yohe, A globally coherent fingerprint of climate change impacts across natural systems, *Nature*, **421,** 37-42 (2003).

Pauly, D., V. Christensen, J. Dalgaard, R. Froese and F. Torres, Fishing down marine food webs, *Science*, **279,** 860-863 (1998).

Pauly, D., V. Christensen and R. Froese, Fishing down aquatic food webs, *American Scientist,* **88,** 46-51 (2000).

Pauly, D., J. Alder, E. Bennett, V. Christensen, P. Tydemers and R. Watson, The future for Fisheries, *Science*, **302,** 1359-1361 (2003).

Peterson, T.C., V.S. Golubev and P.Y. Groisman, Evaporation losing its strength, *Nature,* **377,** 687-688 (1995).

Rahmstorf, S., Ocean circulation and climate during the last 120,000 years, *Nature*, **419**, 207-214 (2002).

Rahmstorf, S., The current climate, *Nature*, **421,** 699 (2003).

Reynolds, R. and T. Smith, Improved global sea surface temperature analyses using optimum interpolation, *Journal of Climate*, **7,** 929-948 (1994).

Roberts, C., C.J. McClean, J E.N. Veron, J.P. Hawkins, G.R. Allen, D.E. McAllister, C.G. Mittermeier, F.W. Schueler, M. Spaulding, F. Wells, C. Cynne and T.B. Werner, Marine biodiversity hotspots and conservation priorities for tropical reefs, *Science,* **295,** 1280-1284 (2002).

Roderick,R. and G.D. Farquhar, The cause of decreased pan evaporation over the past 50 years, *Science*, **298,** 1410-141 (2002).

Roemmich, D., Ocean warming and sea level rise along the Southwest US coast, *Science*, **257,** 373-375 (1992).

Roemmich, D. and J. McGowan, Climatic warming and the decline of zooplankton in the California current, *Science,* **267,** 1324-1326 (1995).

Root, T.L., J.T. Price, K.R. Hall, S.H. Schneider, C. Rosenzweig and J.A. Pounds, Fingerprints of global warming on wild animals and plants, *Nature*, **421,** 57-60 (2003).

Russak, V., Is the radiation balance in the Baltic Sea Region changing?, *Ambio*, **23,** 160-163 (1994).

Santer, B.D., M.F. Wehner, T.M.L. Wigley, R. Sausen, G.A. Meehl, K.E. Taylor, C. Ammann, J. Arblaster, W.M. Washington, J.S. Boyle and W. Bruggemann, Contributions of anthropogenic and natural forcing to recent tropopause height changes, *Science*, **301,** 479-483 (2003).

Santer, B.D., T.M.L. Wigley, G.A. Meehl, M.F. Wehner, C. Mears, M. Schabel, F.J. Wentz, C. Ammann, J. Arblaster, T. Bettge, W.M. Washington, K.E. Taylor, J.S. Boyle, W. Bruggemann and C. Doutriaux, Influence of satellite data uncertainties on the detection of externally forced climate change, *Science*, **300,** 1280-1284 (2003).

Schar, C., P.L. Vidale, D. Luthi, C. Frei, C. Haberli, M.A. Liniger and C. Appenzeller, The role of increasing temperature variability in European summer heatwaves, *Nature*, **427,** 332-336 (2004).

Seager, R., D.S. Battisti, J. Yin, N. Gordon, N. Nuik, A.C. Clement and M.A. Cane, Is the Gulf Stream responsible for Europe's mild winters?, *Journal of the Royal Meteorological Society*, **128,** 2563-2586 (2002).

Sheppard, C.R.C., Predicted recurrences of mass coral bleaching mortality in the Indian Ocean, *Nature*, **425,** 294-297 (2003).

Strong, A.E., E.J. Kearns and K.K. Gjovig, Sea surface temperature signals from satellites -- An update, *Geophysical Research Letters,* **27,** 1667-1670 (2000).

Takahashi, T., S.C. Sutherland, C. Sweeney, A. Poisson, N. Metzl, B. Tilbrook, N. Bates, R. Wanninkhof, R., A. Feely, C. Sabine, J. Olafsson and Y. Nojiri, Global sea-air CO_2 flux based on climatological surface ocean pCO_2 , and seasonal biological and temperature effects, *Deep Sea Research II*, **49,** 1601-1622 (2002).

Thompson, D.V.J. and S. Solomon, Interpretation of recent southern hemisphere climate change, *Science,* **296,** 895-899 (2002).

Trenberth, K., TOGA and atmospheric processes, p.117-125 in A. Berger, R.E. Dickinson and J.W. Kidson (eds.), *Understanding Climate Change*, American Geophysical Union, Washington DC (1989).

Vellinga, M. and R A. Wood, Global climate change impacts of a collapse of the Atlantic thermohaline circulation, *Climate Change,* **54,** 251-267 (2002).

Vinnikov, K.V. and N.C. Grody, Global warming trend of mean tropospheric temperature observed by satellites, *Science*, **302,** 269-272 (2003).

Visser, K., R. Thunell and L. Stott, Magnitude and timing of temperature change in the Indo-Pacific warm pool during deglaciation, *Nature*, **421,** 152-155 (2003).

Wiley , D.P., R. Frey, H. Zhang and W.P. Menzel, *Extending HIRS high could trends with MODIS,* NASA http://modis.gsfc.nasa.gov/sci_team/meetings/200207/presentations/menzel.pdf. (2002).

Williiams, E.H. and L. Bunkley-Williams, The world-wide coral bleaching cycle and related sources of coral mortality, *Atoll Research Bulletin*, **335,** 1-71 (1990).

Wunsch, C., The interpretation of short climate records, with comments on the North Atlantic and Southern Oscillations, *Bulletin of the American Meteorological Society*, **80,** 245-255 (1999).

Wunsch, C., Moon, tide, and climate, *Nature,* **405,** 743-744 (2001).

Wunsch, C., What is the thermohaline circulation? *Science,* **298,** 1179-1181 (2002).

Note added in proof: The following recent reports from Levitus, Barnett and co-workers further document the consequences of warming throughout the world's oceans. These reports substantiate the data we present in this paper on satellite-derived surface ocean warming.

Antonov, J., S. Levitus and T. Boyer, Steric sea level variations during 1957-1994; importance of salinity, *Geophys. Res. Letters*, **107**, 1-8 (2002).

Barnett, T.P., D.W. Pierce, K.M. AchutaRao, P.J. Gleckler and B.D. Santer, J.M. Gregory and W.M. Washington, Penetration of human-induced warming into the world's oceans, *Sciencexpress/2 June 2005*, pp. 1-9, *Science*, 1112418 (2005).

Boyer, T., S. Levitus, J. Antonov, R. Locarnini and H. Garcia, Linear trends in salinity for the world ocean, 1955-2003, *Geophys. Res. Letters*, **32** (L01604), 1-4 (2005.

Hansen, J., I. Nazarenko, R. Ruedy, M. Sato, J. Willis, A. Del Genio, D. Koch, A. Lacis, K. Lo, S. Menon, T. Novakov, J. Perlwitz, G. Russell, G.A. Schmidt and N. Tausnev, Earth's energy imbalance: Confirmation and implications, *Science*, **308**, 1433-1435 (2005).

Levitus, S., J. Antonov and T. Boyer, Warming of the world ocean, 1955-2003, *Geophys. Res. Letters,* **32** (L02604), 1-4 (2005).