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ENSO-Driven Ocean Extremes and Their Ecosystem Impacts

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ABSTRACT

El Niño–Southern Oscillation (ENSO) events can cause extremes in the ocean environment that have substantial impacts on marine ecosystems. In the shallow-water/coastal marine environment, ENSO-related extremes in sea level and seawater temperature have been found to impact coral, kelp, seagrass, and mangrove ecosystems. Coastal impacts from sea level extremes include exposure of shallow-water ecosystems and inundation in low-lying areas. Ocean temperature extremes, including marine heatwaves, cause coral bleaching and can impact kelp and seagrass density. This chapter reviews knowledge and understanding of ENSO's role in sea level extremes and ocean temperature extremes, and their impacts on these key shallow-water/coastal marine ecosystems.

18.1. INTRODUCTION

El Niño–Southern Oscillation (ENSO) events are due to coupled ocean-atmosphere dynamics operating in the equatorial Pacific Ocean (chapters 2 and 3). Nevertheless, this globally dominant mode of interannual climate variability has important teleconnections and impacts (section VI). In particular, extremes in sea level and ocean temperature associated with ENSO can be highly detrimental to marine ecosystems. Importantly, shallow-water marine ecosystems, which have high biodiversity and represent critical regions for fisheries and aquaculture, can be vulnerable to these ocean extremes (Smale et al., 2019).

This chapter reviews our knowledge of the role of ENSO events on extremes in sea level and seawater temperature, and concomitant impacts on shallow-water/coastal marine ecosystems. For seawater temperature, we only examine warm water extremes in relation to ENSO events that appear to be driving significant changes to ecosystems against the background of rising ocean temperatures. For sea level, we examine both high and low extremes (which are also increasing against the backdrop of rising global sea levels) in relation to ENSO events, as both can be critically important to ecosystems. Our examination of marine ecosystem impacts is primarily focused on the important foundational species of coral, kelp, seagrass, and mangrove.

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18.2. EXTREMES IN SEA LEVEL AND SEAWATER TEMPERATURE

Here we provide background understanding of what constitutes extremes in sea level and seawater temperature. We also provide a review of the role that ENSO plays in causing or modulating these extremes.

18.2.1. Sea Level Extremes

18.2.1.1. Background

Extreme sea levels (either high or low) occur as a result of various processes that operate on a wide range of time and space scales. These range from tides, which operate on subdaily time scales, to weather and synoptic systems operating on daily to multiday time scales, to interannual changes associated with ENSO, to sea level rise associated with greenhouse warming. Moreover, multiple processes may combine to produce the most severe sea level extremes. Contributions from seasonal and interannual factors such as the variations in ocean temperature, salinity, and circulation also play a role by influencing mean regional sea level and/or by influencing the weather conditions (e.g. tropical cyclones, monsoons, and extratropical depressions) that can cause sea level extremes from storm surges and surface waves.

Extreme high sea levels are of concern because they cause coastal flooding, saltwater contamination, and erosion in the coastal zone (Barnard et al., 2015). Extreme low sea levels can cause coastal ecosystems to be exposed to other stressors. Due to different ways in which sea levels can affect urban and natural environments, there is no single definition for an extreme sea level. Thresholds above which sea levels may be considered extreme include tidal metrics such as the Highest Astronomical Tide or Mean High Water Springs (i.e. near the annual high-water mark), or statistical estimates of heights associated with particular return periods (e.g. Average Recurrence Intervals) that are required for coastal planning or engineering applications. Scientific applications may also consider high percentile thresholds as a means to define extreme sea levels. In addition to sea level height, the duration of coastal flooding or strength of coastal currents may be important in determining the severity of coastal impacts. Here, we consider extreme sea level characteristics in a general sense as those associated with coastal inundations or exposures of shallow ecosystems (i.e. not fully submerged in water anymore).

Growing evidence suggests that the characteristics of extreme sea level are experiencing long-term changes as global sea levels gradually rise (Menéndez & Woodworth, 2010; Woodworth & Menéndez, 2015). Changes in the frequency and intensity of these extremes can be related to multiple factors. Most directly, climate change is expected to alter extreme sea level frequency and intensity via a number of pathways. For example, rising mean sea level due to ocean thermal expansion and land ice melt will alter regionally the background sea level on which extremes occur. Higher mean sea levels can also interact nonlinearly with other processes such as tides, waves, and storm surges to alter extreme water levels. Hoeke et al. (2015) undertook a numerical modeling study in Apia, Samoa, and showed that sea level rise reduced the amount of wind and wave setup occurring during tropical cyclone–induced storm surges. The deeper water from sea level rise reduced the hydraulic roughness, which led to a reduction in coastal sea levels caused by wind and wave setup, but it also increased the wave energy reaching the coast by 200% due to the decreased wave dissipation on outer reefs.

Climate change is also expected to affect the intensity, frequency, seasonality, and tracks of weather systems that cause storm surges and waves and therefore extreme sea levels (Chand & Walsh, 2009; Walsh et al., 2012). For example, McInnes et al. (2014, 2016) employed numerical modeling to show that for Samoa and Fiji, the projected future increase in tropical cyclone intensity together with long return periods (200 years and longer) would slightly lower storm tide 50-year return periods. However, the projected rise in sea levels increased the total height of storm tides for Fiji overall.

Finally, climate change may also affect the behavior of ENSO (see chapter 13; e.g. Cai et al., 2015). This will in turn influence extreme sea levels, particularly in the Indo-Pacific region through its influence on regional sea level and wind and weather events such as tropical cyclones (see chapter 17), with consequent effects on waves and storm surges (the effect of climate change on ENSO is investigated in chapter 13).

18.2.1.2. Role of ENSO

In the tropical Pacific Ocean, ENSO is the dominant process affecting sea level on monthly-to-interannual timescales (Zhang & Church, 2012; Figure 18.1), with changes exceeding ±30 cm over several months recorded by satellites and tide gauges, especially during and after strong El Niño and La Niña events (e.g. Wyrtki, 1984; Merrifield et al., 1999). The anomalously high regional sea level in the central and eastern (western) tropical Pacific during El Niño (La Niña) events can increase the likelihood of extreme water levels impacting the coast, since the background sea level is one of the key factors affecting frequency and intensity of water level extremes (Menéndez & Woodworth, 2010; Woodworth & Menéndez, 2015).

Pacific sea level anomalies are mostly related to wind-driven shifts of the tropical thermocline, which can propagate across the basin either eastward as equatorial Kelvin waves or westward as oceanic Rossby (planetary) waves. Ocean Kelvin waves also propagate to the

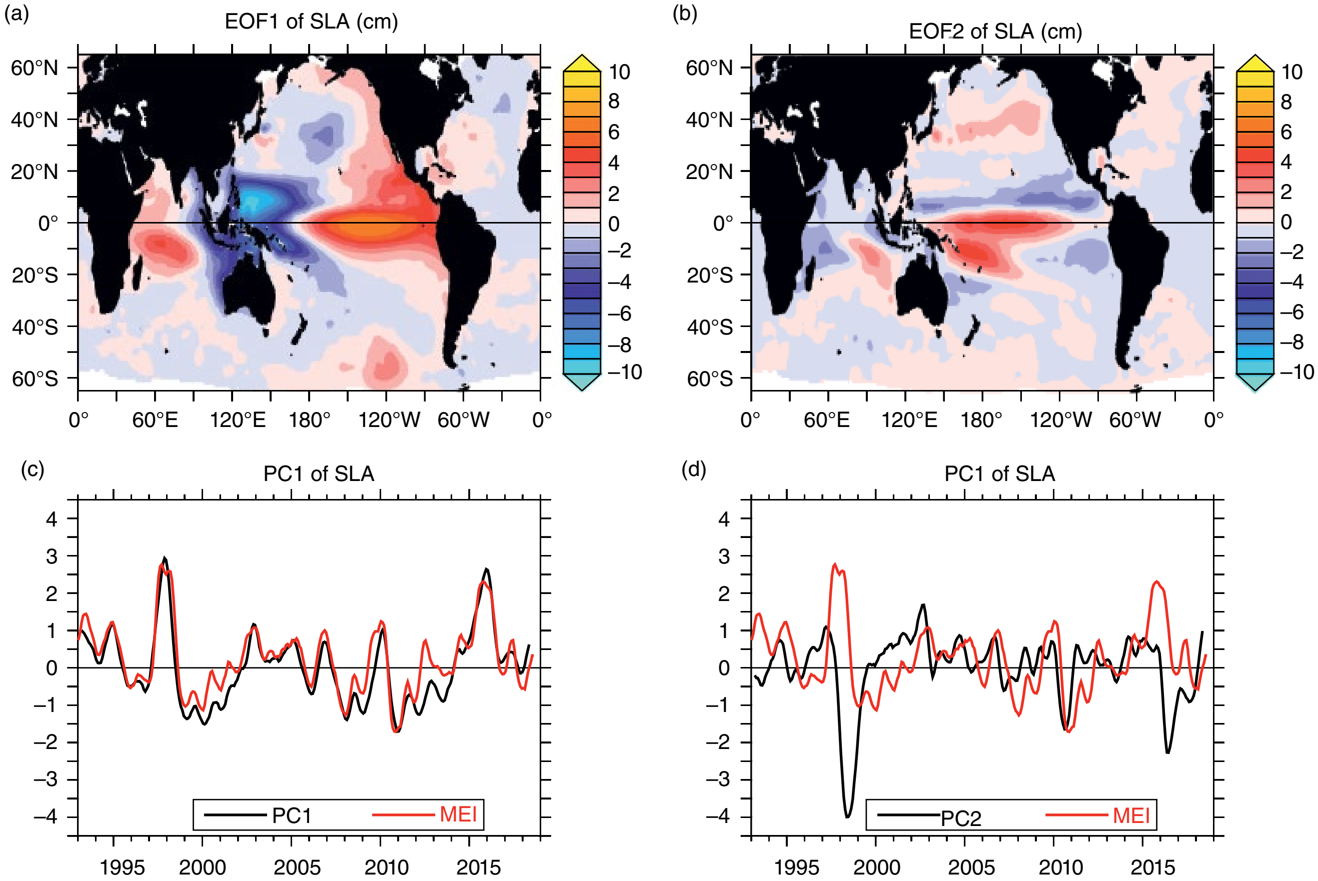

Figure 18.1 Empirical orthogonal function (EOF) analysis of global sea level anomalies (SLAs). (a, b) The first and second EOFs based on monthly 1x1° satellite altimetry observations over 1993–2018 provided by Australia CSIRO (https://research.csiro.au/slrwavescoast/sea-level/measurements-and-data/sea-level-data/). (c, d) Corresponding principal components (PCs) in comparison with the Multivariate ENSO Index. To focus on natural variability, monthly global mean sea level has been removed and the altimetry records have been detrended locally before EOF analysis. All time series in (c, d) are smoothed by a 5-month running mean filter.

extratropics along coastal waveguides at the eastern sides of ocean basins, for example, along the west coast of North and South America and west coast of Australia, affecting coastal sea level and circulation (chapter 15). Seesaws in east-west sea level occur across the Pacific mostly in-phase with ENSO (Wyrtki, 1984), with sea level increasing (decreasing) in the east (west) during El Niño (La Niña) (Figure 18.1a). Occasionally, a weaker north-south seesaw in sea level (e.g. Delcroix & Rual, 1997) also takes place in the tropics that typically persists long after a strong El Niño event ends (Figure 18.1b; Widlansky et al., 2014). Particularly during strong El Niño events, sea level drops around tropical western Pacific islands, first in the Northern Hemisphere and later in the Southern Hemisphere, but rises in the eastern Pacific. Around the peak of an El Niño, high sea levels occur in the central and eastern equatorial Pacific and along the eastern boundary of the Pacific in both hemispheres (i.e. the North and South American coasts). Coastal high sea level anomalies during El Niño have been observed as far north and south as Alaska and the southern tip of South America, respectively (Chelton & Davis, 2002; Enfield & Allen, 2002; Barnard et al., 2017). During La Niña events, the sea level pattern mostly reverses, although nowhere are the anomalies typically as large as during strong El Niño. Sea levels outside of the Pacific Ocean are also affected by ENSO via atmospheric teleconnections which cause oceanic anomalies in other basins such as the Atlantic (Sweet & Park, 2014; Hamlington et al., 2015).

El Niño and La Niña events also sometimes indirectly affect sea level through changes in the occurrence or intensity of storms such as tropical cyclones in the Pacific (Chand et al., 2013) as well as in other ocean basins (e.g. Camargo et al., 2007), which cause localized storm surges, surface wind waves, and also swells of wave energy that can propagate across the Pacific (unless refracted by an island; see chapter 17). These higher-frequency and mostly localized storm phenomena cause more extreme water level variations compared to the sea level fluctuations directly associated with ENSO. Conversely, the occurrence of El Niño and La Niña events can influence the coastal impacts of severe storms when they occur. For example, in December 2008, a major inundation event, triggered by swell waves from an intense low pressure system in the North Pacific Ocean, caused significant inundation across a number of islands within six nations in the western tropical Pacific Ocean from Wake Atoll in the north to Papua New Guinea and the Solomon Islands in the south. A contributing factor to the severity of the impacts was shown to be the positive sea level anomalies of about 10–20 cm across the region caused by a La Niña event that was occurring at the time (Hoeke et al., 2013).

The coastal impacts of sea level variability can be exacerbated by large astronomical tides which compound the sea level anomalies to produce either extremely high or low water-level events. High sea levels, combined with powerful storm surges or waves, can wreak havoc at the coast in the form of inundations of low-lying areas (Barnard et al., 2015), especially around the time of highest tides (Hoeke et al., 2013). Conversely, below-normal sea levels make the lowest tides even lower, which sometimes exposes shallow-water ecosystems such as reef flats to air and may cause coral die-offs (Ampou et al., 2017).

Hemer et al. (2010) showed that wave direction in the Tasman Sea is influenced by ENSO with waves in this region that are mainly from the southeast undergoing a rotation toward being from the south during El Niño and from the east during La Niña. The rotation in wave direction with ENSO events has been found to influence erosion along Australia's east coast (Ranasinghe et al., 2004; Harley et al., 2011), such that during El Niño the northern end of a beach widens (accretes) while the southern end erodes, resulting in a net clockwise rotation of the beach. During La Niña events an anticlockwise rotation occurs.

Climate change is likely to affect the behaviour of extreme ENSO events (chapter 13; Cai et al., 2015), which would likely cause associated effects on sea level variability, especially in the Indo-Pacific region. Using global coupled general circulation models, future projections suggest that climate change will enhance ENSO-related sea level extremes by up to 25% in the tropical Pacific (Widlansky et al., 2015). The future change pattern is consistent with more extreme swings of the major wind convergence zones such as the South Pacific Convergence Zone (Cai et al., 2012).

The effects of future changes to ENSO and extreme wave energy reaching the coast have been investigated by Mentaschi et al. (2017), who find a significant increase in wave energy along 29% and a significant decrease along 26% of the global coastline in the future. The positive trends in the southern tropical Pacific region and the northeast Pacific, together with the decreases projected for the western Pacific, are shown to be linked to an intensification of the ENSO pattern and a shift of climate toward El Niño conditions. For the southern tropical Pacific, the increases are driven by storms and convective activity in the eastern Pacific, while the positive link between El Niño and the Aleutian Low pressure in the northeast Pacific is linked to positive trends in wave energy there. For the western Pacific, generally colder, drier and less stormy conditions during El Niño episodes lead to a reduced frequency of severe wind and wave conditions in the future (Mentaschi et al., 2017).

ENSO-related regional sea level anomalies and tropical cyclone behaviour and their links with extreme sea levels have been studied to some extent for particular coastlines (Feng & Tsimplis, 2014; Sweet & Park, 2014), and some studies have attempted to quantify the effects of ENSO on extreme sea levels from storm surges at the island scale (McInnes et al., 2014, 2016). However, the role of ENSO on extreme waves is more challenging. Coastal wave extremes are sensitive to local coastal morphology, particularly shoreline slope (Hoeke et al., 2013; Aucan et al., 2019). Along much of the global coastline, particularly in small islands, such information is lacking, as are in situ observations of extreme coastal wave and sea levels to quantify the local impacts of extreme sea levels, waves, and their relationship to ENSO.

Due to the consequences to vulnerable coasts, associated with changing sea levels and ENSO conditions, a number of scientific challenges must be addressed to produce more robust future predictions and projections. Already, seasonal forecasts of sea level extremes (e.g. Miles et al., 2014), while still experimental, are helping coastal communities adapt to the impacts of rising sea levels as well as the shorter-term variability associated with ENSO. Yet current-generation global climate models are challenged in resolving sea level dynamical processes, especially around shallow coastal regions (Church et al., 2013). Furthermore, remote teleconnections (i.e. ENSO-related fluctuations outside of the tropical Pacific) are not fully understood, either in the present climate or future projections. Next-generation higher-resolution models (Griffies et al., 2015), or dynamical downscaling with regional high-resolution ocean models (Liu et al., 2016; Zhang et al., 2017), may provide improved predictions of sea level extremes.

18.2.2. Ocean Temperature Extremes

18.2.2.1. Background

Ocean temperature extremes (OTEs) occur when ocean temperatures exceed a suitably defined extreme threshold (either hot or cold). The temperature threshold can be either an absolute one (e.g. 1°C above normal summer maximum temperature in the case of coral bleaching risk (Donner, 2011) or 12°C winter temperature in the case of the spiny sea urchin off southeastern Australia (below which larval development is poor; Ling et al., 2008)) or a relative one (e.g. the 90th percentile of the temperature distribution; Hobday et al., 2016). OTEs can have moderate to severe impacts on marine ecosystems, which will be discussed in more detail in the following section. Periods of prolonged and sustained OTEs at a particular location may be considered marine heatwaves (MHWs; Hobday et al., 2016) or marine cold spells (Schlegel et al., 2017). A number of prominent MHWs have occurred in recent years, including in the northern Mediterranean Sea in 2003 (Sparnocchia et al., 2006; Olita et al., 2007), off Western Australia in 2011 (Pearce & Feng, 2013), in the northwest Atlantic in 2012 (Chen et al., 2014), and in the northeast Pacific from 2013 to 2016 (Bond et al., 2015; Di Lorenzo & Mantua, 2016). MHWs have received considerable attention recently due to the historical record indicating significant increases in MHW frequency and duration since the early 20th century (Oliver et al., 2018a), as well as future projections indicating that these trends will likely accelerate (Frölicher et al., 2018).

OTEs may occur at any depth through the water column. However, most research to date has focused on sea surface temperatures (SSTs), primarily due to the lack of high spatial and temporal resolution subsurface temperature data. Given the focus on surface temperatures, the understanding of local physical drivers of OTEs has primarily been in the context of mixed-layer heat budget analyses (Benthuysen et al., 2014; Chen et al., 2014; Oliver et al., 2017). Local drivers of OTEs include (i) anomalous air-sea heat fluxes associated with changes in cloud cover and radiation or winds that affect latent and sensible heat fluxes; (ii) anomalous horizontal advection by changes in the large-scale circulation, mesoscale structures, or surface Ekman currents; and (iii) vertical processes including mixing or upwelling (Holbrook et al., 2019). The resulting changes in temperature will also be modulated by the background ocean state, for example, an anomalously shallow mixed layer will be susceptible to larger temperature variations. Individual OTEs will be triggered, sustained, and terminated by different combinations of these terms. For example, the 2015–2016 Tasman Sea MHW (Oliver et al., 2017) and 2011 Ningaloo Niño off Western Australia (Feng et al., 2013) were primarily initiated by greater heat transport associated with western and eastern boundary current intensification, respectively, although air-sea interactions also played a role (Benthuysen et al., 2014). Conversely, the 2017–2018 Tasman Sea MHW (Perkins-Kirkpatrick et al., 2019) and the Blob (Bond et al., 2015) were triggered by atmospheric systems that primarily modified air-sea heat fluxes.

The timing, intensity, and frequency of OTEs may be modulated by large-scale modes of climate variability, such as ENSO, the Indian Ocean Dipole, or the North Atlantic Oscillation. This can occur by these modes' modulating ocean temperatures directly, as in the case of ENSO in the tropical Pacific, or indirectly by driving complex atmospheric (chapter 14) or oceanic (chapter 15) teleconnections, which occur remotely from the main center of action of the climate mode. A number of studies have linked specific events to such remote ENSO teleconnections. These are described in the following section. Recently, Holbrook et al. (2019) used a common framework to identify MHW characteristics and to examine the influence of large-scale climate modes on MHWs around the world. They showed that the different flavors of ENSO (refer chapter 4) appear as the dominant drivers of MHW characteristics in much of the tropical Indian Ocean and many parts of the extratropical Pacific Ocean, in addition to the tropical Pacific. For example, the number of days experiencing MHW conditions in the northeast Pacific almost doubles (halves) when the central equatorial Pacific temperature anomalies (described by the Niño-3.4 index) is positive (negative). In many other parts of the extratropical Pacific, low-frequency expressions of ENSO like the Pacific Decadal Oscillation (PDO) or Interdecadal Pacific Oscillation (IPO), which modulate background SST on decadal timescales, are also significant predictors of MHW occurrence.

18.2.2.2. Role of ENSO

Coupled ocean-atmosphere feedbacks associated with ENSO generate large SST anomalies in the eastern and central tropical Pacific that can give rise to OTEs lasting for a season or longer. In addition, tropical ENSO disturbances can transmit to remote regions via atmospheric (chapter 14) or oceanic (chapter 15) teleconnections, including planetary waves and large-scale circulation, providing the conditions favorable for MHWs.

ENSO has the strongest effect on MHW properties in the eastern and central tropical Pacific (Oliver et al., 2018a; Figure 18.2). In those regions, El Niño events drive long-duration MHW events with high intensities (Figure 18.2a,d,g). Average durations are as long as 60 days in parts of the ENSO-dominated eastern tropical Pacific (Figure 18.2g), but these events occur infrequently, typically less than one event per year (Figure 18.2a). In other parts of the tropical oceans, MHW durations are typically 5–10 days with one to three events per year. ENSO tends to increase the frequency of MHWs in all ocean basins in the tropics, but particularly across the Pacific (Figure 18.2b). Outside of the tropics, El Niño and La Niña events are both associated with increases in the mean MHW duration and intensity in the northeast

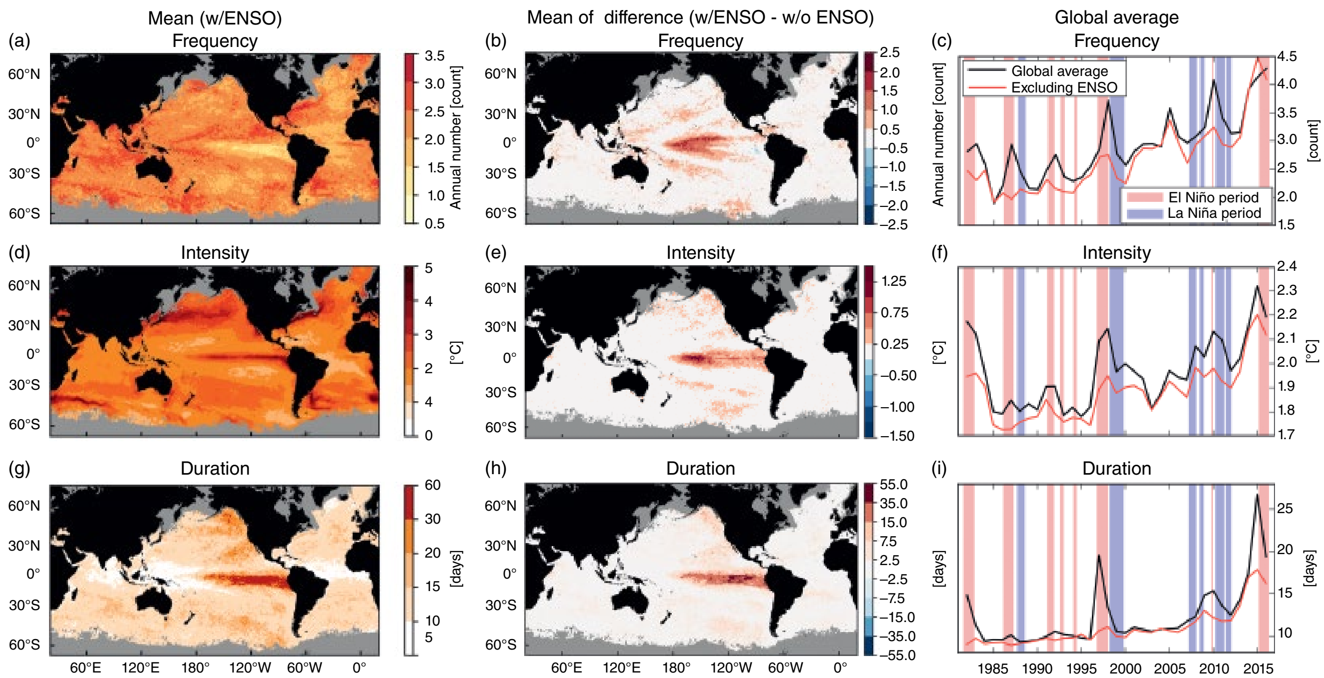

Figure 18.2 Marine heatwave (MHW) properties and the impact of ENSO. Local MHW (a) frequency, (d) intensity, and (g) duration are shown averaged over the 1982–2016 period based on NOAA OI SST data. The contribution of ENSO to these average MHW properties is shown in (b, e, h). This was calculated by first removing the influence of ENSO from the underlying SST, statistically using the Multivariate ENSO Index (MEI), and then subtracting the resultant ENSO-independent MHW patterns from the original patterns shown in (a, d, g). Associated globally averaged time series of MHW (c) frequency, (f) intensity, and (i) duration are shown before (black lines) and after (red lines) removing the influence of ENSO. Light red and blue shading indicate El Niño and La Niña periods, respectively, defined by +/-1 std. dev. of the MEI for at least 3 months consecutively. (Figure adapted from Oliver et al., 2018a)

Pacific Ocean, off western Australia, and coastal California (Figure 18.2e,h). ENSO also tends to increase MHW frequency in the mid- and high latitudes of the Pacific Ocean. At global scales, ENSO also drives significant interannual variations in MHW properties. During the strongest El Niño events (i.e. 1982–1983, 1997–1998, and 2015–2016), when averaged globally, there was typically 0.5–1 extra MHW event (Figure 18.2c), with intensity increases of 0.1°C–0.2°C (Figure 18.3f) and annual number of MHW days increasing by 5–10 days (Figure 18.2i).

A number of specific high-impact MHWs outside of the central and eastern tropical Pacific have been linked to ENSO events. To describe these events, we have applied the new categorization scheme of Hobday et al. (2018) that expresses the severity reached by events. Various mechanisms come into play in generating remote temperature responses that can take part in initiating, maintaining, and terminating MHWs. In the atmosphere, changes in the strength and location of tropical convection associated with the zonal displacement of the western Pacific warm pool can affect the Walker Circulation and the regions of convergence/divergence across the tropical oceans of all basins. Convection changes also trigger planetary Rossby waves that drive remote changes in atmospheric circulation, including wind speed and direction and cloudiness that can influence ocean mixed layer temperatures (Lee et al., 2010; Di Lorenzo & Mantua, 2016; e.g. chapter 14). Oceanic Kelvin waves also propagate to the extratropics along coastal waveguides at the eastern sides of ocean basins, for example, along the west coast of North and South America and the west coast of Australia, affecting coastal temperatures, sea level, and circulation (chapter 15).

Changes in the Walker Circulation link ENSO changes to the Indian Ocean, helping to trigger Indian Ocean Dipole

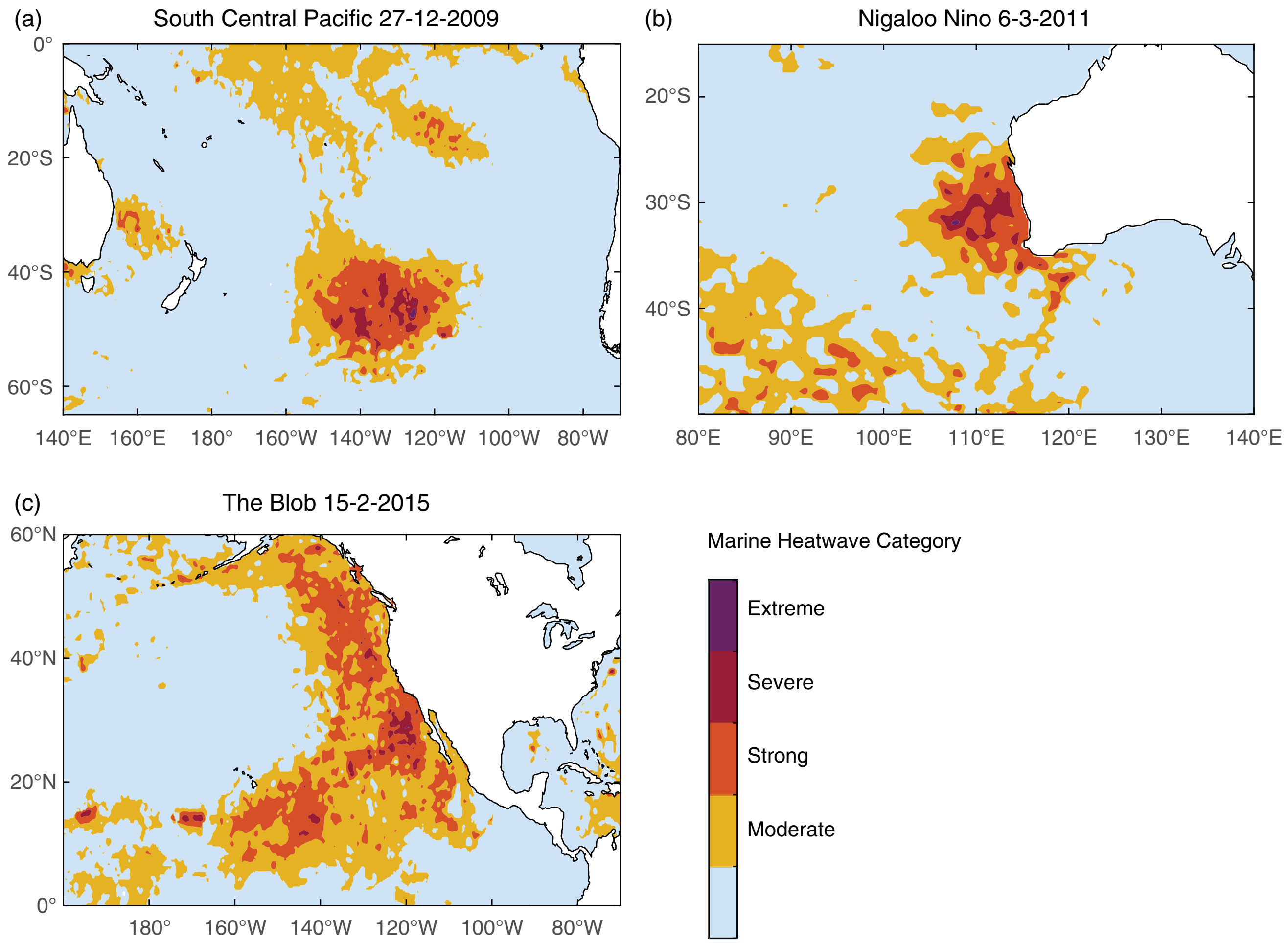

Figure 18.3 Categories for three high-impact marine heatwaves associated with ENSO events: (a) South central Pacific during the 2009–2010 central Pacific El Niño, (b) Ningaloo Niño, associated with the 2010–2011 La Niña, and (c) the latter stages of the North Pacific "Blob," associated with the weak El Niño conditions of 2014–2015. Category definitions are given in Hobday et al. (2018).

(IOD) events in the months leading up to the ENSO peak (Saji et al., 1999), and a basin-wide warming across the tropical Indian Ocean during and after the peak of ENSO events. For example, the IOD event associated with the extreme 2015–2016 El Niño was implicated in an extended MHW in the waters to the north of Australia (Oliver et al., 2018b), and the broad-scale warming of the Indian Ocean associated with the 1997–1998 extreme El Niño was linked to an intense MHW and extensive coral mortalities in the Seychelles. More generally, MHWs and associated bleaching events are more likely in the tropical southeast Indian Ocean as a result of increased insolation and a weaker Australian monsoon during El Niño (Zhang et al., 2017).

A number of unprecedented warming events outside of the tropics are also believed to have been triggered by both El Niño and La Niña events. In the central South Pacific during the austral summer of 2009–2010, SST anomalies exceeded five standard deviations (Lee et al., 2010) concurrent with a record-breaking central Pacific El Niño (Figure 18.3a). The event was linked to an atmospheric Rossby wave train stretching into the subtropics that formed a blocking high-pressure system over the region. This led to an anomalous inflow of warmer air and weaker wind speeds with an associated decrease in turbulent heat losses from the ocean. Wind changes also weakened the normal northward flow of cold surface waters in the Ekman layer (Lee et al., 2010). As such, multiple atmospherically forced processes combined to generate this extreme event.

The west coast of Australia experienced an unprecedented MHW that peaked in February 2011 when temperatures were 2°C–4°C warmer than normal for about 3 months (Figure 18.3b). The event led to significant ecosystem impacts and damage that has persisted to the present day (Wernberg et al., 2013, 2016). This event has also been linked to one of the strongest La Niña events on record. Enhanced Pacific trade winds led to sea level increases in the western Pacific that propagated through the Indonesian Archipelago and along the west coast of Australia as coastally trapped oceanic Kelvin waves. The enhanced cross-shore sea level gradient intensified the Leeuwin Current, advecting more warm water southward. In addition, an atmospheric teleconnection to the La Niña (a Gill-Matsuno response) suppressed the seasonal southerlies that normally weaken the Leeuwin Current and reduced the regional wind strength, thereby suppressing heat losses from the ocean (Feng et al., 2013; Caputi et al., 2016). Thus, a combination of remote ocean and atmospheric teleconnections combined to generate this unprecedented event.

ENSO may have also played a role in the extreme persistence of "The Blob" (Figure 18.3c): a multiyear MHW in the northeast Pacific. The event had important ecological implications, with large numbers of sea mammal and bird deaths and harmful algal blooms that caused closures of important shellfish fisheries along the western U.S. coastline. The initiation of the MHW has been linked to a persistent high-pressure ridge that occurred between October 2013 and January 2014 and an associated reduction in wind speeds (leading to reduced ocean heat loss) and anomalous warm northward advection in the Ekman layer (Bond et al., 2015). Di Lorenzo and Mantua (2016) suggest that the high-pressure system was part of the basin-wide North Pacific Oscillation that favors the development of an El Niño. They suggest that the resulting warming of the tropical Pacific generated an atmospheric Rossby wave response that manifested as a deep low-pressure system in the open northeast Pacific Ocean. This caused the warm SST anomalies to shift toward the North American coastal region and allowed the MHW to persist through the summer of 2015.

Future projections of MHWs (Frölicher et al., 2018) indicate a significant increase in the probability of MHWs due to anthropogenically driven global warming, particularly in the tropical oceans. This may raise the background likelihood of MHWs in this region and therefore exacerbate the risk due to ENSO-driven extreme MHWs. Given the influence of ENSO on MHWs, changes in ENSO intensity could also affect MHW characteristics. However, there is little consensus around how ENSO will change in the future, except perhaps for suggested increases in the frequency of the most extreme events (chapter 13).

18.3. IMPACTS ON SHALLOW-WATER MARINE ECOSYSTEMS

Shallow-water marine ecosystems are vulnerable to extremes in sea level and seawater temperature. In the following subsections, we introduce the key shallow-water marine ecosystem foundation species of coral reefs, rocky reef kelp forests, sea grasses, and mangroves. We examine the impacts on these shallow-water marine ecosystems from sea level and ocean temperature extremes, and more specifically associated with ENSO event occurrences. All of these ecosystems are sensitive to environmental change and extremes. The specific sensitivity varies between ecosystems. In the case of seagrass and kelps, they have limited propagule dispersal and require sunlight; thus, they cannot simply avoid warming waters by retreating into deeper (cooler but darker) waters. Corals have a narrow thermal tolerance but can persist in deeper waters. Mangroves occupy the interface between land and sea and are thus impacted by both marine and atmospheric conditions. Flow-on effects from ecosystem impacts to humans are discussed in chapter 19.

18.3.1. Tropical Coral Reef Ecosystems

18.3.1.1. Background

Coral reefs, some of the most biodiverse ecosystems on Earth, are threatened by climate change and episodic warming events like El Niño (Hoegh-Guldberg et al., 2007; Ainsworth et al., 2016). Severe stress events are already affecting corals and are expected to increase in the near future, even under moderate warming scenarios (van Hooidonk et al., 2016), threatening fundamental services provided by coral reefs, including food and economic stability, that support tens of millions of people in over 100 countries (Salvat, 1992; Moberg & Folke, 1999). The health of hard (scleractinian) corals is fundamentally important to the persistence and biodiversity of coral reefs, since corals form complex reef structures providing habitat for many thousands of reef-associated species. The impact of episodic warming events can be further exacerbated by local stressors, including overfishing, pollution, and disease (Hughes et al., 2003; Wiedenmann et al., 2012; Vega Thurber et al., 2014). Warming events that affect corals may occur due to a number of cyclic and stochastic climatic events, such as El Niño, La Niña, or anomalous summer conditions (Zhang et al., 2017; Eakin et al., 2018). In particular, severe warming events, such as a strong El Niño, can decimate even remote and protected reefs (e.g. Aeby et al., 2003; Hughes et al., 2017). Therefore, understanding the dynamics of El Niño severity is necessary to enable prediction of coral resilience over the next century.

Corals form an obligate nutritional symbiosis with Symbiodiniaceae (the symbiont, previously called zooxanthellae or *Symbiodinium*; Muscatine & Cernichiari, 1969). This symbiosis provides photosynthetic metabolites to host corals, ultimately allowing corals to grow and build the carbonate skeletons fast enough to withstand the natural forces of physical and biological erosion to create coral reef habitat (Muscatine & Porter, 1977). Originally, it was thought that there was only one type of symbiont, but advances in molecular analysis have revealed that there are multiple genera within Symbiodiniaceae that can change in abundance over time (Rowan, 1995; Baker, 2003; LaJeunesse et al., 2018). These different symbionts vary in their ecological functions and response to stress (Stat & Gates, 2011; Baker et al., 2018). Since symbioses can vary in time and space, they are a source of local, regional, and species-specific variability in coral susceptibility to episodic heat stress events such as El Niño.

During periods of intense and prolonged warming, this coral symbiosis can break down and Symbiodinaceae are expelled from the coral tissue causing the host coral to appear white or "bleached" (Brown, 1997). Although other sources of stress can cause coral bleaching (e.g. cool temperatures, anomalous salinity, and pollution), we focus this section on bleaching caused by high-temperature stress. The link between temperature stress and mortality was forged through reef observations during El Niño warming. Although one of the first reports of mass coral bleaching was associated with the 1982–1983 El Niño (Glynn, 1983), the link to El Niño warming was not made at that time. However, as research into this early event continued, evidence built for the connection between El Niño warming and mass coral bleaching (Glynn & D'Croz, 1990; Williams & Bunkley-Williams, 1990). Additional research has shown that the probability of coral bleaching on any particular reef is not dependent on a specific temperature but rather local thermal thresholds (Gleeson & Strong, 1995). In areas with seasonal temperature change, corals have been more susceptible to thermal stress during the local summer warm season, when thermal thresholds are more likely to be crossed. Coral bleaching risk has been commonly predicted and described using the metric "degree-heating weeks" (DHW, unit °C-weeks; NOAA Coral Reef Watch, 2000; Liu et al., 2014), which sums temperature anomalies (>1°C) above the maximum annual mean accumulated over the previous 12 weeks as a measure of cumulative heat stress. Due to timing and local conditions, each El Niño event has its own spatial and temporal signature of heat stress, and the DHW metric captures the specific duration and intensity of warming affecting coral reefs at any one location. Depending on the amount of heat stress, there is some capacity for corals to persist and recover after bleaching. Although if warming is extreme or prolonged, corals may die (McClanahan, 2004). While warming can fundamentally transform coral communities and decimate reefs (Hughes et al., 2019), the relatively short-term nature of El Niño warming may promote coral adaptation to warming and increase resilience to future events in some cases by selecting for resilient genotypes (Guest et al., 2012). However, as the return times between bleaching events decrease (Hughes et al., 2018b), corals will likely become more threatened with each new El Niño event.

18.3.1.2. Impacts from ENSO-Related Ocean Extremes

El Niño events have instigated several coral bleaching events since intensive reef monitoring began in the early 1980s (Heron et al., 2016). In particular, three "global" bleaching events occurred during the 1997–1998, 2009–2010, and 2015–2016 El Niño events, while more regionally confined bleaching events occurred during the 1982–1983, 1986–1987, 2002–2003, and 2005 El Niño events (Oliver et al., 2018). El Niño warming is now superimposed on the warming of the global oceans, increasing the probability of exceeding coral thermal thresholds compared to the past (Hughes et al., 2018b; Lough et al., 2018). This is also evident in the overwhelming dominance of ocean warming that occurred during the 2015–2016 El Niño event (Figures 18.4 and 18.5). Overall, El Niño–associated warming significantly increases coral bleaching and mortality, although the intensity of effects can be variable across regions and events (Figure 18.5; reviewed in Claar et al., 2018). Here, we note that the warming caused by La Niña tends to pale in comparison to warming caused by El Niño events. Therefore, while La Niña events can also cause some coral bleaching due to localized or regional warming, El Niño is the primary ENSO-related driver of bleaching at the large scale.

The first well-documented case of large-scale coral bleaching occurred during the 1982–1983 El Niño (Glynn, 1983, 1984, 1988; Williams & Bunkley-Williams, 1990). Bleaching intensity was regionally variable, with some locations experiencing extreme bleaching. For example, 95% coral mortality was observed during this event on some eastern Pacific reefs (Glynn, 1990), and up to 100% mortality was documented at some sites in Indonesia (Brown & Suharsono, 1990). These losses were severe, and El Niño events of this magnitude can even cause extinction of endemic coral species. In Panama, this El Niño caused the probable extinction of two hydrocoral species (Glynn & de Weerdt, 1991). Reefs in Panama were further impacted by low-tide exposure that occurred during anomalous low sea levels associated with the subsequent La Niña events in 1988–1989 and 1993, causing significant reef erosion that had not recovered 17 years later (Eakin, 2001), although nearby Costa Rican reefs were well on their way to recovery 20 years after the event (Guzman & Cortes, 2006). Exposures of shallow reefs in the northwestern and south-central Pacific have also been observed, respectively, during and after strong El Niño events (Widlansky et al., 2014). In the Samoan Islands, for example, such events are referred to as *taimasa* (kai-ma-sa), which means smelly reef.

The first recorded global coral bleaching event coincided with the 1997–1998 El Niño and the subsequent strong La Niña (Wilkinson & Science, 1998). A cascade of mass bleaching events during this El Niño caused serious degradation of more than 16% of the world's tropical coral reefs (Wilkinson, 2002). For example, during this global bleaching event there was 90% mortality on some Indian Ocean reefs (Wilkinson & Hodgson, 1999). Coral recovery after El Niño can be slow. After the 1997–1998 El Niño, Brazilian reefs took more than a decade to recover to prebleaching levels (Kelmo & Attrill, 2013), and an isolated reef system off western Australia took 12 years to recover to prebleaching coral cover (Gilmour et al., 2013). Following this strong El Niño, scientists proposed that increased mass coral bleaching was linked to increased El Niño activity (Stone et al., 1999).

The moderate 2002–2003 El Niño caused mass bleaching and mortality in the Phoenix Islands (central Pacific; Obura & Mangubhai, 2011). Islands in the central equatorial Pacific may face a double risk during El Niño: this region tends to be strongly influenced by El Niño–associated warming, and corals in warmer regions (measured by long-term mean SST, which is typically highest near the equator) may be more susceptible to heat stress (Claar et al., 2018). This variability in susceptibility may be due to adaptation of higher-latitude reefs to seasonal temperature variability (Donner, 2011), since equatorial reefs generally experience relatively stable thermal climates on an intra-annual scale and therefore may be less prepared for episodic temperature extremes associated with El Niño. Central Pacific reefs experienced El Niño–associated bleaching conditions 10 times between 1960 and 2016, with the 2015–2016 El Niño event being unprecedented in magnitude during that time (Barkley et al., 2018).

The 2009–2010 El Niño impacted reefs across the Pacific Ocean and Caribbean Sea. Southeast Asian reefs were among the most impacted, losing 18% of their coral during the 2010 bleaching event (Tun et al., 2010). The 2009–2010 El Niño also caused repeat bleaching at several locations that had been affected by previous El Niño events. In Lakshadweep (Indian Ocean), reefs that bleached during the previous 1997–1998 and the 2009–2010 El Niño events were more resistant to bleaching and mortality but slower to recover after the latter event (Yadav et al., 2018).

The largest global bleaching event to date was associated with the 2015–2016 El Niño. During this event, some locations exceeded a thermal stress threshold (24°C-weeks) that was not expected to occur on any reef until approximately 2050 (Hoegh-Guldberg, 2011), reaching an unprecedented 35°C-weeks on Jarvis Island in the central Pacific (Brainard et al., 2018). Heat stress persisted in the central Pacific for more than a year, making 2015–2016 the longest duration thermal stress measured to date. Although the central Pacific accumulated the largest amount of heat stress during this event, intense warming occurred in many other regions as well (Claar et al., 2018). In Australia, the 2015–2016 El Niño catastrophically transformed nearly one third of the Great Barrier Reef (29% of 3,863 individual reefs), dramatically diminishing coral communities (Hughes et al., 2018a). Researchers are currently integrating and analyzing coral bleaching data from this event, and upcoming research will likely give us an even clearer understanding of how coral reefs are influenced by a combination of El Niño and anthropogenic warming.

With long recovery times and decreasing return times between coral bleaching events (Hughes et al., 2018b), El Niño–associated warming paints a grim picture for the future of coral reefs (Langlais et al., 2017). However, some corals may be able to acclimate or adaptively respond to warming events, making them better prepared for the next bleaching event (Guest et al., 2012; Palumbi et al., 2014; Dziedzic et al., 2019). With coral reef conservation in mind, further research is needed to deter-

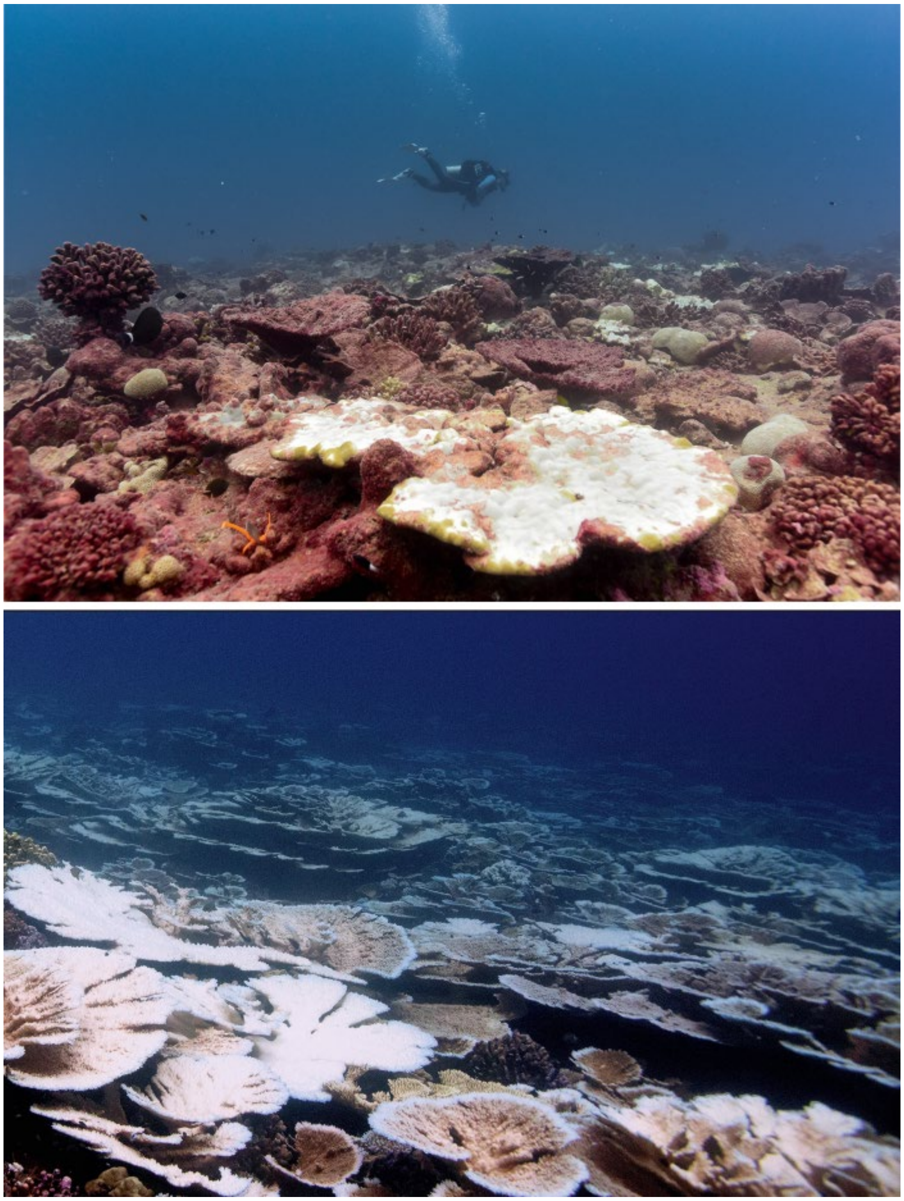

Figure 18.4 Photo images of coral bleaching and mortality in the central equatorial Pacific (Kiritimati Island, Kiribati) during the 2015–2016 El Niño event. Top panel shows a bleached coral colony (*Porites*) in the center of the photo as well as widespread mortality of nearly all reef-building coral colonies in March 2016. Bottom panel shows the start of coral bleaching in July 2015 for large plating corals (*Acropora*), and variability in bleaching severity from entirely bleached to only moderately affected colonies. (Photo credits: Danielle Claar [top] and Kristina Tietjen [bottom], Baum Lab, University of Victoria)

mine how ENSO variability influences coral survival, as well as when, and why, some corals adapt to El Niño.

18.3.2. Kelp Ecosystems

18.3.2.1. Background

Kelps are photosynthetic macroalgae belonging to the group generally known as seaweeds. Seaweeds are sensitive to environmental change because they are sessile, with limited propagule dispersal, and sensitive to temperature (Wahl et al., 2015). As they require sunlight, seaweeds cannot simply avoid warming waters by retreating into deeper (cooler but darker) waters.

Kelps are the best known of the seaweeds, as they form large forests that may rise up to 40 meters from the seafloor to the surface (e.g. *Macrocystis*) or form dense meter-high canopies over rocky reefs (e.g. *Ecklonia*, *Laminaria*). The more than 100 species of kelps are

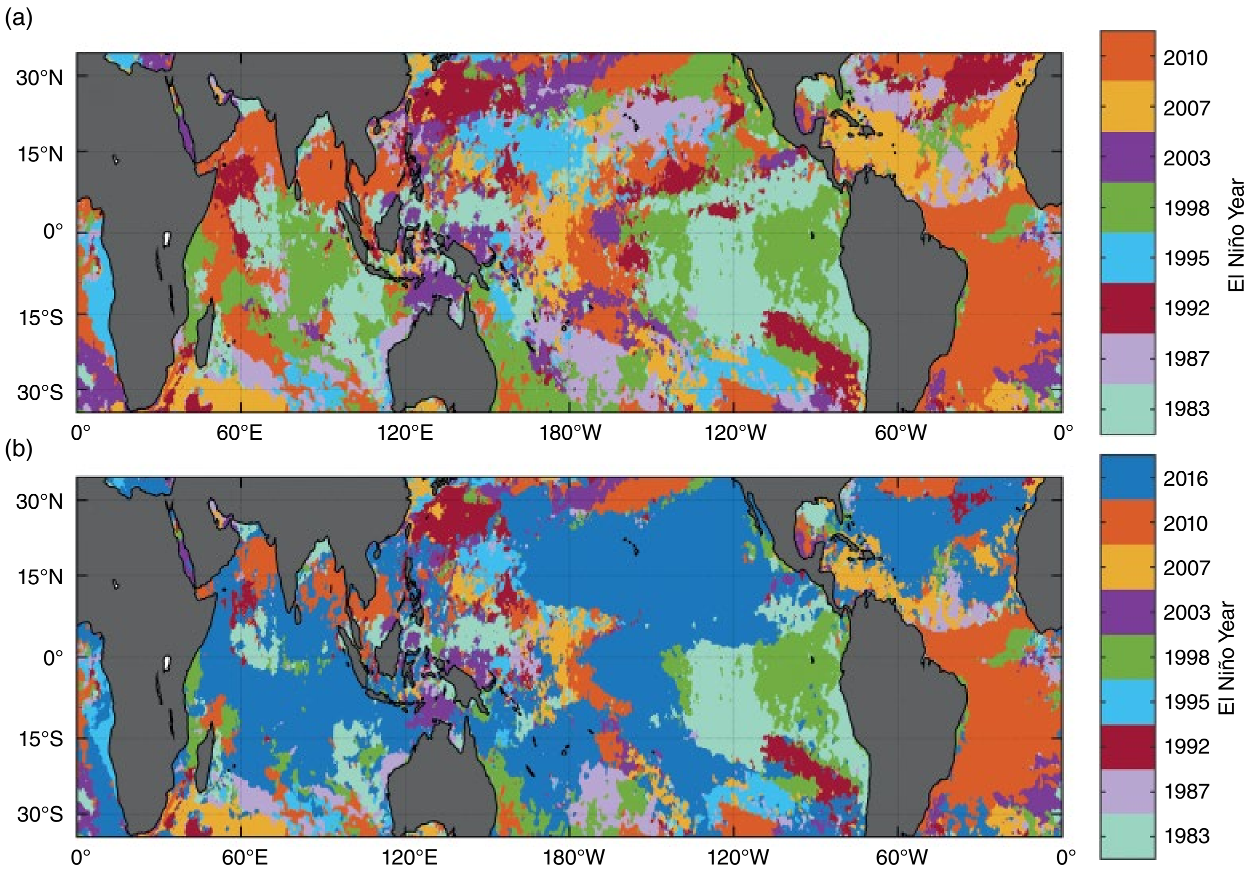

Figure 18.5 El Niño events with the greatest heat stress. Both panels show which El Niño event caused the greatest maximum degree-heating weeks for each area. Note that this figure does not demonstrate bleaching response, only maximum cumulative heat stress per El Niño event. The events are color-coded by year. The 1997–1998 El Niño event was the most severe event in the eastern Pacific around the South American coast. (a) All El Niño events from 1982 to 2010, showing how much heterogeneity there is in the geographic distribution of the most extreme heat stress. (b) All El Niño events since 1982, including the 2015–2016 El Niño event, demonstrating the coral heat stress homogenization that occurred during this most recent warming event. (Figure and caption reprinted from Claar et al., 2018)

distributed along temperate coastlines worldwide, with a limited number of species also occurring in subpolar waters of both hemispheres (Graham et al., 2007). These forests are home to a diverse range of species, including commercially important abalone, rock lobster, and other shellfish and provide a wide range of other ecosystem services (Bennett et al., 2016). Loss of kelps from rocky reefs subsequently leads to the absence of hundreds of associated species (Ling et al., 2008; Vergés et al., 2014).

Seaweeds such as kelps directly respond to changes in variables such as temperature and nutrients that are affected by ENSO events. Kelps are indirectly affected by changes in other ecosystem processes that are affected by ENSO events, such as competition, consumption, and fouling by other organisms that grow on their fronds (Vega et al., 2005; Wahl et al., 2015). Warm surface waters are generally depleted in nutrients, and as kelps have limited storage of nutrients, effects are felt after short periods of above-average temperatures (Graham et al., 2007). Recovery of kelps following El Niño events occurs relatively quickly in California (Graham et al., 2007). However, long-term declines in Tasmania have been attributed to anthropogenic warming, increased presence of low-nutrient waters along the coast (Wahl et al., 2015), and the influx of herbivores from lower latitudes (Ling et al., 2008).

18.3.2.2. Impacts from ENSO-Related Ocean Extremes

The influence of ENSO events on rocky reefs and their kelp forests is clear in many regions of the world. Best known are the El Niño–related changes in temperature and nutrient availability that dramatically reduced the size of *Macrocystis* kelp forests in California during the 1982–1983 event (Dayton & Tegner, 1984). In southern

California, for example, it has been shown that kelp growth becomes nutrient limited below approximately 1 μM nitrate, which typically occurs when water temperatures rise above 16°C (Graham et al., 2007). El Niño events lead to depression of the thermocline off California, which shuts down nutrient replenishment via coastal upwelling. Dramatic loss of these kelp forests occurs during major El Niño events (Tegner & Dayton, 1987), with mortality of 100% reported in many *Macrocystis* forests in southern and Baja California following the 1982–1983 and 1997–1998 El Niño events (Graham et al., 2007). Loss of kelp forests can also be exacerbated by large storms associated with these extreme events (Dayton & Tegner, 1984).

Other oceanographic processes can limit the impact of El Niños. In northern Chile, forests of *Lessonia trabeculata* and *Macrocystis integrifolia* were maintained during the 1997–1998 El Niño due to persistence of coastal upwelling (Vega et al., 2005). These cells of coastal upwelling along a coastline can transport kelp propagules following an El Niño and repopulate areas that have suffered local kelp extinctions. The opposite conditions, while expected to be favorable for kelps, can also bring surprises. In the same region of northern Chile, intensification of upwelling associated with the 1998–2000 La Niña led to increased surface nutrient availability. However, increased abundance of a grazing sea urchin species led to local extinction and range reduction for both species of kelps (Vega et al., 2005). The examples show that both direct and indirect effects play a role in mediating the effect of ENSO phases, and generality across space and time is limited (Wahl et al., 2015).

Kelp forests have been shown to be resilient to disturbance from El Niño warming in the eastern Pacific (Tegner et al., 1997), in that kelp forests recover after these events. However, long-term warming and extreme events have led to dramatic changes in their distribution and abundance off southern Australia (Johnson et al., 2011; Wernberg et al., 2011). Increased frequency of warm ocean extremes coupled with reduced surface nutrients is likely to lead to widespread decline of kelp forests and their associated communities (Wernberg et al., 2016).

18.3.3. Seagrass Ecosystems

18.3.3.1. Background

Seagrasses form a critical component of many nearshore environments, helping to stabilize sediments and store carbon. The approximately 70 species of seagrass are widely distributed around the globe but are at their most extensive and diverse in Australia (Poloczanska et al., 2007). They occur in shallow marine waters such as estuaries, protected bays, lagoons, and reef platforms protected from strong water movement, but also in deeper waters (to 70 m) in areas where water clarity is high (Connolly, 2012). The critical factors for seagrass growth are light, temperature, CO_2, nutrients, and suitable substrate.

Seagrasses living in shallow waters are subject to wide temperature fluctuations seasonally and interannually. They are considered more vulnerable to changes in water quality than changes in temperature, including salinity and sediments that directly smother plants or indirectly reduce the availability of light (Connolly, 2012). They provide food for megafauna such as turtles and dugongs, as well as critical habitat for birds and recreationally and commercially important fish and other species (Waycott et al., 2009).

There is limited evidence regarding environmental drivers of seagrass dynamics, due in part to the lack of long time series. Recent extreme events have shown that, like other coastal habitats, seagrasses and their associated communities are also affected.

18.3.3.2. Impacts from ENSO-Related Ocean Extremes

A significant impact of ENSO on seagrasses is associated with heavy rainfall events which can lead to turbid flood plumes that reduce available light for seagrasses. Elevated levels of nutrients transported to the nearshore environment by floods can promote phytoplankton and epiphyte growth, further limiting the light and oxygen available to seagrasses (McKenzie et al., 2012). For example, during the strong 2010–2011 La Niña, a series of tropical cyclones crossed the coast of Queensland, Australia (Hodgkinson et al., 2014). This, in combination with monsoonal conditions and generally heavy rainfall, resulted in record river flows and large sediment inputs over the seagrass beds of the adjacent Great Barrier Reef, in addition to the direct loss of seagrass beds in the path of the cyclones. Severe declines in seagrasses were reported, with >70% of all seagrass beds declining by >20% and seagrass condition in all regions rated as "very poor" and at historically low levels (McKenzie et al., 2014). Following these floods, there were high levels of mortality of the seagrass-dependent green turtles and dugongs (Meager & Limpus, 2014). This long-term analysis showed that peak mortality of dugongs (and inshore dolphins) followed sustained periods of elevated freshwater discharge and low air temperature, with a strong relationship between annual mortality and the Southern Oscillation index (Meager & Limpus, 2014), an often-used indicator of ENSO strength.

On the other side of Australia, the marine heatwave in 2011 (La Niña conditions) in Western Australia resulted in damage to about 36% of Shark Bay's seagrass meadows (Arias-Ortiz et al., 2018). These losses in seagrass habitat were estimated to lead to between 2 and 9 Tg of CO_2 released to the atmosphere during the following 3 years, increasing emissions from land-use change in Australia by 4% to 21% per annum. The reduction in seagrass habitat and quality corresponded with a decline in the health status of largely herbivorous green turtles (*Chelonia mydas*) over the following 2 years, providing evidence of long-term, community-level impacts of the event (Thomson et al., 2015).

The impact of El Niño and La Niña on seagrass beds is an indirect one, based on flooding and sediment loads in coastal waters rather than direct temperature effects. Marine heatwaves have nevertheless led to dramatic declines in seagrass meadows. When compounded by other stressors, these events cause extensive seagrass mortality, with subsequent starvation for species that feed on seagrass (Thomson et al., 2015).

18.3.4. Mangrove Ecosystems

18.3.4.1. Background

Tropical coasts around the world support mangrove forests which provide a wide range of ecosystem services (Halpern et al., 2008). Mangrove forests are responsible for major components of the primary productivity of coastal habitats that support a diverse assemblage of fish and fisheries. The physical structure of mangrove forests provides both shelter and a stable substrate for flora and fauna, as well as increasing soil stability on which subterranean communities of fish, crustaceans, and detritus recyclers rely (Nagelkerken et al., 2008). The poleward limit of mangrove distribution is set by low temperatures, and mangroves are absent from coastal areas where mean temperatures in winter months fall below 4°C. They extend poleward where sufficiently warm ocean currents permit and frost damage is reduced. Mangrove forests have highest diversity in the wet tropics, with diversity decreasing on temperate coasts and in arid regions (Lovelock & Skilleter, 2012). Mangrove forests require fresh water for survival. Although they live in saline waters, many mangrove species live close to their salinity tolerance levels. Lowered sea levels, increased salinity, and decreases in freshwater runoff can lead to deaths of individual plants and stands of mangroves (Lovelock et al., 2017).

18.3.4.2. Impacts from ENSO-Related Ocean Extremes

Impacts of ENSO events on mangroves have received relatively little attention until recent times. An earlier study by Drexler and Ewel (2007) showed that a mangrove ecosystem in Micronesia responded negatively to the 1997–1998 El Niño–related drought and increased salinity in this coastal region, and that mangrove forest structure and functioning may be potentially affected by such disturbances for repeated drought cycles. Further, the study shows that mangrove ecosystems are vulnerable to impacts from such short-term climatic fluctuations.

Most recently, both the role of ENSO and climate change have been considered for mangrove areas around Australia (Lovelock et al., 2017) and the Pacific coast of Columbia (Riascos et al., 2018). Based on a study of mangrove seedlings and forests of Colombia, Riascos et al. (2018) suggest that mangrove forests might be expected to show little change in regions where precipitation is projected to increase. Additionally, they suggest that climatic variations associated with ENSO phases may be important for mangrove reproduction, dispersion, and recruitment across the tropical eastern Pacific, including Panama, Costa Rica, and Ecuador (Riascos et al., 2018).

The 2015–2016 El Niño was associated with dramatic dieback of mangroves across more than 1000 km in the Gulf of Carpentaria, Australia (Lovelock et al., 2017; Babcock et al., 2019). The dieback affected up to 6% of the overall Gulf of Carpentaria mangrove community, and in some regions the dieback affected up to 26% of the mangrove stands, with 100% mortality in some of these stands (Babcock et al., 2019). The dieback was attributed to both abnormally low El Niño–related sea level, which was compounded by lower-than-average rainfall over recent years, and record high temperatures in the preceding 6 months (Duke et al., 2017). Modeling analysis demonstrates that the 2015–2016 El Niño was the dominant factor affecting the extremely low sea level in the Gulf at the time (Harris et al., 2017). It is likely that the mangrove forests suffered from a combination of soil moisture stress, loss of monthly inundation of the upper intertidal zone during neap tides, and abnormally hot temperatures over an extended period.

The combination of global warming and extreme events is likely to threaten mangrove habitats due to both direct and indirect effects. Mangrove areas killed or weakened during El Niño events may be subject to additional erosion as a result of tidal action and tropical cyclones (Duke et al., 2017). Mangrove forests sequester large amounts of carbon, which could be liberated to the atmosphere following diebacks and thus act as a positive feedback for climate warming.

18.4. DISCUSSION AND CONCLUSIONS

This chapter has reviewed current knowledge regarding ENSO-related extremes in sea level and ocean temperature and their impacts on the shallow-water marine ecosystem foundation species of coral, kelp, seagrass, and mangrove. As the dominant global mode of interannual climate variability, ENSO plays a critical role in sea level and sea temperature fluctuations, influencing marine ecosystems. These ocean extremes may be directly related to dynamical processes in the tropical Pacific or the consequence of atmospheric or oceanic teleconnections and modulated regional processes in the extratropics or other basins. Finally, climate change represents an additional "wicked" dimension that is already increasing sea level extremes and marine heatwave frequency and intensity, and may also be affecting ENSO variability. In combination with large-scale natural ENSO variations, climate change influences on ENSO, and current and future projected coastal population growth, we fully expect that marine ecosystems will continue to experience unprecedented environmental pressures and impacts.

This review highlights the following:

• ENSO plays a critical role in both modulating and triggering marine heatwaves and sea level extremes, which impact shallow-water marine ecosystems through their exposure to thermal stress, sea level change and coastal inundation.

• Tropical coral ecosystems live near the upper limits of their thermal tolerances. As such, exposure to relatively mild but persistent marine heatwaves can cause bleaching: i.e. when coral expel their symbiotic algae (zooxanthellae; Symbiodiniaceae), potentially leading to mortality. ENSO events play a substantial role in the prevalence of marine heatwaves globally, with the most severe coral bleaching events typically occurring during El Niño event periods. With current and projected global warming trends, increased ocean temperatures and extremes pose a critical threat to the future of coral reefs around the world.

• Kelp ecosystems respond directly to changes in temperature and nutrients, both factors that are influenced by ENSO events. Increased frequency of marine heatwaves coupled with reduced surface nutrients is likely to result in widespread decline of kelp forests and their associated communities.

• Seagrass ecosystems tend to be indirectly but significantly impacted by El Niño/La Niña due to heavy rainfall events, freshwater river flood plumes and increased sediment loads, and resultant lowered salinity and light levels.

• Mangrove ecosystems exist close to their salinity tolerance levels. While mangroves live in saline coastal waters, they also require fresh water for their survival. Studies of mangrove ecosystems in Micronesia, the Pacific coast of Columbia, and Australia have shown that mangrove ecosystems are sensitive to ENSO variations via local changes in temperature, rainfall, and sea level.

• Impacts of ENSO through extremes in sea level and ocean temperature are becoming more severe due to background warming and sea-level rise.

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