Proceedings of the 12th International Coral Reef Symposium, Cairns, Australia, 9-13 July 2012
10A Modelling Reef Futures

Ghost of bleaching future: Seasonal Outlooks from NOAA's Operational Climate Forecast System

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Abstract. Using models to inform the possible future of coral reefs can happen on many scales. At the seasonal timescale, the National Oceanic and Atmospheric Administration’s (NOAA) Coral Reef Watch (CRW) and National Centers for Environment Prediction (NCEP) recently made a major advance in NOAA’s ability to predict thermal stress capable of causing mass coral bleaching: a newly-developed global seasonal outlook system based on NOAA’s operational Climate Forecast System (CFS). These outlooks predict the probability of thermal stress events capable of causing large-scale, mass coral bleaching, using a weekly, 28-member ensemble of sea surface temperature forecasts from the CFS. The new system builds upon the first global seasonal bleaching outlook system; collaboration between CRW and NOAA’s Earth System Research Laboratory used a statistical climate model to produce the first seasonal bleaching outlook system released in 2008 at the 11th International Coral Reef Symposium. This paper describes the new CFS-based outlook, initial testing using a series of hindcast and forecast simulations, and the performance of the system during recent bleaching seasons.

Key words: Coral bleaching, modeling, prediction, SST

Introduction

Mass bleaching of coral reefs has occurred with increasing frequency in recent decades. The US National Oceanic and Atmospheric Administration’s (NOAA) Coral Reef Watch (CRW) provides critical information to reef managers and scientists based on near-real-time satellite monitoring of thermal stress conducive to coral bleaching (Liu et al. 2006). However, many users have requested information on the likelihood of coral bleaching months in advance. Longer lead-time information helps managers prepare for the bleaching, as many actions laid out in bleaching response plans are expensive and/or controversial (Maynard et al. 2009).

In 2008, CRW released the world’s first prediction tool for forecasting coral bleaching weeks to months in advance (Liu et al. 2009). However, that system was based on a statistical global sea surface temperature (SST) forecast model, the Linear Inverse Model (LIM) (Penland and Matrosova 1998), limiting the system to a single, deterministic seasonal bleaching outlook. CRW has now partnered with the NOAA National Centers for Environmental Prediction (NCEP) to develop a next-generation global seasonal bleaching outlook based on an operational ensemble prediction system for SST, providing a dynamical, probabilistic seasonal coral bleaching thermal stress outlook delivering advance warning to coral reef managers, scientists, stakeholders, and the public. Here we introduce this bleaching outlook system and provide an initial evaluation of its performance.

Material and Methods

NCEP Climate Forecast System

The new seasonal bleaching outlook system is based on NOAA NCEP’s Climate Forecast System Version 1 (CFSv1) (Saha et al. 2006), a fully coupled ocean–land–atmosphere dynamical seasonal prediction system. For its atmosphere, CFSv1 uses the 2003 version of the NCEP Global Forecast System model at T62 horizontal resolution with 64 vertical layers, and for its ocean it uses the Geophysical Fluid Dynamics Laboratory Modular Ocean Model version 3 (MOM3) (Pacanowski and Griffies 1998) with zonal resolution of 1° and meridional resolution of 1⁄3° between 10°S and 10°N, gradually increasing to 1° poleward of 30°S and 30°N. The ocean has 40 vertical layers with 10 m vertical resolution from the surface to 240-m depth. The atmosphere and ocean components are coupled daily without any flux adjustment. The CFS is initialized using oceanic conditions from the NCEP Global Ocean Data Assimilation System (GODAS) (Saha et al. 2006), with SSTs relaxed to Reynolds OISST (Reynolds et al. 2002) with a time scale of 5 days. Atmospheric and terrestrial initial conditions are obtained from near-real-time observations assimilated using the

NCEP/Department of Energy (DOE) reanalysis-2 (R2; Kanamitsu et al. 2002) system.

CFS retrospective and real time operational forecasts
For determining systematic error in the forecast system, an extensive set of retrospective forecasts (hindcasts) was made for the time period from 1981 to 2006. For each month, CFSv1 produced three sets of hindcasts from initial conditions around the 11th, 21st, and 1st day of the month, each set consisting of five hindcasts from an identical oceanic initial state and five observed atmospheric and land initial conditions that are one day apart. Therefore, there are 15 hindcasts each month with each predicting forward in time to 270 days from the initial date.

CFSv1 became operational at NCEP in October 2004. It produced one forecast run each day from October 2004 to January 2005, increasing to four forecast runs per day from January 2008 to present. As with the hindcasts, each real time forecast predicts SST 270 days from the initial date.

Seasonal Bleaching Thermal Stress Outlook System
Through collaboration with NCEP, CRW developed a new seasonal tropical coral bleaching outlook system based on the SST forecasts and hindcasts from the CFSv1. The prediction system provides a probabilistic forecast of regions with the potential to exhibit thermal stress conducive to coral bleaching ranging from three weeks to 18 weeks ahead. The system spans oceans from 45ºS to 45ºN with a fixed 1ºx1º spatial resolution. In the tropics, the sub-1ºx1º daily predictions of SST (i.e., the temperature of the surface 10-meter layer) from CFSv1 are averaged to produce 1ºx1º SST predictions for the outlook.

The algorithm for deriving bleaching thermal stress from CFS SST predictions was derived based on the algorithms used by CRW to produce its near-real-time global satellite coral bleaching monitoring products (Liu et al. 2006). In its satellite monitoring product suite, CRW measures HotSpots (current thermal stress) as the difference between the satellite-observed SST and the climatologically averaged temperature for the warmest month at that pixel. Since both intensity and duration of thermal stress contribute to bleaching, CRW's Degree Heating Weeks (DHW) index sums all values of HotSpot ≥ 1.0 ºC during each 12-week period. CRW's Bleaching Alert Area product shows areas where bleaching thermal stress has reached predefined bleaching stress levels (Table 1). A Bleaching Watch indicates that SST exceeds the maximum monthly mean (MMM) climatology but has not yet reached the bleaching threshold (MMM + 1 °C), beyond which the DHW accumulation begins and a Bleaching Warning is issued. Alert Level 1 indicates DHW has reached 4 ºC-weeks and coral bleaching is likely. Alert Level 2 indicates DHW has reached 8 ºC-weeks and both widespread bleaching and significant mortality are likely.

Stress Level	Definition	Effect
No Stress	HotSpot ≤ 0	--
Bleaching Watch	0 < HotSpot < 1	--
Bleaching Warning	1 ≤ HotSpot and 0 < DHW < 4	Possible Bleaching
Bleaching Alert Level 1	1 ≤ HotSpot and 4 ≤ DHW < 8	Bleaching Likely
Bleaching Alert Level 2	1 ≤ HotSpot and 8 ≤ DHW	Mortality Likely

Table 1: CRW's bleaching thermal stress levels based on CRW's satellite-based coral bleaching HotSpot and Degree Heating Weeks (DHW) products .

In the seasonal bleaching outlook system, the HotSpot prediction is calculated as the difference between CFSv1 SST forecasts and MMM for a given location with lead-time from 1 (the day after an initial condition day) to 270 days in the future. Derivation of MMM for CFSv1 SSTs is described in detail below.

To derive a daily DHW forecast from the daily HotSpot forecast, 84 consecutive daily HotSpots are needed. For any predicted day for lead-time within one to 83 days, observed HotSpot values for the initial condition day and/or earlier days need to be accumulated into the DHW along with the forecast HotSpots. As OISST is used in the GODAS that provides the initial SST conditions for the CFS, 1ºx1º OISSTv2 SSTs are used to produce daily observed HotSpots for the initial condition day and earlier. Testing revealed that a HotSpot threshold for DHW accumulation of 0.8 °C for OISST-based HotSpots, instead of the 1.0 °C threshold used in the satellite-based products, yielded results most similar to CRW's satellite-based DHW. Hence, 0.8 °C was chosen as the threshold for accumulating both OISST DHWs and for CFSv1 DHW forecasts (Table 2).

Because variability in forecast SSTs generally is smaller compared to observed SSTs, we use a reduced and declining HotSpot threshold for accumulating the DHWs similar to the approach used in CRW's LIM-based, statistical, seasonal coral bleaching outlook system (Liu et al. 2009). In the CFS-based outlook system, we applied a HotSpot threshold ($HotSpot_{vary}$) that decreases linearly from 0.8 °C at day zero of the forecast (initial conditions) to 0 °C at day 70 (the end of ten weeks) and beyond. Accumulation of thermal stress (DHW) begins, and a Bleaching Warning is issued, when the HotSpot value reaches the threshold, $HotSpot_{vary}$ (Table 2). As any non-zero HotSpot value would result in DHW accumulation beyond day 69, a new threshold, DHW_{low} was defined to start at 0 ºC-weeks at day 0 and increase linearly to 2.0 ºC-weeks at day 70. This maintains the Bleaching Watch level for low accumulated stress throughout all forecast lead-times (Table 2).

Outlook Stress Level	Definition	Effect
No Stress	HotSpot $\leq$ 0	--
Bleaching Watch	0 < HotSpot and DHW < DHW_{low}	--
Bleaching Warning	$HotSpot_{vary} \leq$ HotSpot and DHW_{low} < DHW < 4	Possible Bleaching
Bleaching Alert Level 1	$HotSpot_{vary} \leq$ HotSpot and 4 $\leq$ DHW < 8	Bleaching Likely
Bleaching Alert Level 2	$HotSpot_{vary} \leq$ HotSpot and 8 $\leq$ DHW	Mortality Likely

Table 2: The stress levels adapted for use with CFSv1 forecasts.

Each day, four sets of daily HotSpot and DHW forecasts are produced from the four separate runs of CFSv1 SST out to a lead-time of 270 days. All the daily forecasts (four sets a day) from a 7-day calendar week form a 28-member ensemble. For each ensemble member, the median of the seven daily HotSpot and DHW values for each forecast week is compared to the levels in Table 2 to determine the weekly bleaching thermal stress outlook. These combinations provide 28-ensemble-member weekly probabilistic outlooks.

A probabilistic outlook is produced for each forecast week within the seasonal time range (usually three to four months after the initial condition week). The percentage of the 28 members reaching a particular thermal stress level is calculated to yield the probability of reaching each thermal stress level listed in Table 2 (see also CRW (2012)). The 28 outlook values for each 1ºx1º grid cell for each target week are sorted and ranked from the lowest thermal stress level to the highest thermal stress level, regardless which initial condition run a value originates from. The composite of the maximum thermal stress values of all the weekly outlooks over the seasonal time range is produced for each ranking, resulting 28 composites ranging from lowest to highest stress. The seasonal outlook system displays the distribution of thermal stress levels predicted by 90% and 60% of the 28 composites as probability-level outlook maps, shown in Fig. 1 (noting the 2010 bleaching event in the southern Caribbean). The system also maps the probability of reaching each of the four thermal stress levels, calculated as the percentage of the 28 maximum composites reaching each level (Fig. 2).

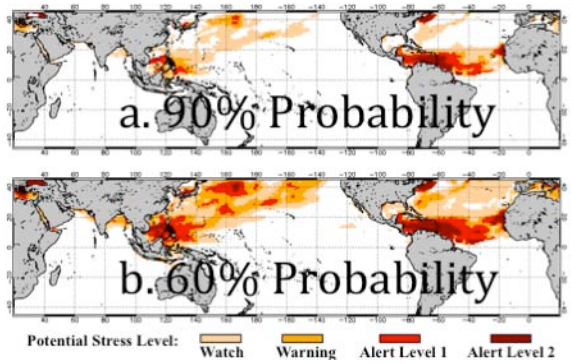

Figure 1: Outlook charts for Aug. – Nov. 2010 from 3 Aug. initial conditions. Map shows areas with 90% (a) and 60% (b) likelihoods of reaching each of the four thermal stress levels.

Note that these maps provide the likelihood of stressful temperatures for all ocean waters, even where reefs are not present. This is necessary because marking only reefs on global or regional scale maps would make them almost impossible to see, and because ocean currents frequently advect waters onto and off of reefs, making conditions in waters surrounding reefs highly pertinent, especially for multi-month composites.

Climatologies for the CRW Bleaching Outlook

CFSv1 monthly SST hindcasts (averaged from daily hindcasts with 15 members per month) for 1985-2006 with lead-time up to nine months were used to derive lead-time dependent monthly mean SST climatologies. The result was one value for each grid cell for each calendar month for each lead-time from 1 to 270 days after initial conditions, from which the maximum monthly mean (MMM) SST value was picked for each grid cell and lead-time. CRW's current operational satellite-based products use a climatology derived from the period 1985-1990 plus 1993. To avoid introducing a bias due to oceanic warming over recent decades, for each grid point the 1985-2006 time series of CFS monthly SST hindcasts were linearly detrended to October 1988, the centroid of the time period used for the operational climatology. The CFSv1 climatology was then calculated by averaging the bias-adjusted means for each month and lead-time. A climatology for OISST data was derived in the same fashion using daily values from 1985-2006. These follow the methodology being used to derive CRW's new high-resolution climatologies from 1985-2010 Pathfinder satellite-SSTs.

Results

Bleaching Outlook Forecasts of 2005-2011

Bleaching outlooks for years 2005-2011 were produced based on archived daily CFSv1 SST real-time forecasts. The seasonal outlook for Aug. – Nov.

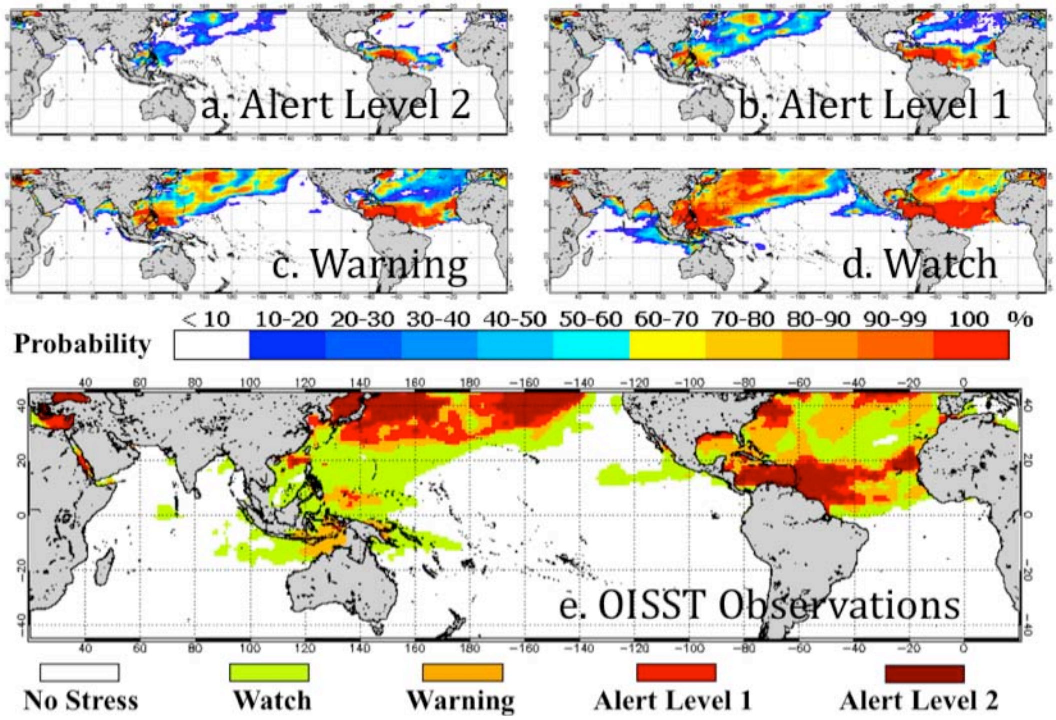

Figure 1: Forecast of August – November 2010 from 3 Aug. initial conditions (a-d) shown from 0-100% likelihood. The observed thermal stress levels calculated from OISST are shown for comparison (e).

2010, when major bleaching occurred in the southern Caribbean, based on the initial conditions on 3 Aug. 2010, is presented in Fig. 2 a-d. The maximum composite of the weekly OISST Bleaching Alert Area images for the corresponding outlook season are provided in Fig. 2e for comparison.

Skill Analysis for Weekly CFSv1 SSTs

Weekly anomaly correlations were calculated between CFSv1 SST real-time forecasts for years 2005-2011 and observed OISST at 1°x1° resolution. The CFSv1 SSTs are ensemble means of 2 forecast runs during Feb. 2005 – Dec. 2007 and 4 forecast runs thereafter. Weekly SST anomalies are the means of seven daily SST anomalies. The daily anomalies were calculated as the SSTs minus the daily climatologies developed from years 1981-2006. The anomaly correlations (skill) for lead-time of week 1 through week 12 are shown in Figure 3. While SST in the Niño-3.4 region (Trenberth 1997) is probably the single most predictable entity, the CFSv1 was not tuned to enhance SST forecast skill for any particular region of the oceans. Significant skill was seen in SST forecasts through week 12 for many coral reef regions, including the central Pacific Ocean, the Caribbean Sea, and the main Hawai'ian islands. However, skill drops off earlier in other regions, including the Indian Ocean, the Coral Triangle, and the Great Barrier Reef. Interestingly, much lower skill after week four was found for the Gulf of Mexico and around Florida than for the Caribbean Sea.

Skill analyses for the seasonal thermal stress outlooks will be performed as part of the ongoing conversion to CFS version 2. However, as thermal stress is derived from SST, forecasts of thermal stress should be no more skillful than SST forecasts and is likely to follow a similar pattern.

Discussion

This new seasonal outlook system has significant advantages over CRW's earlier seasonal bleaching outlook (Liu et al. 2009). The new system provides users with probabilistic forecasts, increased information content, and quantified degree of certainty and uncertainty of potential future bleaching events. This provides resource managers with a much improved information base upon which to choose whether to take action well in advance of the event or take a wait-and-see approach. Additionally, the use of an operational NOAA forecast model to build the new system means that continued advances in the Climate Forecast System should be easily transitioned into the seasonal bleaching outlooks. In fact, NCEP recently made version 2.0 of the CFS operational. NCEP and CRW are transitioning CFSv2 SST forecasts into the new seasonal bleaching outlook and to develop a full skill analysis of the system. CRW expects to implement CFSv2-based outlooks in late 2012.

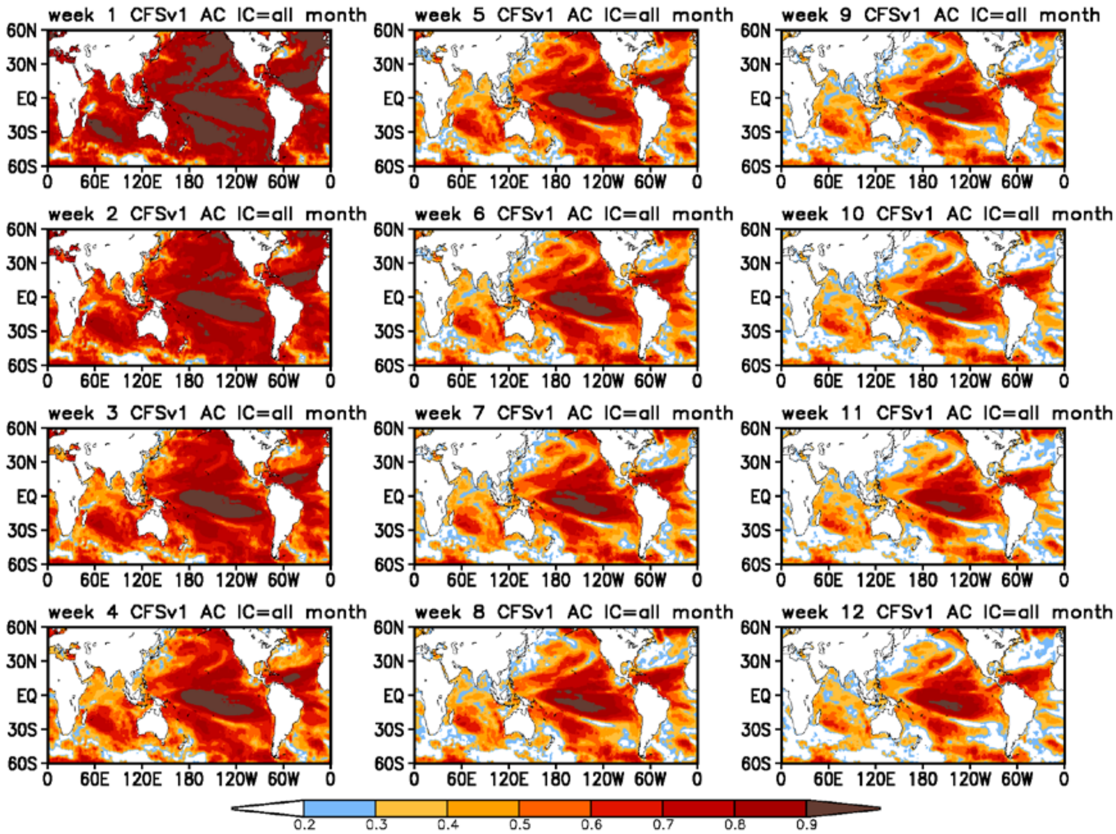

Figure 3: CFSv1 Weekly SST anomaly correlation from all months' initial conditions. Significant skill is seen in certain regions, including Niño 3.4 and the Caribbean, through week 12 while skill drops off earlier in other regions, including the Great Barrier Reef.

The Australian Bureau of Meteorology released a similar dynamical, ensemble-based coral bleaching prediction system built from their Predictive Ocean Atmosphere Model for Australia (POAMA) (Spillman et al. 2011). Where both systems are available, outlooks from the two systems can be compared to better inform resource managers when bleaching threats arise. High confidence in systems such as these increase managers' confidence prior to taking costly or controversial actions to protect corals when bleaching is expected (Maynard et al. 2009).

Acknowledgement

We are grateful for funding from the National Oceanic and Atmospheric Administration's Coral Reef Conservation Program and the National Centers for Environmental Prediction. The manuscript contents are solely the opinions of the authors and do not constitute a statement of policy, decision, or position on behalf of NOAA or the US Government.

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