Climate Goal II: Modeling and Forecasting

Mark Eakin, Coral Reef Watch

Includes a variety of products from

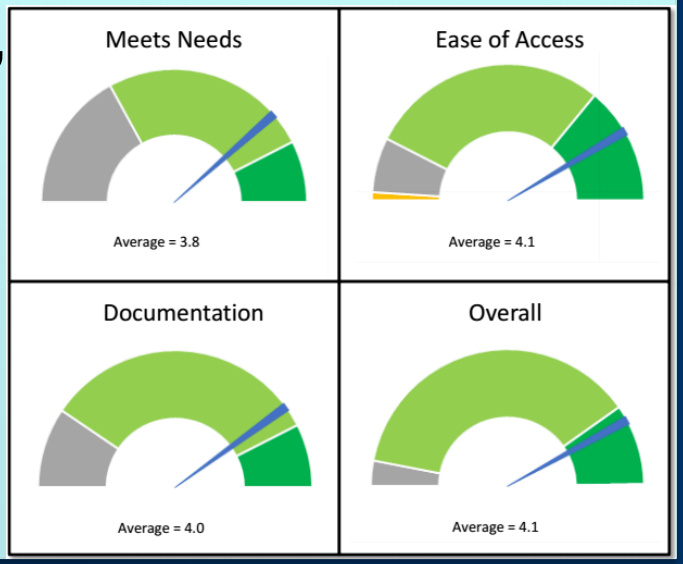
- **Satellites**
- **Ocean-Atmosphere Climate Models**
- **Derived Forecasts (e.g., coral disease)**

Climate Goal II: Modeling and Forecasting

From Coral Managers' Survey:

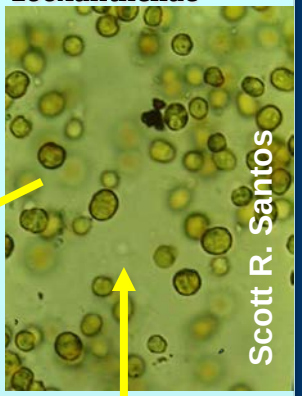
- #6 (3.5) Importance
- #2 (43%) "Top Five" list
- #2 Most used

- #1 (3.8) for Meeting Respondents' Needs
- #1 (4.1) for Ease of Access
- #1 (4.0) for Documentation
- #1 (4.1) for Overall Satisfaction

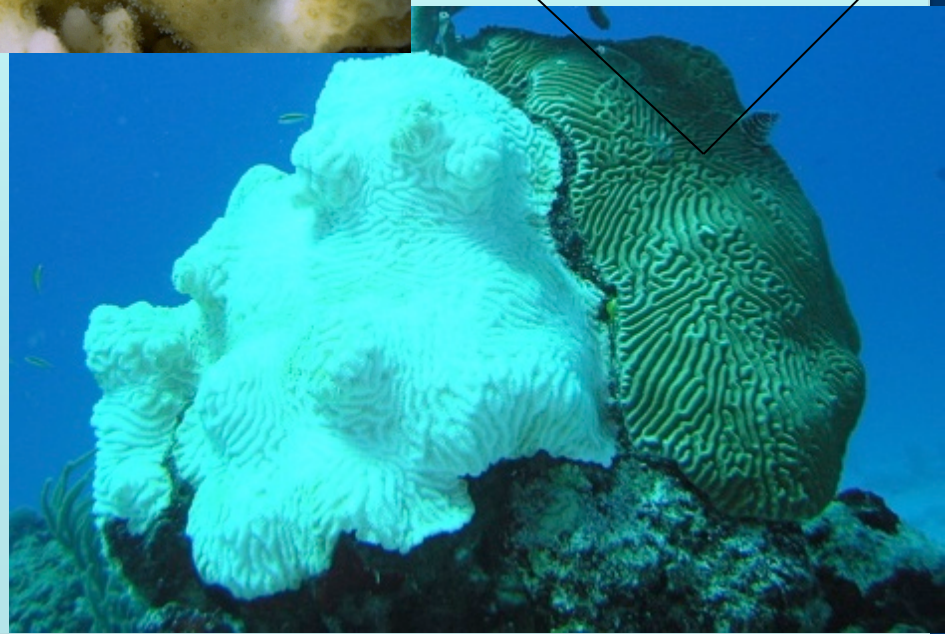


What is Coral Bleaching?

- Most of corals' food comes from photosynthesis
- Corals can "bleach" due to stress
- Corals exposed to high temperatures and/or high light become stressed
- Corals eject their algae; coral appears "bleached"
- If stress is mild or brief, corals recover, otherwise they die



Symbiotic algae



NOAA Coral Reef Conservation Program

American Samoa, December 2014

XL CATLIN SEAVIEW™ SURVEY

NOAA Coral Reef Conservation Program

American Samoa, February 2015

XL CATLIN SEAVIEW™ SURVEY

NOAA Coral Reef Conservation Program

American Samoa, August 2015

XL CATLIN SEAVIEW™ SURVEY

NOAA Coral Reef Conservation Program

Coral Reef Watch – Satellite Products for Coral Reef Managers – Mark Eakin & CRW Team

- Transition old 50km products to next-generation 5km system
- 100x higher resolution, up to 50X more data per pixel
- Enhancements underway to bring 5km to all CRW products
- Higher Resolution products has been the #1 User Request

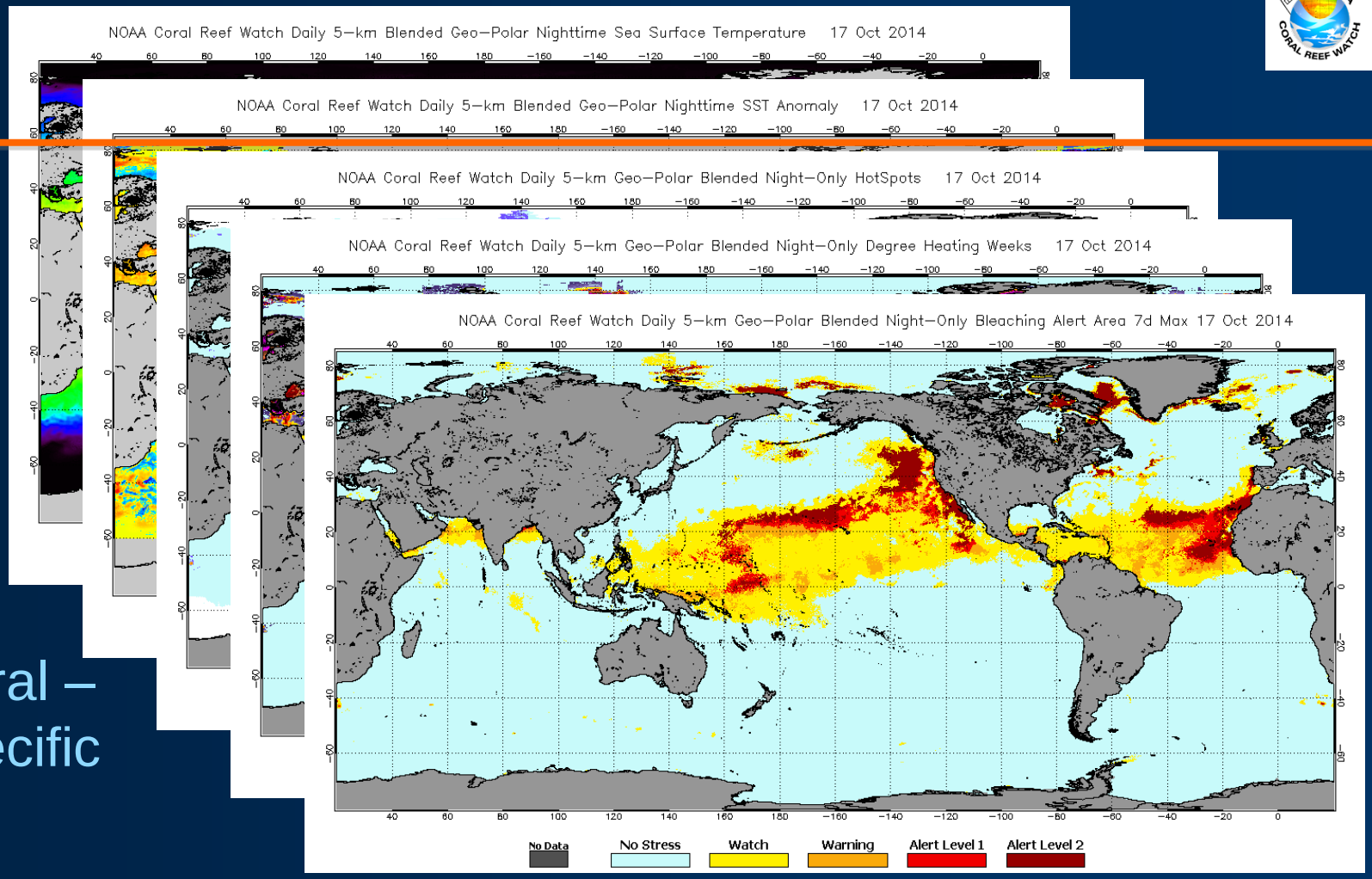
<u>50 km Polar-only (Operational)</u>

- Climatology: 7 year, 50 km (AVHRR)
- Polar-orbiter (1), Max 1 nighttime scene/day

<u>5 km Geostationary-Polar Blend</u>

- Climatology: 22 year, 4 km (Pathfinder AVHRR)
- Polar-orbiters (2) + Geostationary (4), Up to 50 scenes/day

Coral Reef Watch: 5-km Satellite-Based Products

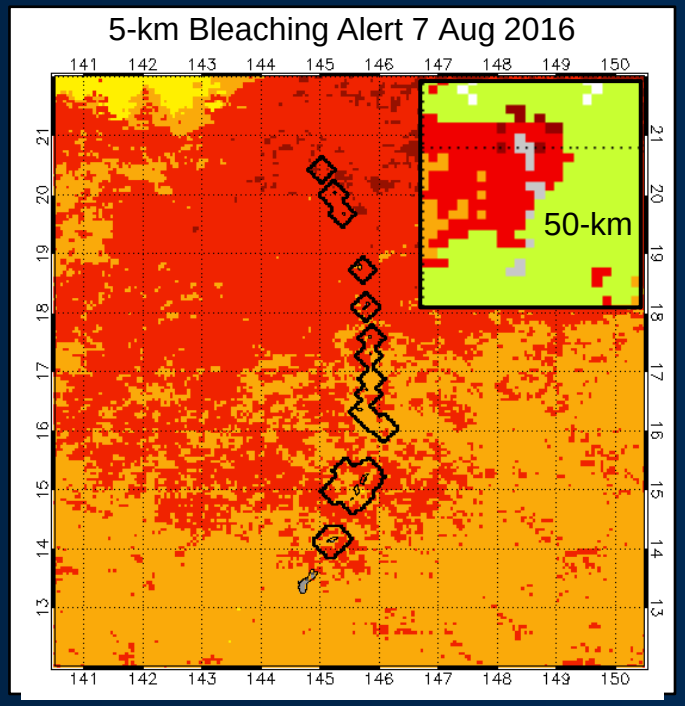


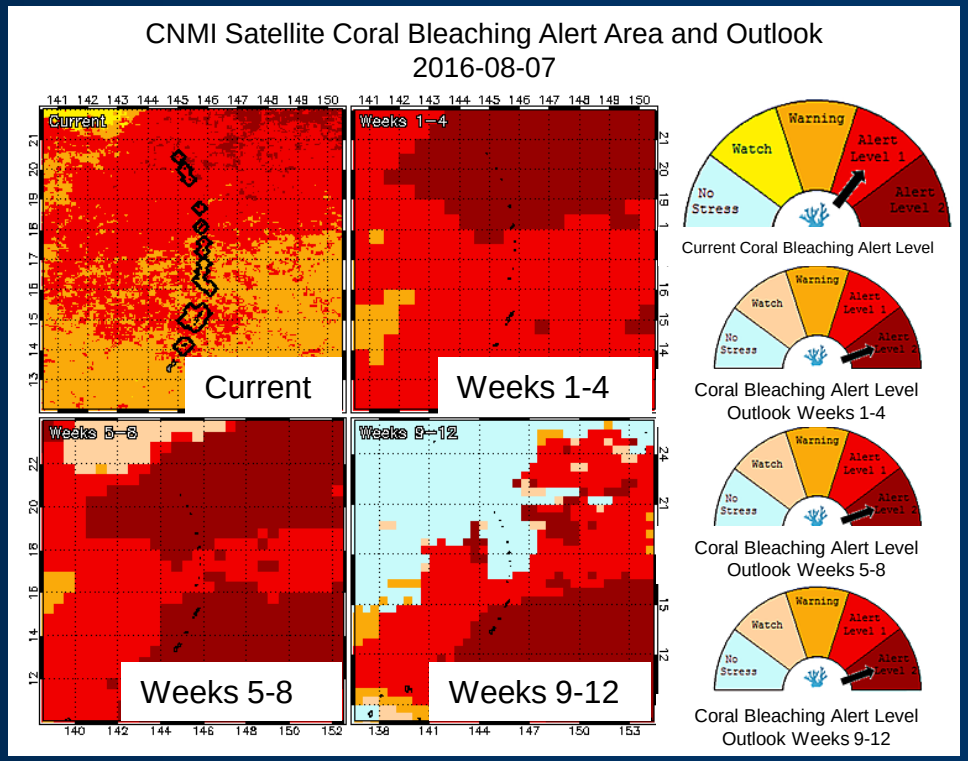
Coral – specific

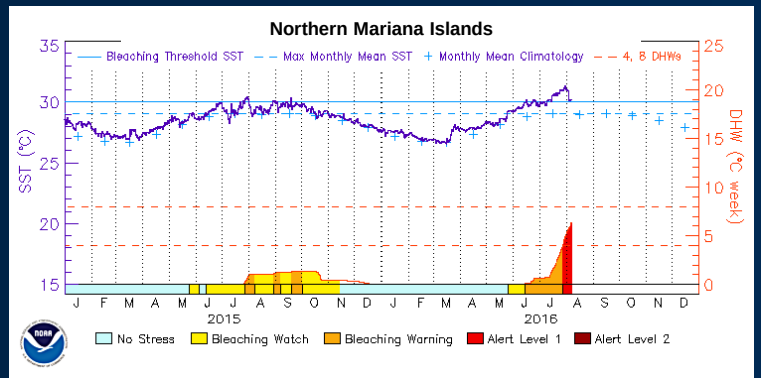
Bleaching Alert Area

NOAA Coral Reef Conservation Program

Coral Reef Watch – Satellite Products for Coral Reef Managers – Mark Eakin & CRW Team

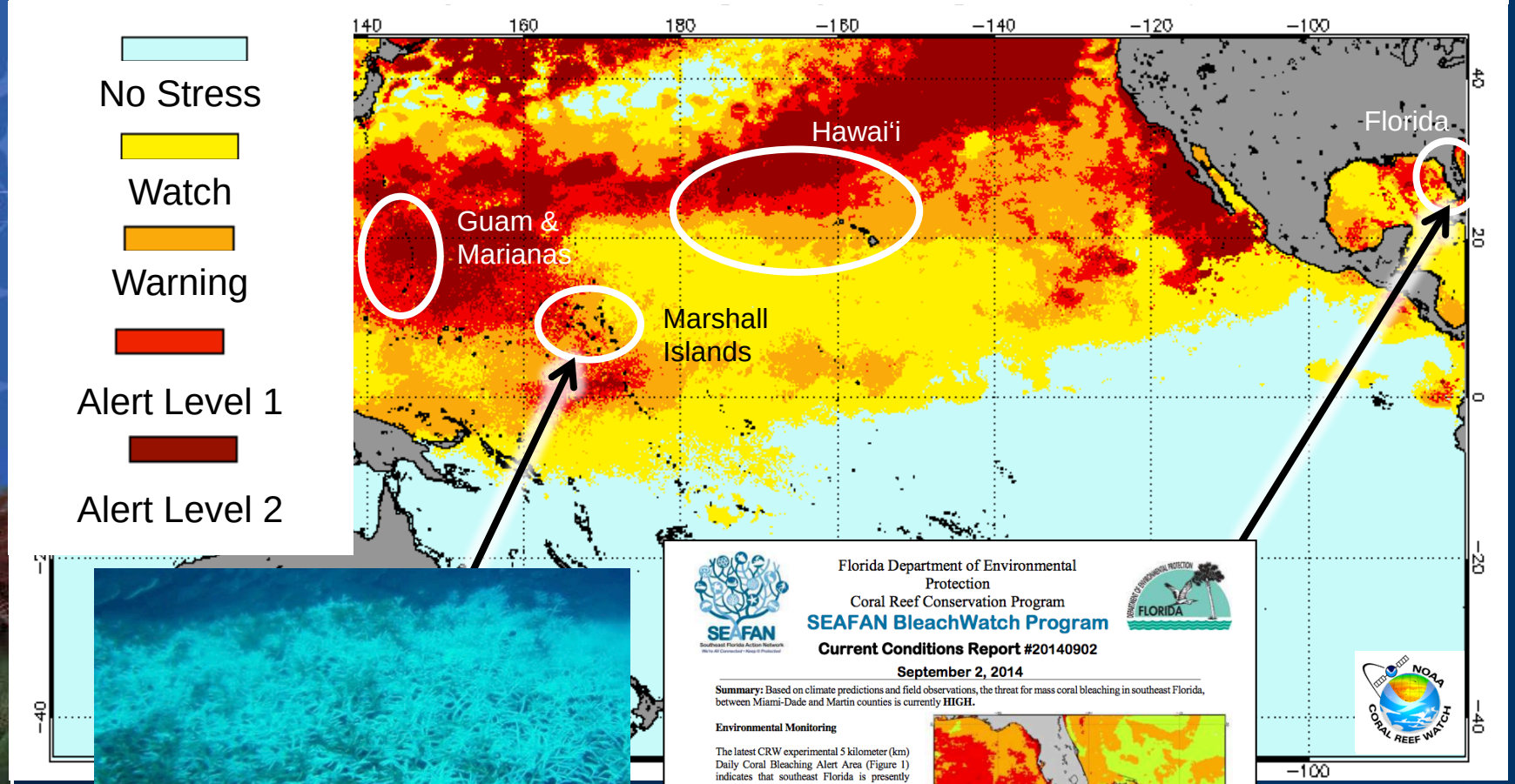


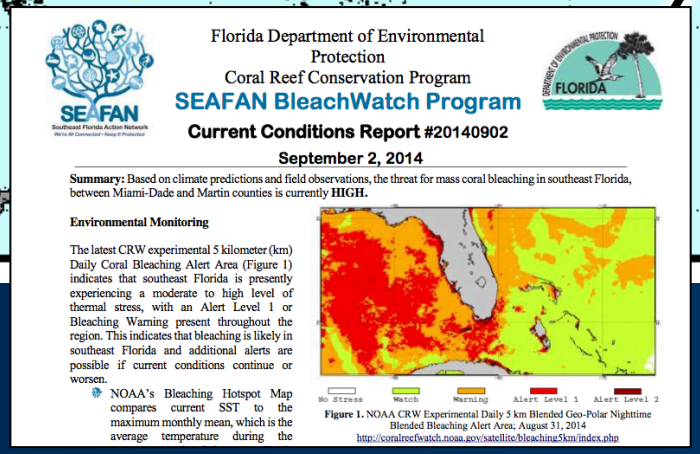




NOAA Coral Reef Conservation Program

NOAA Coral Reef Watch Annual Maximum Satellite Coral Bleaching Alert Area 2014





Florida Department of Environmental Protection
Coral Reef Conservation Program

SEAFAN BleachWatch Program

Current Conditions Report #20140902

September 2, 2014

Summary: Based on climate predictions and field observations, the threat for mass coral bleaching in southeast Florida, between Miami-Dade and Martin counties is currently **HIGH.**

Environmental Monitoring

The latest CRW experimental 5 kilometer (km) Daily Coral Bleaching Alert Area (Figure 1) indicates that southeast Florida is presently experiencing a moderate to high level of thermal stress, with an Alert Level 1 or Bleaching Warning present throughout the region. This indicates that bleaching is likely in southeast Florida and additional alerts are possible if current conditions continue or worsen.

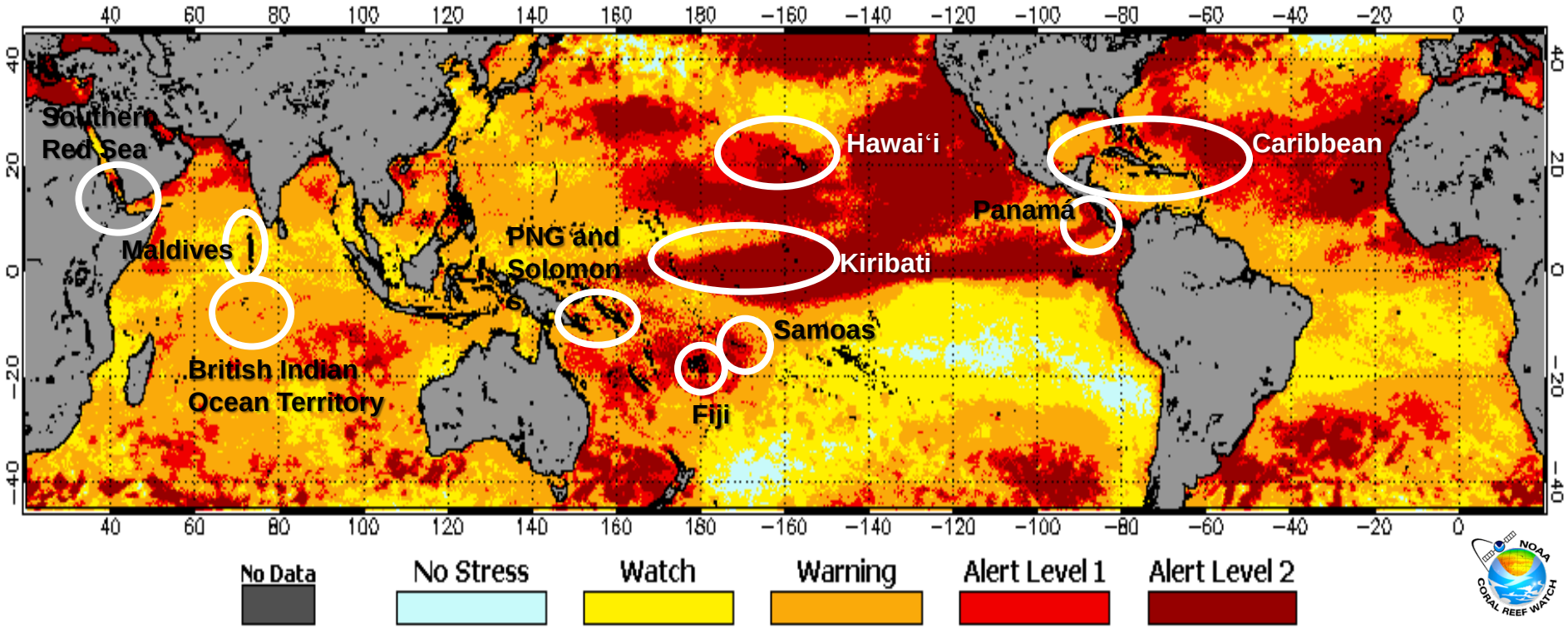
- NOAA's Bleaching Hotspot Map compares current SST to the maximum monthly mean, which is the average temperature during the

No Stress | Watch | Warning | Alert Level 1 | Alert Level 2

Figure 1. NOAA CRW Experimental Daily 5 km Blended Geo-Polar Nighttime Blended Bleaching Alert Area; August 31, 2014
http://coralreefwatch.noaa.gov/satellite/bleaching5km/index.php

NOAA Coral Reef Conservation Program

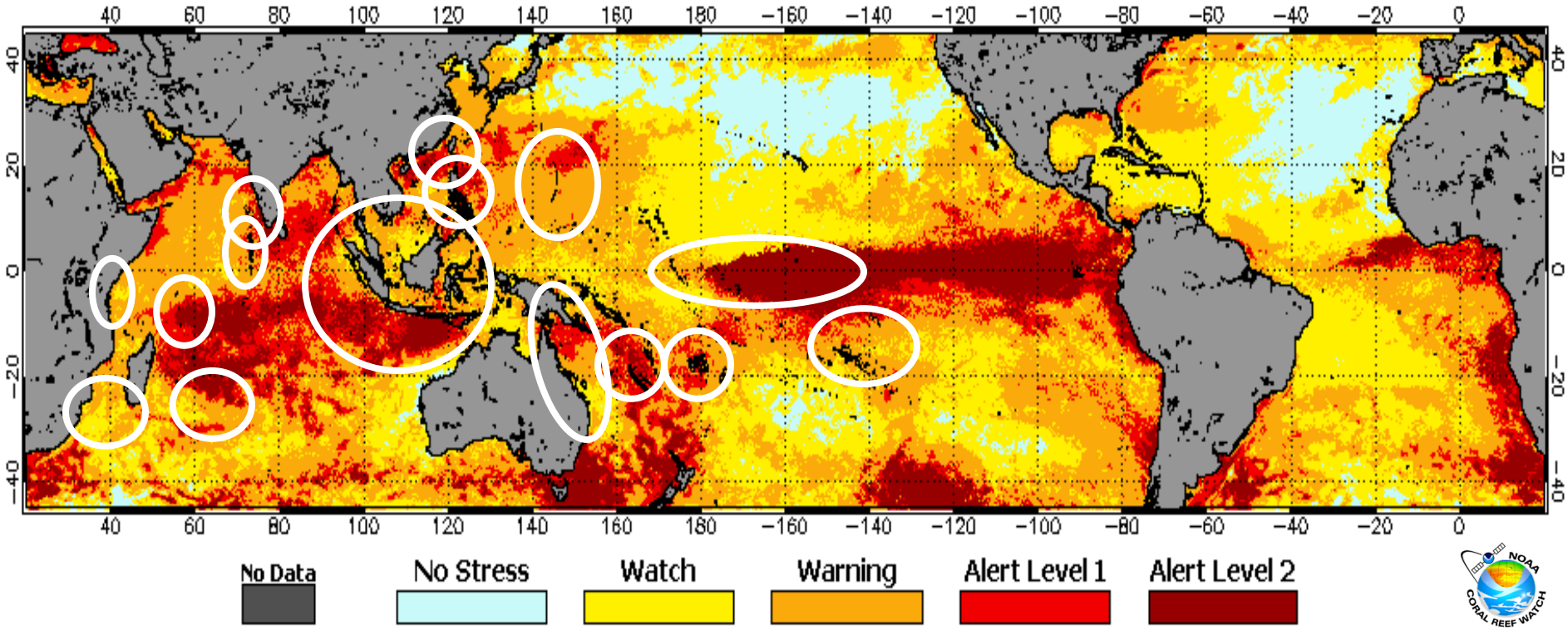
NOAA Coral Reef Watch Annual Maximum Satellite Coral Bleaching Alert Area 2015



"We use Coral Reef Watch bleaching products as triggers for our bleaching response and BleachWatch community engagement programs" – CRCP Coral Managers Survey

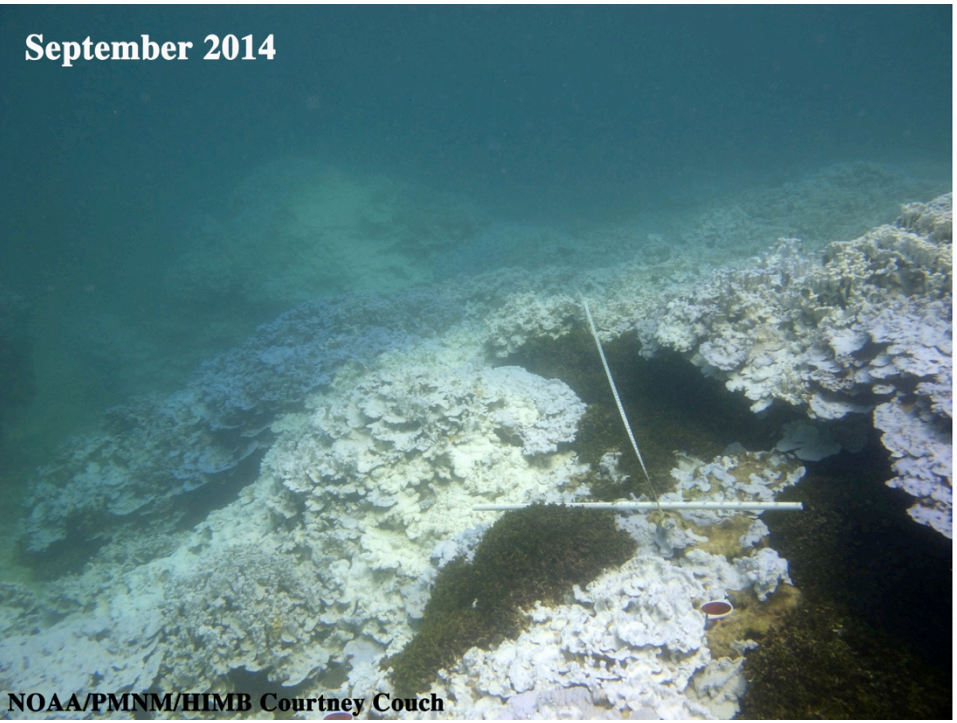
NOAA Coral Reef Conservation Program

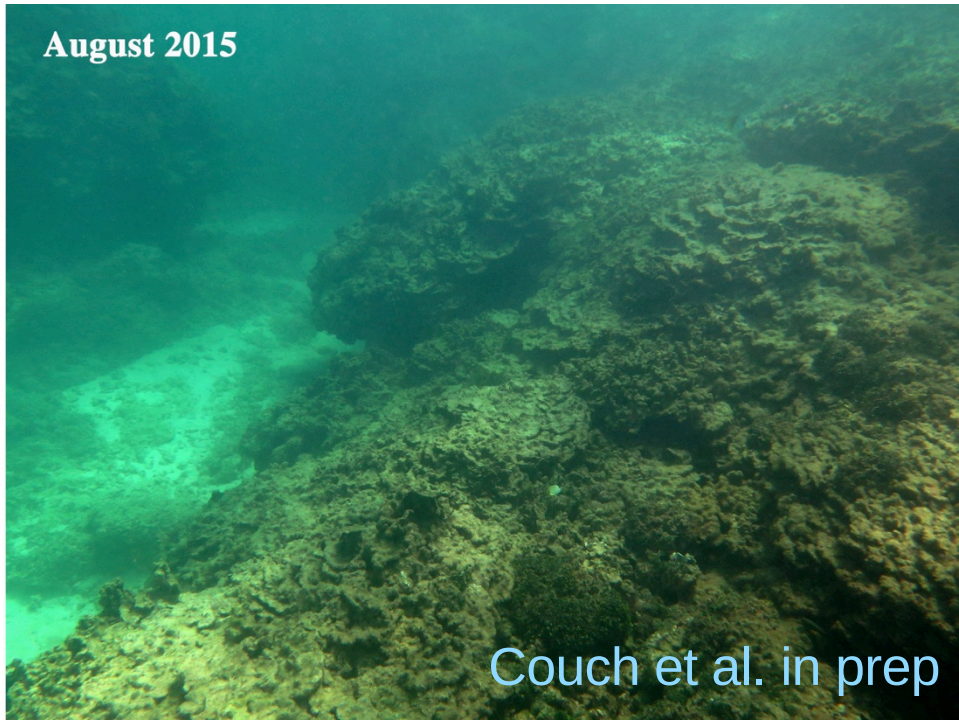
NOAA Coral Reef Watch Maximum Satellite Coral Bleaching Alert Area 1 Jan – 31 July 2016



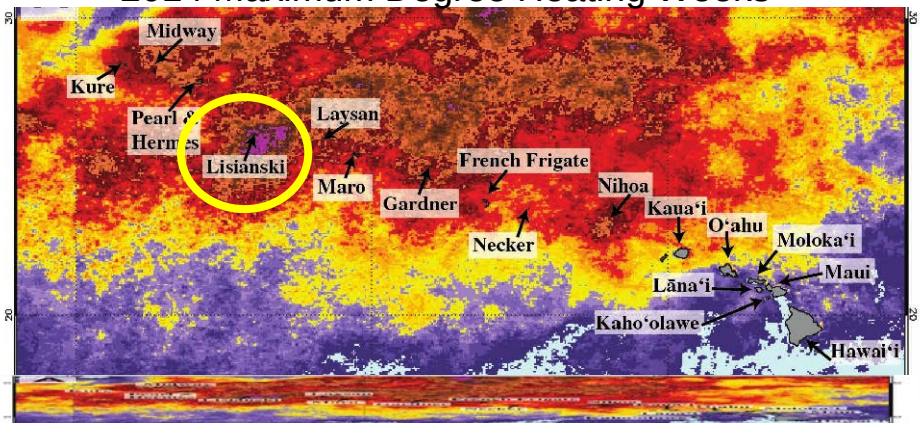
	Western India	Taiwan	Guam/CNMI
Seychelles	Maldives	Vietnam	Kiribati
Kenya/Tanzania	Réunion	Thailand	New Caledonia
Mozambique	Indonesia	Philippines	Fiji
Madagascar	Mauritius	E. Australia	French Polynesia

NOAA Coral Reef Conservation Program





2014 Maximum Degree Heating Weeks



Hi Mark,

27 August 2014

CRW did it again… based on DHW graphs, it looked like Lisianski is starting to toast, and Laysan, Midway, and Pearl and Hermes are just a hair cooler.

Many thanks for excellent and useful products.

Aloha, Randy Kosaki

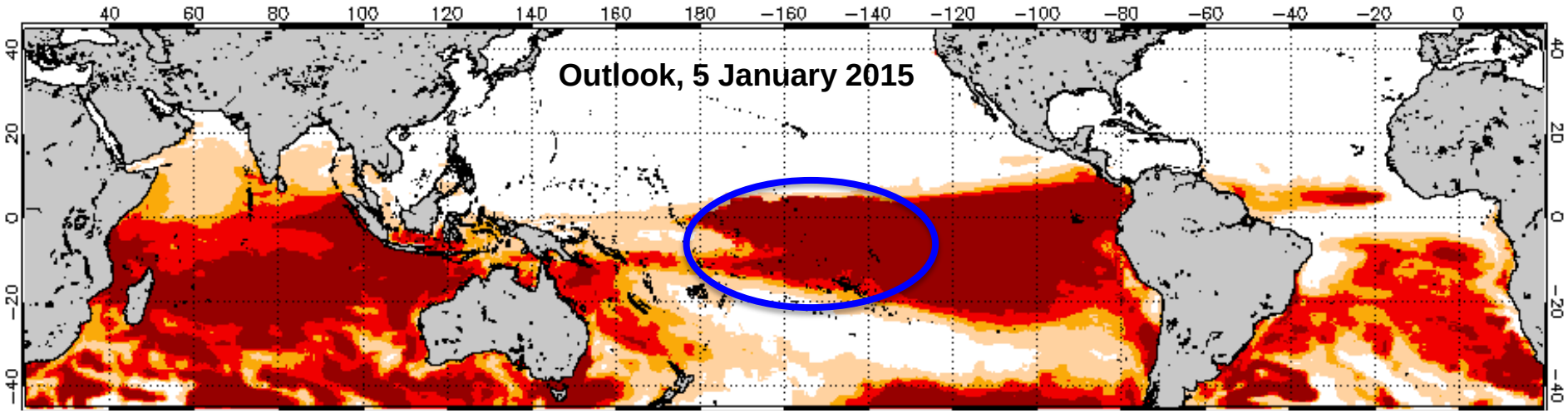
Great Barrier Reef Bleaching: 2016

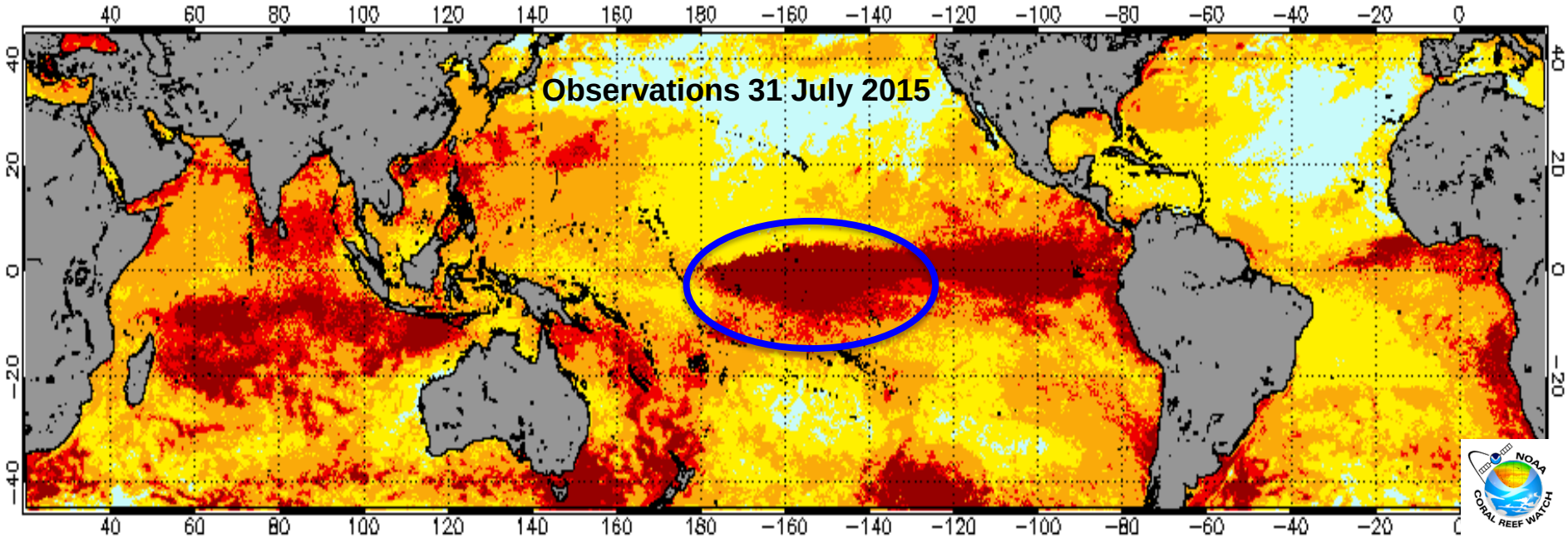
Lizard Island Mortality: 2016

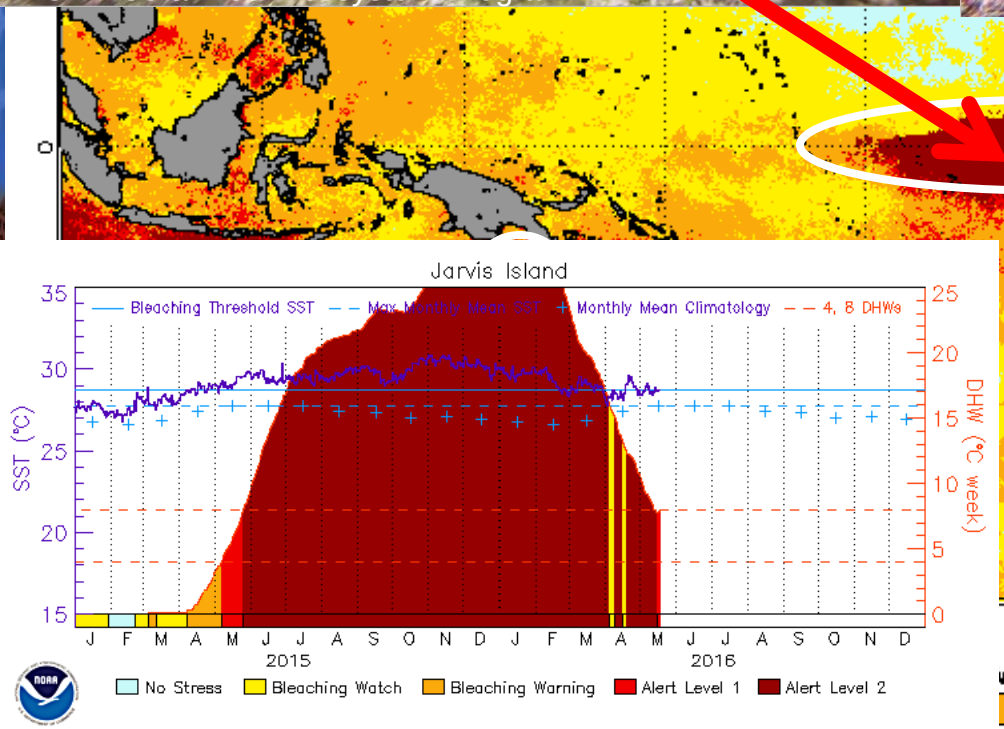
XL CATLIN SEAVIEW™ SURVEY

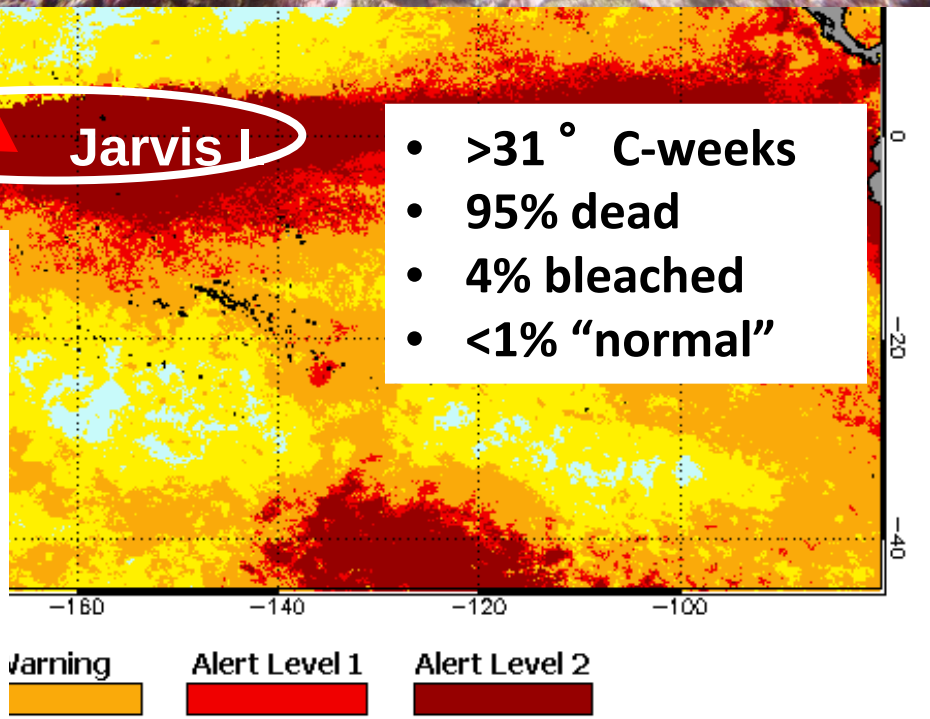
The lack of fish was an indication that there was “complete ecosystem collapse”
Justin Marshall, Univ. of Queensland
The Guardian 21 July 2016

NOAA Coral Reef Conservation Program









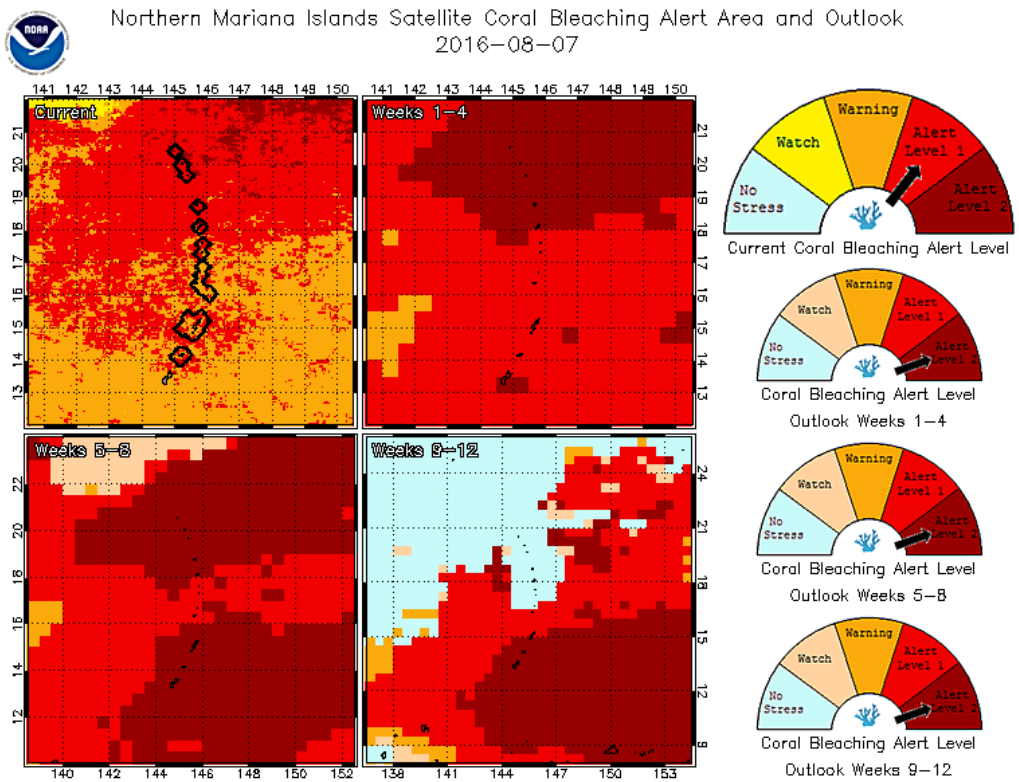
- >31 ° C-weeks
- 95% dead
- 4% bleached
- <1% “normal”

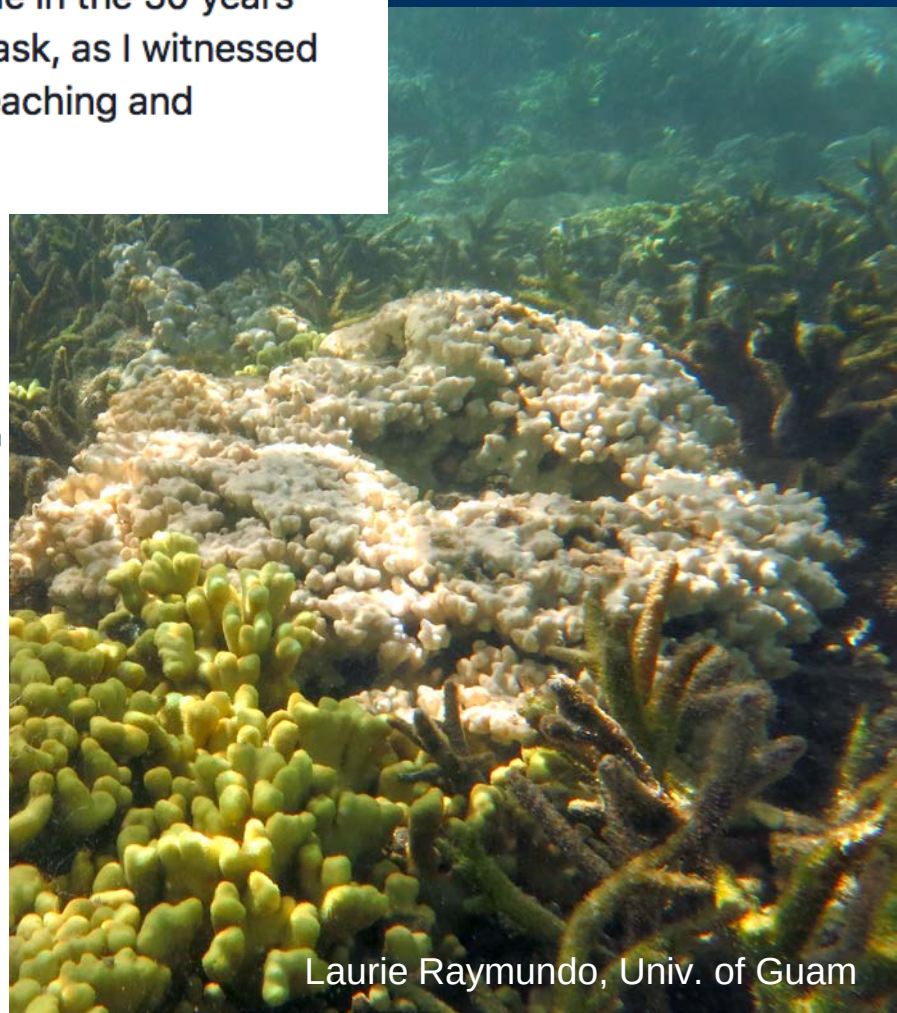
NOAA Coral Reef Conservation Program

Laurie Raymundo

July 29 at 4:55pm ·

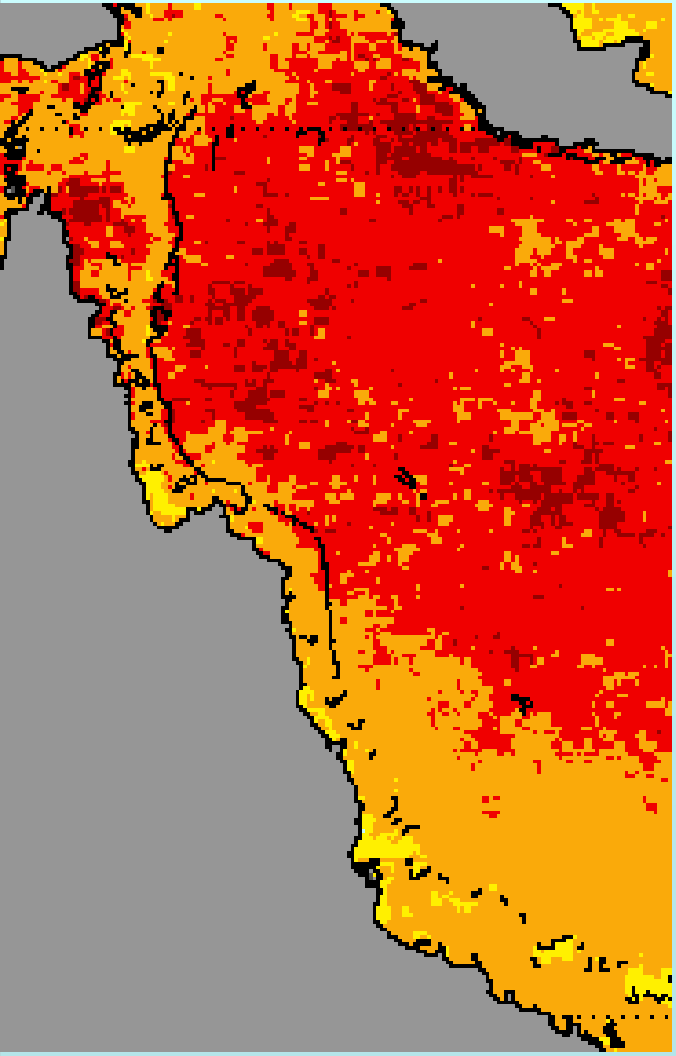
I consider myself to be fairly objective and logical about science. But sometimes that approach fails me. Today, for the first time in the 50 years I've been in the water, I cried for an hour, right into my mask, as I witnessed the extent to which our lovely Tumon Bay corals were bleaching and dying....And it's only July....

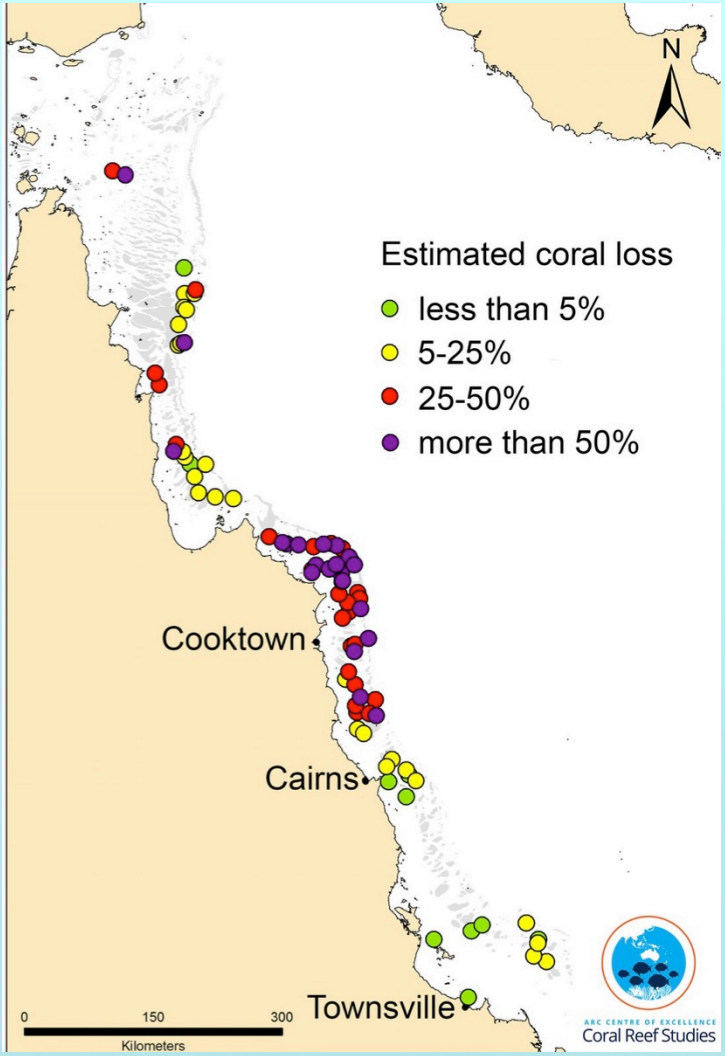




Laurie Raymundo, Univ. of Guam

2016 Mismatch with bleaching: GBR, Coral Triangle, Hawaii





Good News:

- CRW products very useful as a "warning" product

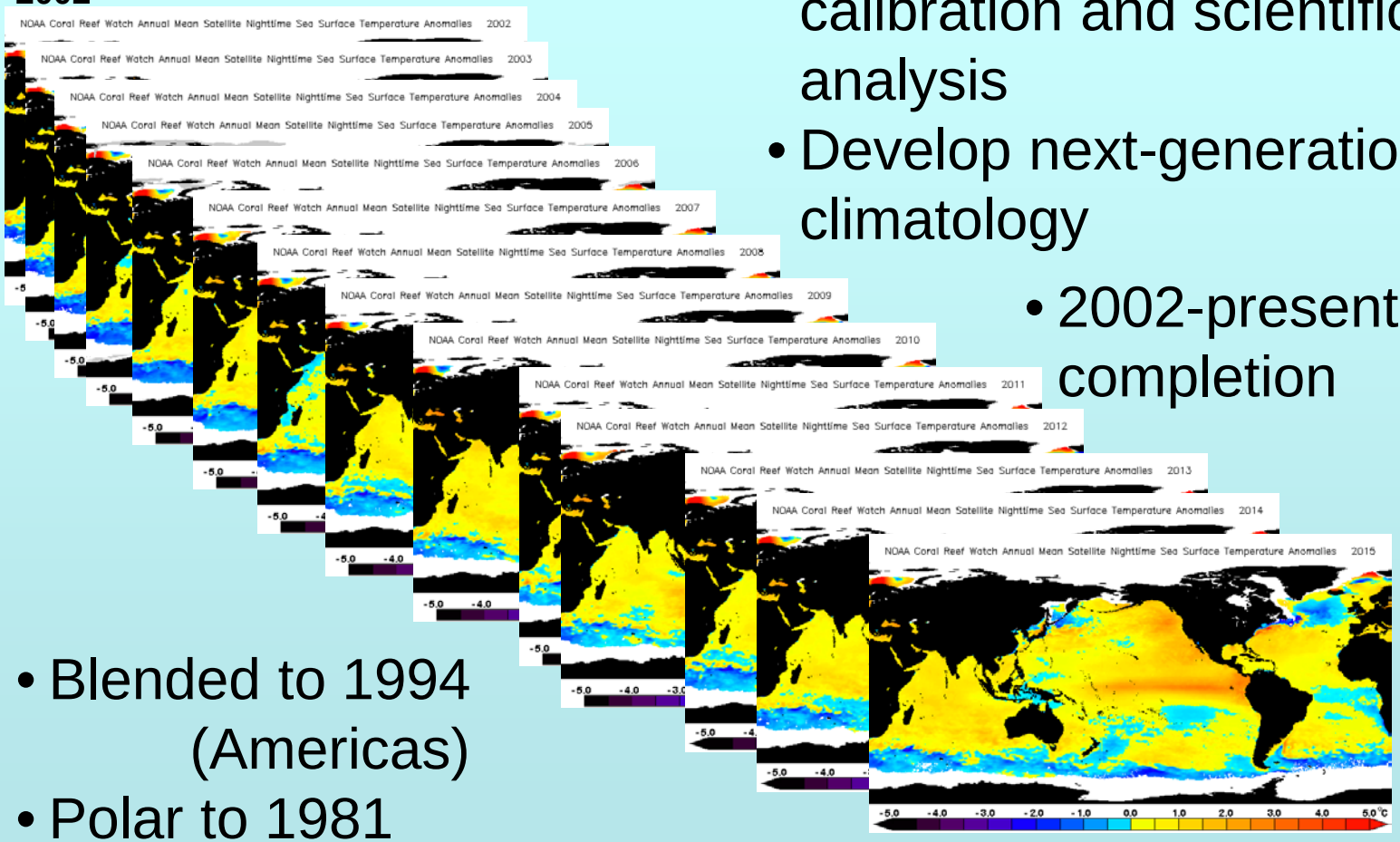
Bad News:

- Mismatch at finer scale
- Major issue climatology from Pathfinder, not SST
- Bleaching observations in most areas inadequate to detect

5 km Geo-Polar Reprocessing

- Consistent dataset for calibration and scientific analysis
- Develop next-generation climatology

2002



2015

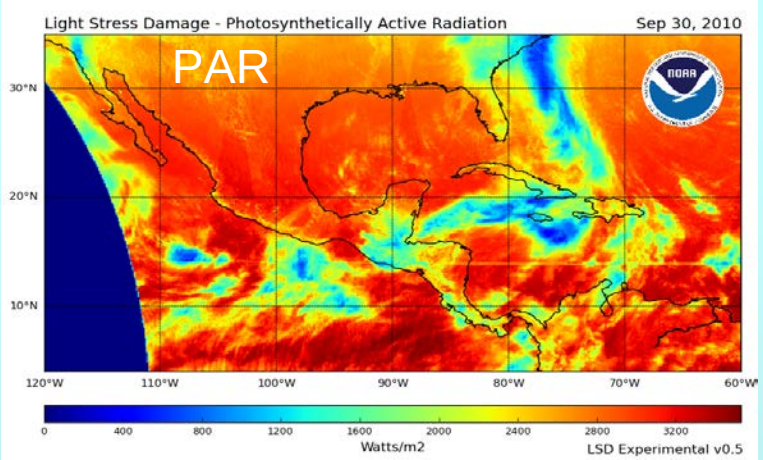
- 2002-present near completion

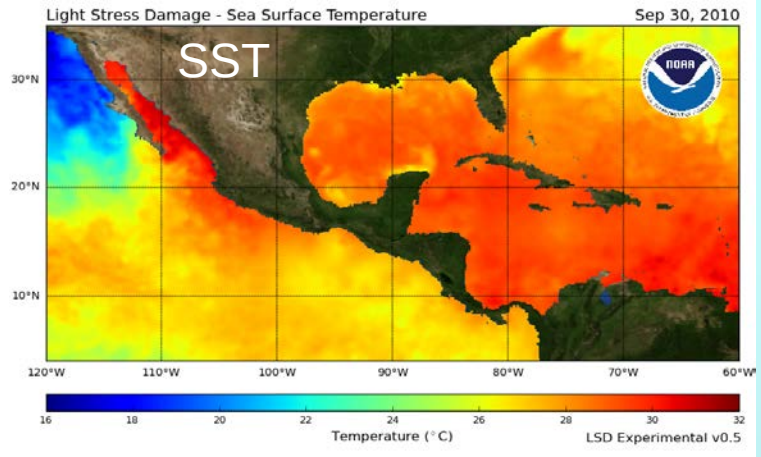
- Blended to 1994 (Americas)
- Polar to 1981
- ~974K funding (7% Coral Program)

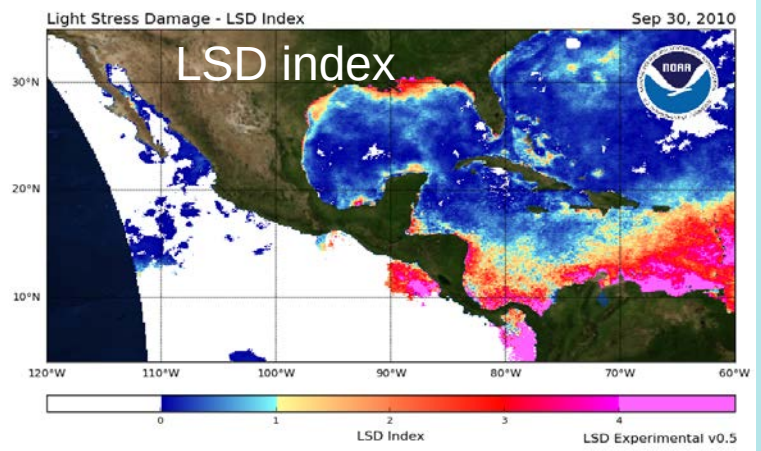
NOAA Coral Reef Conservation Program

Coral Reef Watch – Satellite Products for Coral Reef Managers – Mark Eakin & CRW Team

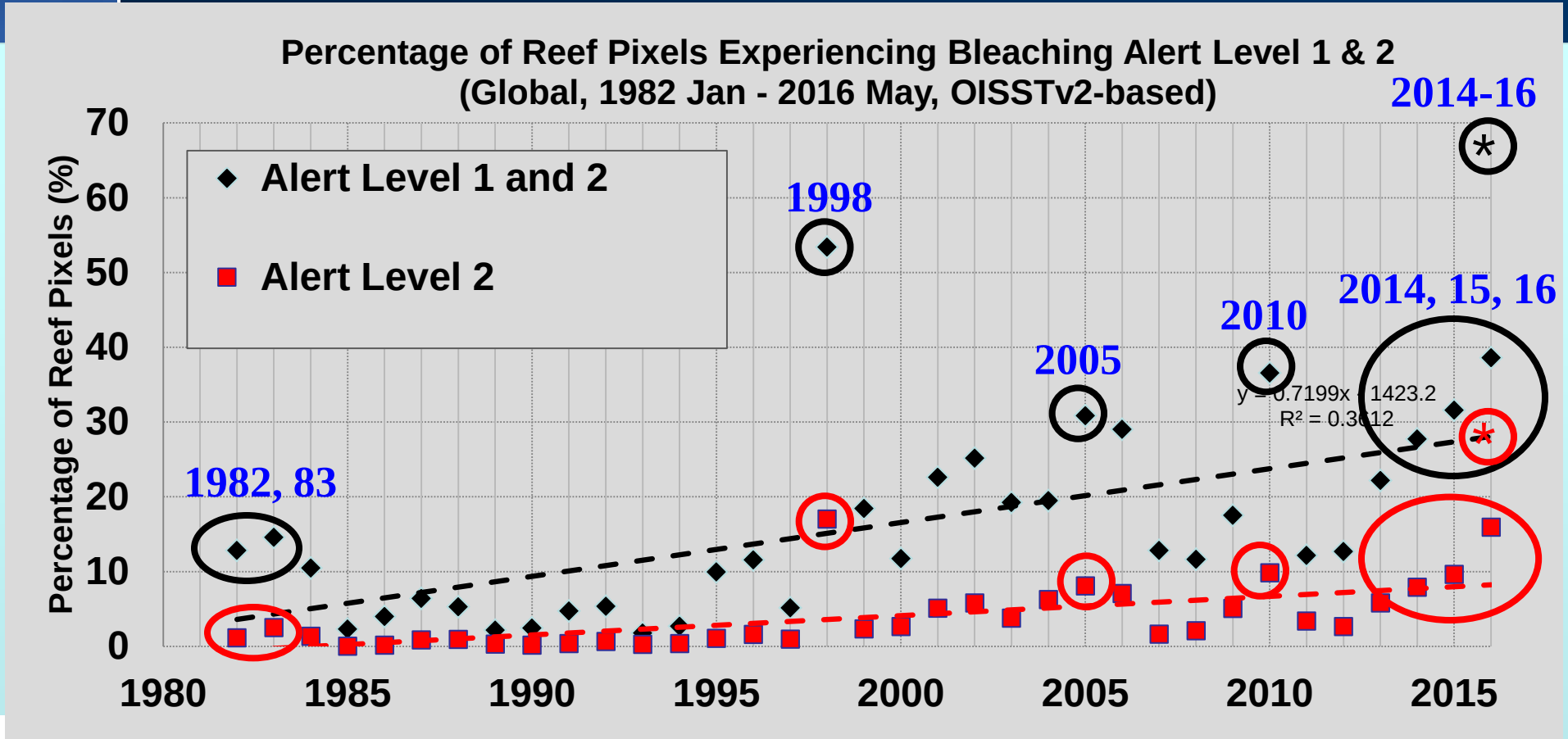
Light Stress Damage Product







NOAA Coral Reef Conservation Program



Ocean Warms, Bleaching Increases

NOAA CORAL REEF CONSERVATION PROGRAM

NOAA Coral Reef Watch Team
http://coralreefwatch.noaa.gov

Mark Eakin

Jacqueline De La Cour (GST)

Gang Liu (GST)

Kyle Tirak (GST)

Erick Geiger (GST)

Alan Strong (GST & SRI)

William Skirving (GST & ReefSense)

Scott Heron (GST & ReefSense)

Andrea Gomez (CCNY & NOAA-CREST)

NESDIS National Environmental Satellite, Data and Information Service

NOAA NESDIS STAR Center for Satellite Applications and Research

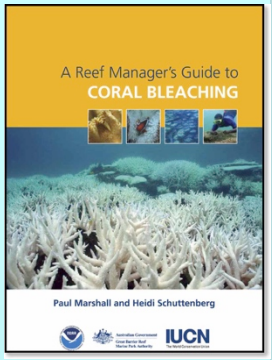
NOAA CORAL REEF CONSERVATION PROGRAM

GLOBAL SCIENCE & TECHNOLOGY, INC.

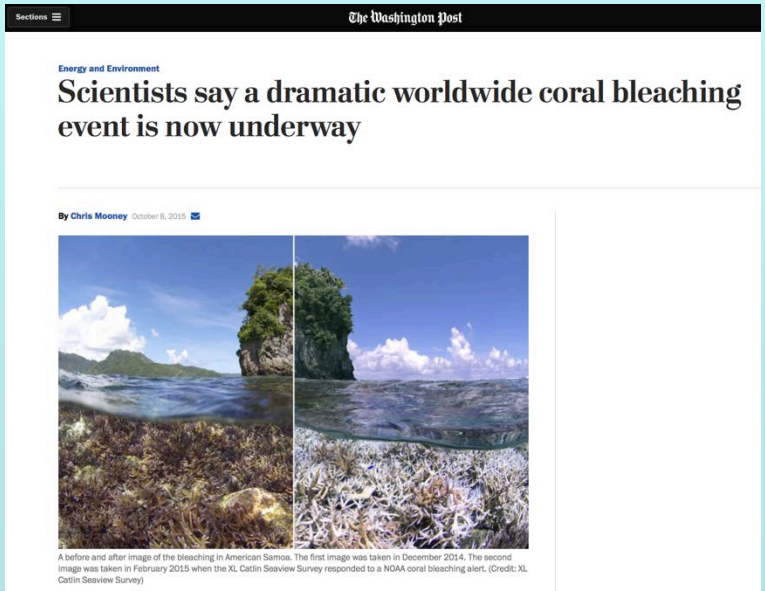
NOAA Coral Reef Conservation Program

Coral Reef Watch – Satellite Products for Coral Reef Managers – Mark Eakin & CRW Team

- All data available online from CRW, E-mail alerts sent to ~750 users
- Analysis products online, provided to NCRMP
- All data archived with CoRIS, NCEI
- Used by managers, scientists worldwide



- 2014-16 event led to major efforts on social media, press



NOAA Coral Reef Conservation Program

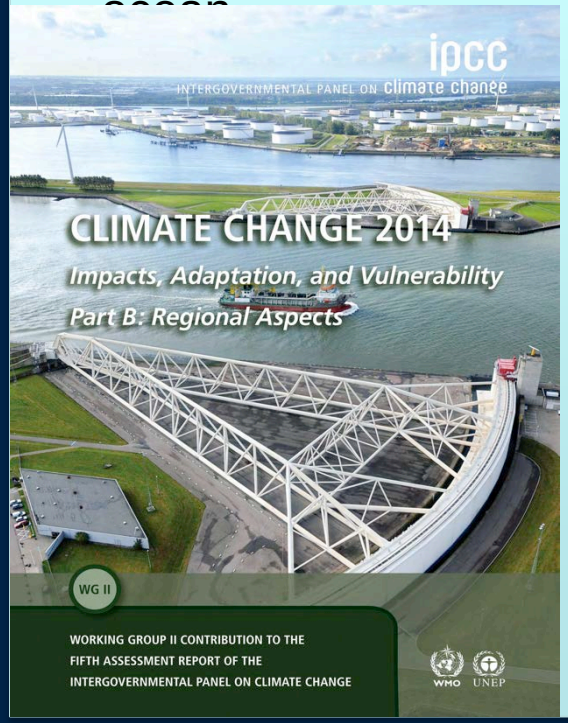
Coral Reef Watch – Satellite Products for Coral Reef Managers – Mark Eakin & CRW Team

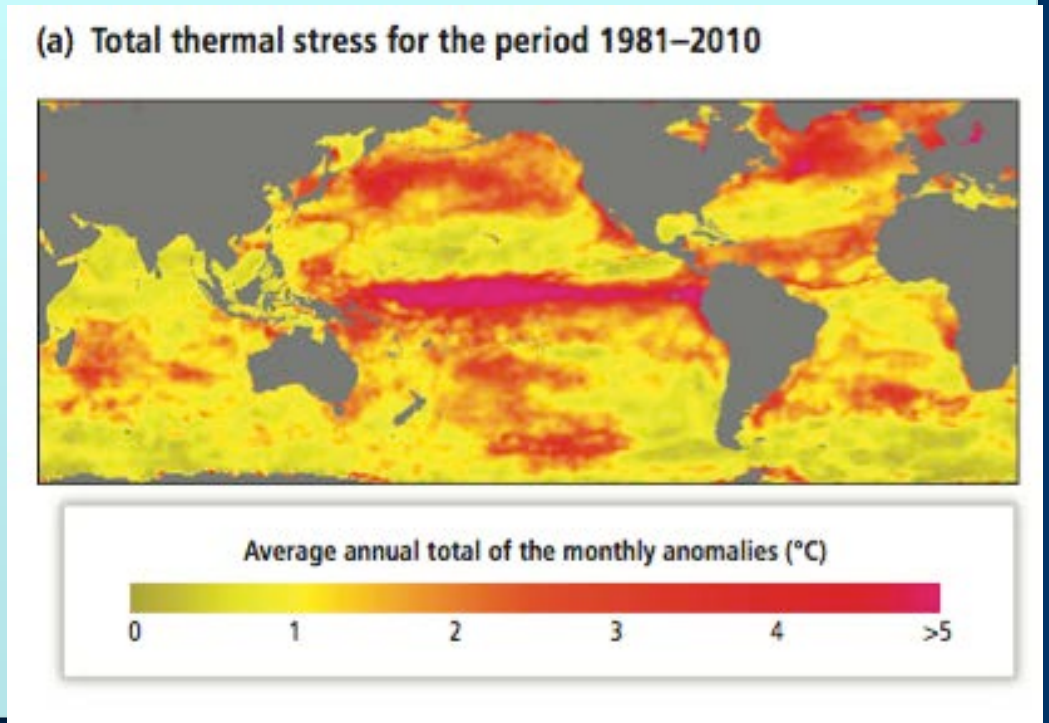
- **Biggest gap:**
  - Lack of international database of bleaching observations
    - GCRMN no longer global
    - ReefBase ineffective since prior to 2010 global bleaching
    - Reef Check data limited to their observations)
- **Biggest concerns:**
  - New Coral Program funding scheme may leave CRW underfunded
  - Likely to stop ocean color development (along with its $500K in matching funds
  - Assure that products are maintained through satellite transitions

NOAA Coral Reef Conservation Program

Coral Reef Watch – Satellite Products for Coral Reef Managers – William Skirving

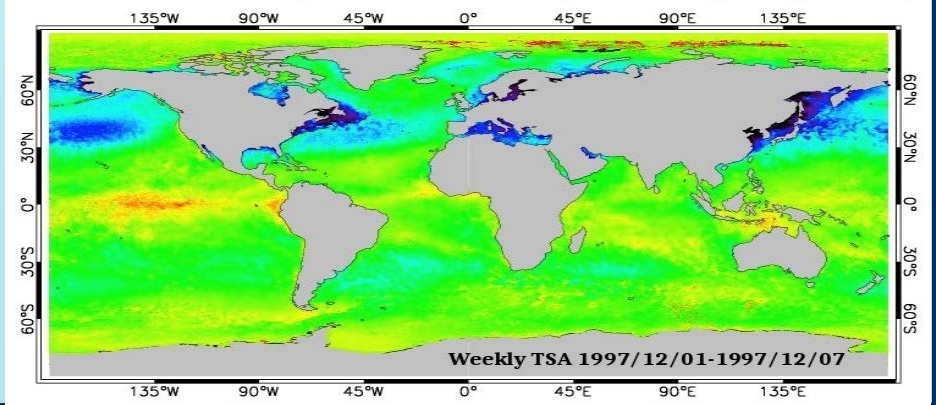
- Coral products for last Intergovernmental Panel on Climate Change 5th Assessment Report (IPCC AR5, WGII)
- First IPCC report with Oceans Chapter
- Key role of CRW methodology in analysis of thermal stress in ocean





The Coral Reef Temperature Anomaly Database – Ken Casey et al.

- Quantifies thermal stress on coral reefs around the world at 4 km resolution 1982-2012 using Pathfinder 5.2, soon to be updated to 2014 based on PFSST 5.3 release (August 2016)
- Available online through NCEI
- Work to be conducted in FY16 on improving the usability of the CoRTAD data set for decision makers
- Developed to investigate relationship between thermal stresses and coral decline



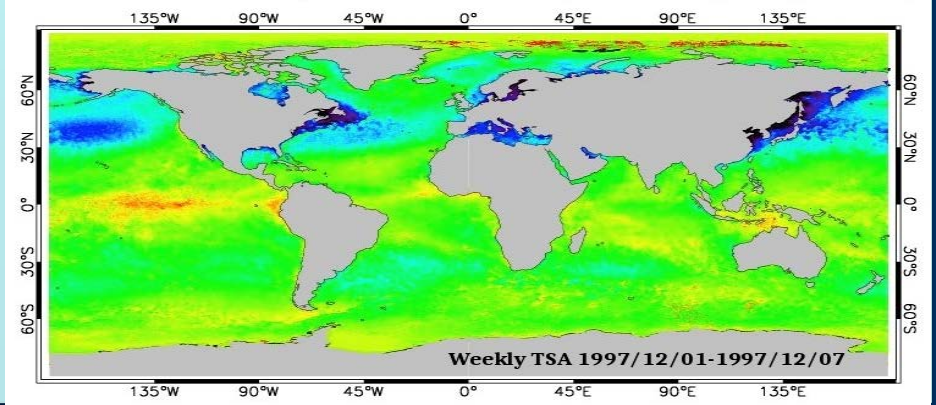
The Coral Reef Temperature Anomaly Database – Ken Casey et al.

- Used in numerous peer-reviewed publications that provide fundamental information needed to design effective management strategies and Marine Protected Areas

- Supports both the development of broad policies and the improvement of specific management actions aimed at reducing coral reef degradation by mitigating climate change effects.

Biggest Concern:

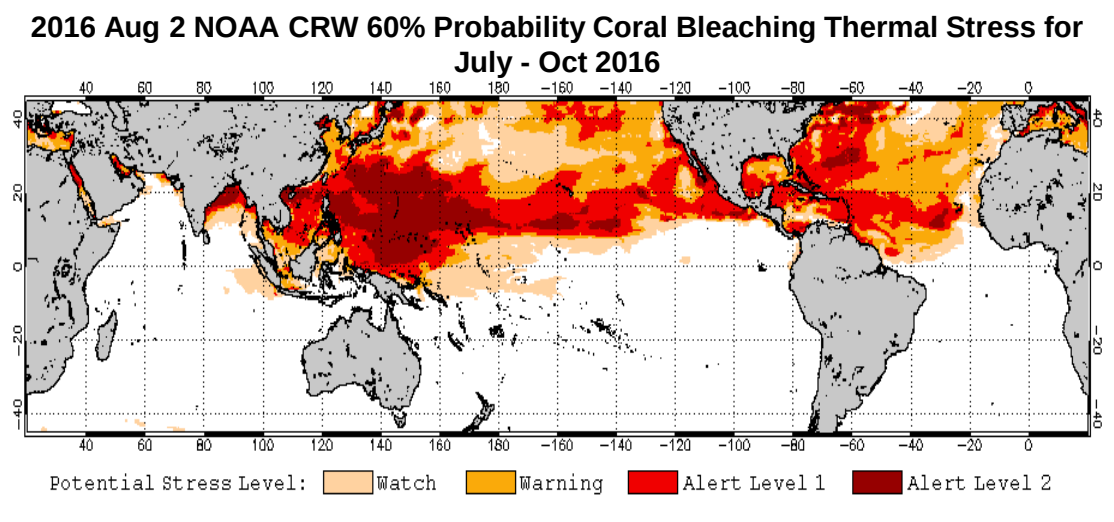
- New Coral Program funding scheme may end CorTAD funding



NOAA Coral Reef Conservation Program

Developing Operational Coral Reef Bleaching Forecasts for Coral Reef Management – Arun Kumar & Gang Liu

- Transition from old statistical model to latest operational dynamical model
- Outlook based on 28 member SST ensemble from NCEP CFSv3
- Further enhancements underway to 112 ensemble members and automated skill statistics
- Outlooks have been #2 user request



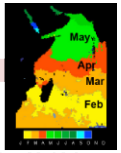
NOAA Coral Reef Conservation Program

Developing Operational Coral Reef Bleaching Forecasts for Coral Reef Management – Arun Kumar & Gang Liu

- Distributed on CRW website
- Widely redistributed & used in US & international bleaching monitoring programs
- Primary need: mechanism to transition to full operations

WESTERN INDIAN OCEAN – Regional coral bleaching alert

DATE OF THIS ALERT: 4 January 2016

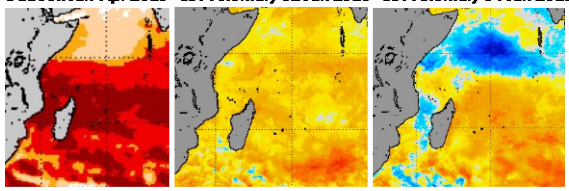


http://www.cordioea.net/bleachingalert/

Contact: bleaching@cordioea.net

NOAA Products – 2 January

Outlook Jan-Apr 2016 SST Anomaly 02 Jan 2016 SST Anomaly 04 Jan 2015



Left: the bleaching warning throughout the WIO is already at moderate to high levels. Middle: the entire WIO is warmer than normal starting the season, compared to the same time in 2015 (right) where large pockets of cool water are evident, and which spread to a larger extent through to the end of January 2015.

Bleaching Alert level is high across all virtual NOAA stations, with only the 3 coolest locations showing no stress (Somalia, Maputo and South Africa), 11 at Bleaching Watch and 7 at Bleaching Warning level.

Tropical Cyclones

None.

Bleaching observations

Grande Comoros:

Initial observations indicate bleaching is already starting on Grande Comore, at a 'moderate' level. *Said Ahamada/AIDE Comoros*

CORDIO

Mote Marine Laboratory / Florida Keys National Marine Sanctuary

Coral Bleaching Early Warning Network

Current Conditions Report #20150602

Updated June 2, 2015

Summary: Based on climate predictions, current conditions, and field observations, the threat for mass coral bleaching within the FKNMS is currently **LOW**.

NOAA Coral Reef Watch 60% Probability Coral Bleaching Thermal Stress Outlook June 2015 Sept. 2015 (experimental)

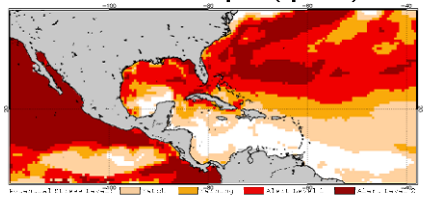


Figure 1. NOAA's Experimental Coral Bleaching Thermal Stress Outlook for June 2015–Sept. 2015
http://coralreefwatch.noaa.gov/satellite/bleachingoutlook_cfu/outlook_cfu.php

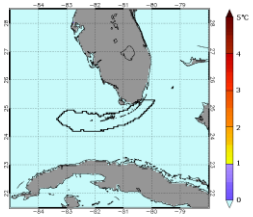


Figure 2. NOAA's Experimental 5km Coral Bleaching HotSpot Map for Florida May 31, 2015.
http://coralwatch.noaa.gov/regions/florida.php

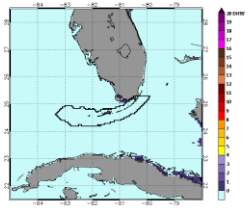


Figure 3. NOAA's Experimental 5km Degree Heating Weeks Map for Florida May 31, 2015.
http://coralwatch.noaa.gov/regions/florida.php

Weather and Sea Temperatures

According to the newly released NOAA Coral Reef Watch (CRW) experimental Coral Bleaching Thermal Stress Outlook, there is potential for coral bleaching throughout the Florida Keys region in the coming months, as well as the rest of Caribbean for the remainder of the summer of 2015 (Fig.1).

Recent remote sensing analysis by NOAA's CRW program indicates that the Florida Keys region is presently experiencing minimal thermal stress. NOAA's new experimental 5 km Coral Bleaching HotSpot Map (Fig.2), which illustrates current sea surface temperatures compared to the average temperature for the warmest month, shows that sea surface temperatures are not elevated above normal in the Florida Keys. Similarly, NOAA's experimental 5 km Degree Heating Weeks (DHW) map, which illustrates how much heat stress has built up over the past 12 weeks (Fig.3), indicates no accumulated temperature stress is currently evident in the Florida Keys region. NOAA's Integrated Coral Observing Network (ICON) monitoring stations, which provide near real time *in-situ* sea temperature data along the outer reef tract throughout the Florida Keys, confirm that temperatures are still below 30°C over the past four weeks (Fig.4), likely due in part to breezy conditions observed during this time frame (Fig. 5). *In-situ* sea temperature data is currently only available at Molasses Reef. Fowey Rocks is not recording any data at this time. Mote Marine Laboratory will continue to monitor the NOAA HotSpot maps, DHW maps, and ICON sea temperature data from NOAA monitoring stations on a weekly basis for the remainder of the bleaching season.

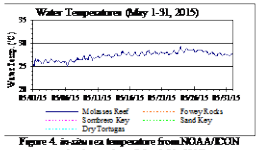


Figure 4. in-situ sea temperature from NOAA/ICON monitoring stations (May 1-31, 2015).

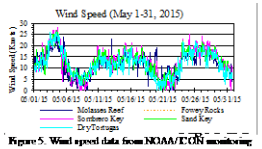
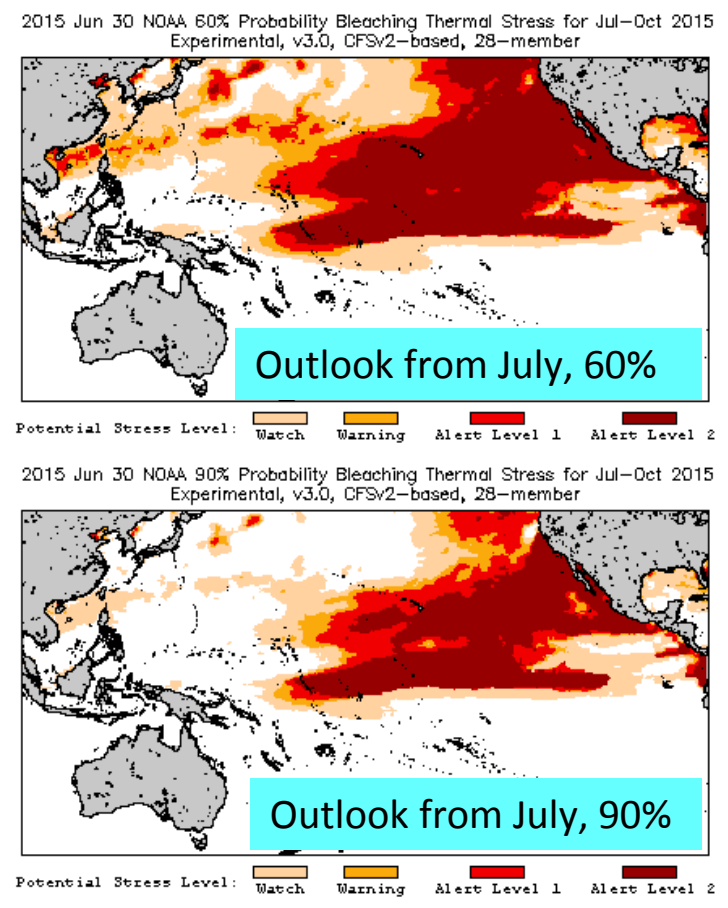


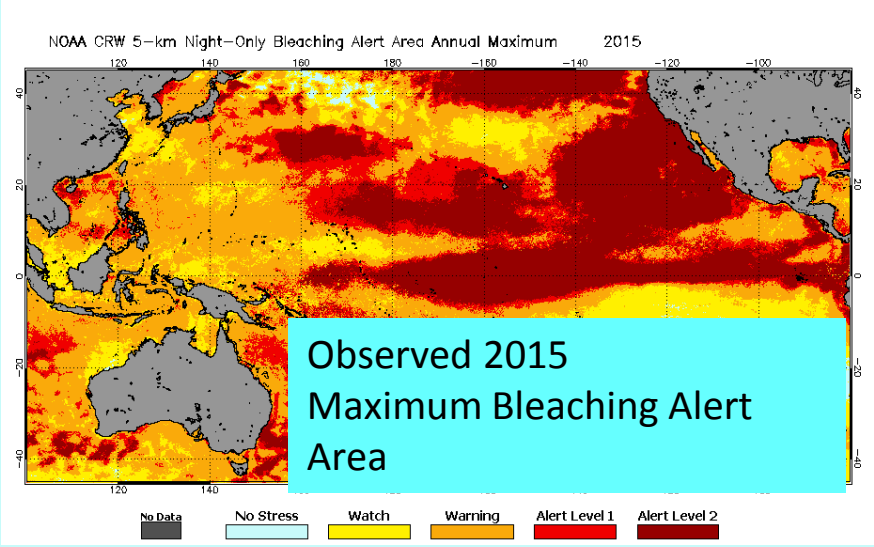
Figure 5. Wind speed data from NOAA/ICON monitoring stations (May 1-31, 2015).

NOAA Coral Reef Conservation Program

Developing Operational Coral Reef Bleaching Forecasts for Coral Reef Management – Arun Kumar & Gang Liu

2015 Four Month Bleaching Outlook: Hawai'i





Developing Operational Coral Reef Bleaching Forecasts for Coral Reef Management – Arun Kumar & Gang Liu

Management Responses:

- 2015 Hawai'i Bleaching – DAR "Ark"

NOAA Coral Reef Conservation Program

Developing Operational Coral Reef Bleaching Forecasts for Coral Reef Management – Arun Kumar & Gang Liu

Management Responses:

- 2015 Thailand Reef Closures

Florida Keys BleachWatch –Sarah Fangman

BLEACHWATCH
MOTE MARINE LABORATORY

Community based reporting of coral bleaching and data integration with existing NOAA coral bleaching early warning products.

NOAA CORAL REEF CONSERVATION PROGRAM

FLORIDA 4 REEF Protect Our Reefs

NATIONAL MARINE SANCTUARIES FLORIDA KEYS

Florida Keys BleachWatch –Sarah Fangman

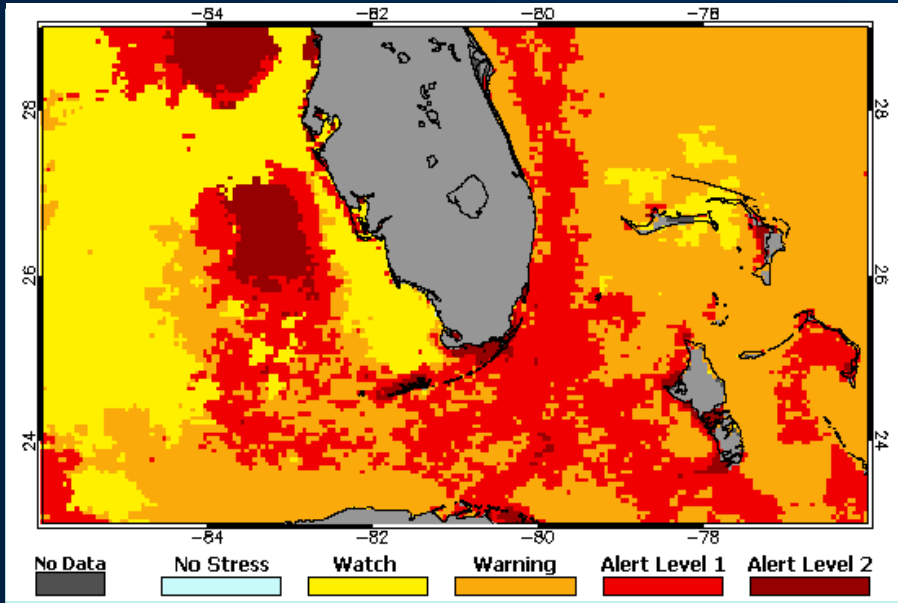
Purpose:

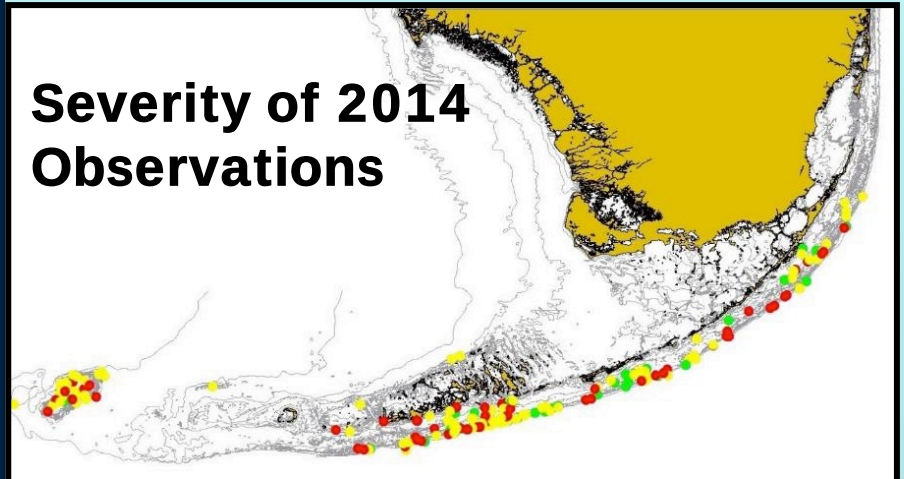
- Monitor environmental conditions.
- Provide an “Early Warning Alert” of coral bleaching
- Involve the community in monitoring coral reef health.
- Provide FKNMS with the reef’s Current Conditions by summaries of the community feedback and environmental conditions
- Rapid feedback to resource managers
- Ground-truth for satellite data

Modeled after GBRMPA program

NOAA Coral Reef Conservation Program

Florida Keys BleachWatch –Sarah Fangman





Mote Marine Laboratory / Florida Keys National Marine Sanctuary

Coral Bleaching Early Warning Network

Current Conditions Report #20160801

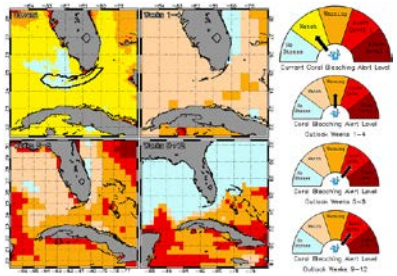


Figure 1. NOAA's 5 km Experimental Current and 60% Probability Coral Bleaching Alert Outlook Areas through September 2016. Updated July 30, 2016.
http://coralreefwatch.noaa.gov/vs/gauges/florida_keys.php

g stations on a weekly basis for the remainder of the bleaching season.

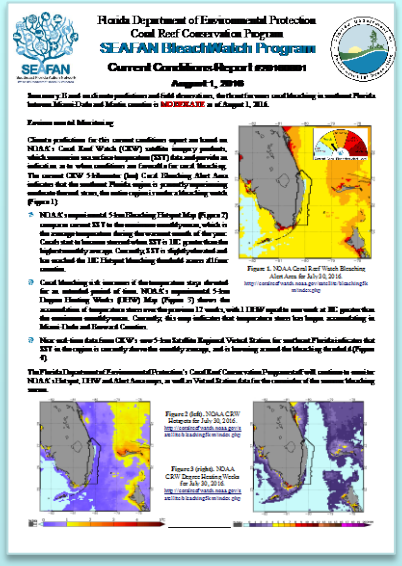
NOAA Coral Reef Conservation Program

Florida Keys BleachWatch –Sarah Fangman

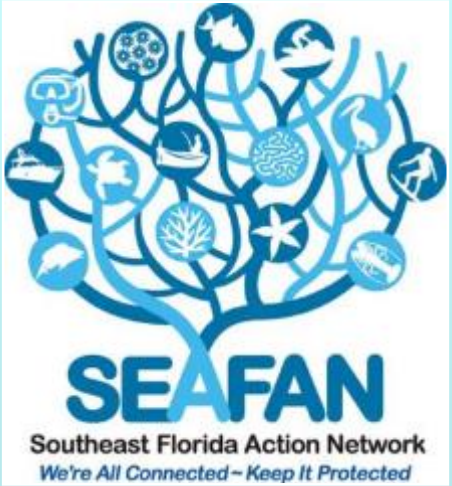
Issues:

- Sustained funding
- Primarily funded by FL License Plate support
- Keeping community engaged

Copied by FL DEP



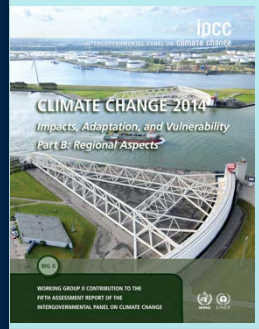
Used as model elsewhere



NOAA Coral Reef Conservation Program

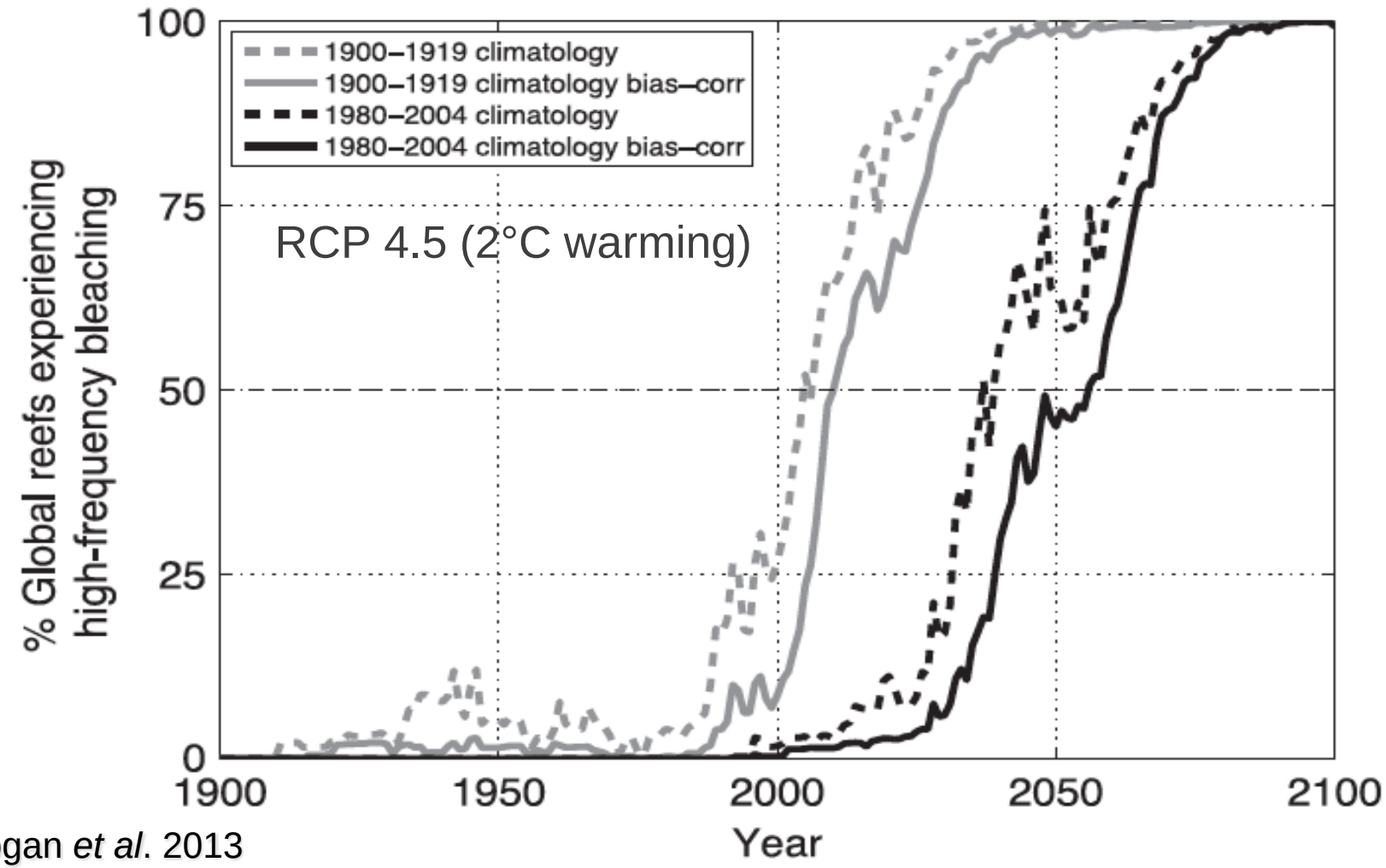
Modeling the Effects of Climate Change and Acidification on Global Coral Reefs – John Dunne et al.

- Use of GFDL model for IPCC 5th Assessment Report
- Analysis of coral bleaching under future scenarios at 4 different Representative Concentration Pathways (1.5°C warming to 4-6°C warming)
- Results cited in IPCC AR5 WGII
- Two major findings:
  - Corals have already adapted/acclimated to warming since early 20th century
  - Estimated potential range of adaptability by corals
    - Temporary adaptation such as symbiont shuffling has insignificant impact
    - Long-term adaptation can help but only delays frequent bleaching onset by a couple of decades unless global warming is held to 1.5°C



NOAA Coral Reef Conservation Program

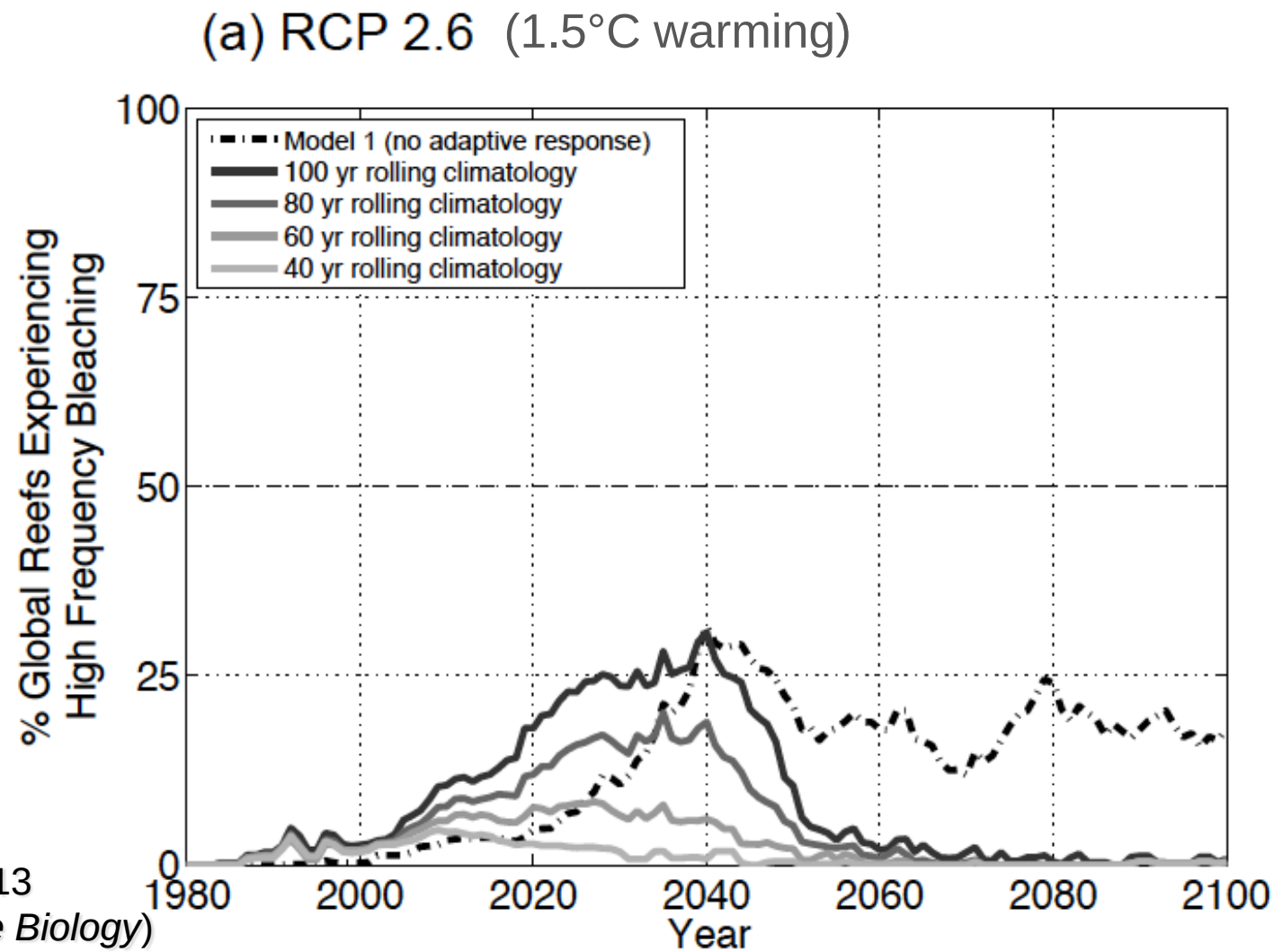
Modeling the Effects of Climate Change and Acidification on Global Coral Reefs – John Dunne et al.



Logan *et al*. 2013
(*Global Change Biology*)

NOAA Coral Reef Conservation Program

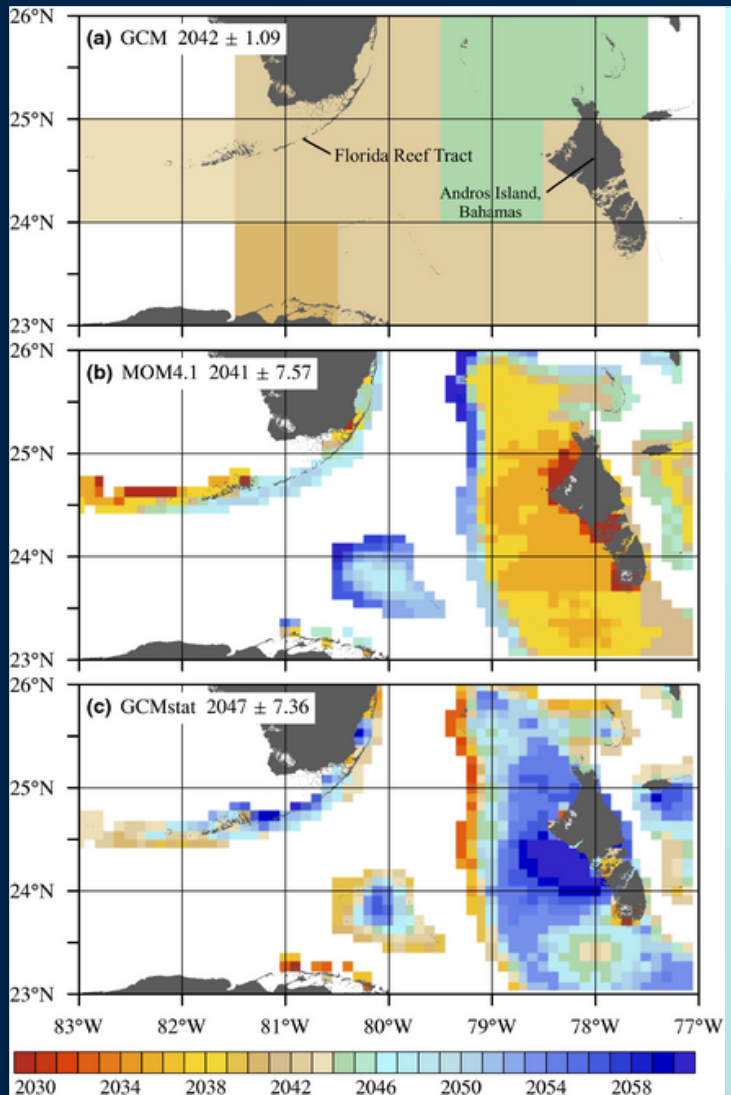
Modeling the Effects of Climate Change and Acidification on Global Coral Reefs – John Dunne et al.



Logan *et al*. 2013
(*Global Change Biology*)

NOAA Coral Reef Conservation Program

Developing Downscaled Climate Models for Coral Reef Management into the 21st Century – John Lamkin et al.

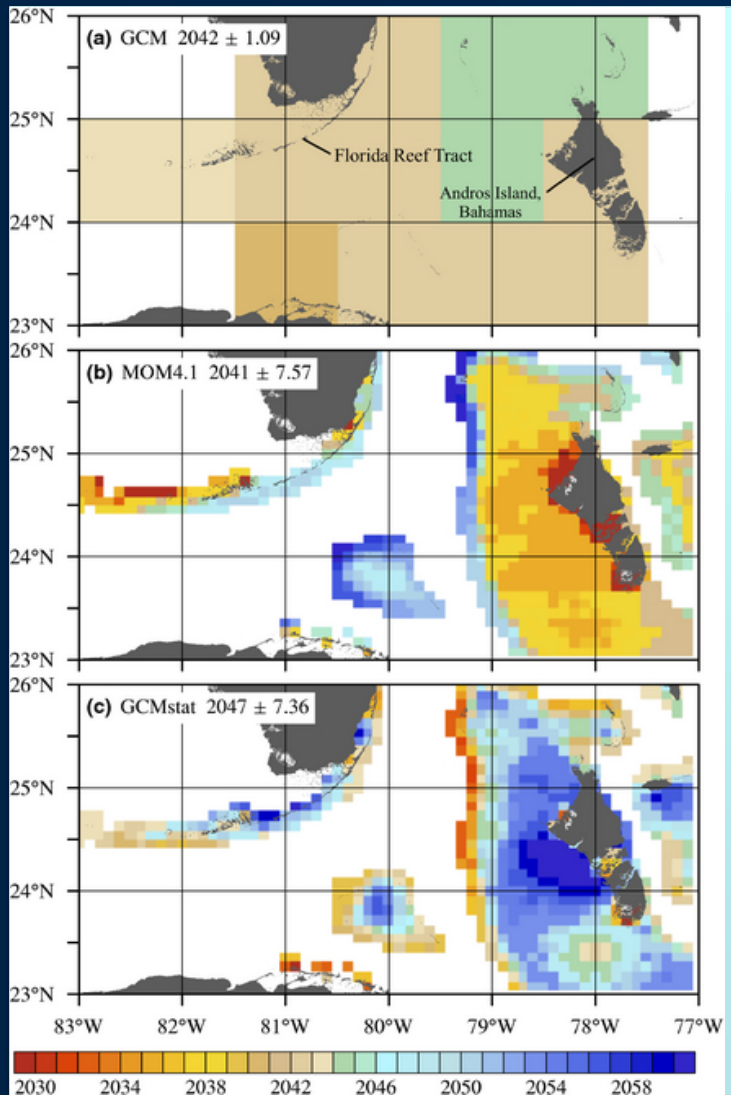


- Used IPCC-AR5 models, a dynamic downscaled model and a statistical downscaling to project the onset of annual coral bleaching conditions in the Caribbean
- The average year for the onset of annual severe bleaching is 2040–2047 for all three projections
- Dynamically downscaled projections suggests an earlier onset of annual severe bleaching linked to projected changes in regional currents
- **Demonstrated the value of a dynamical downscaling for projecting the onset of annual coral bleaching at regional scales**
- Suggested that statistically downscaled projections have to be interpreted with caution.

NOAA/NGI: S.-K. Lee & Y. Liu
USM (F. Hernandez) & SEFSC (J. Lamkin)

NOAA Coral Reef Conservation Program

Developing Downscaled Climate Models for Coral Reef Management into the 21st Century – John Lamkin et al.

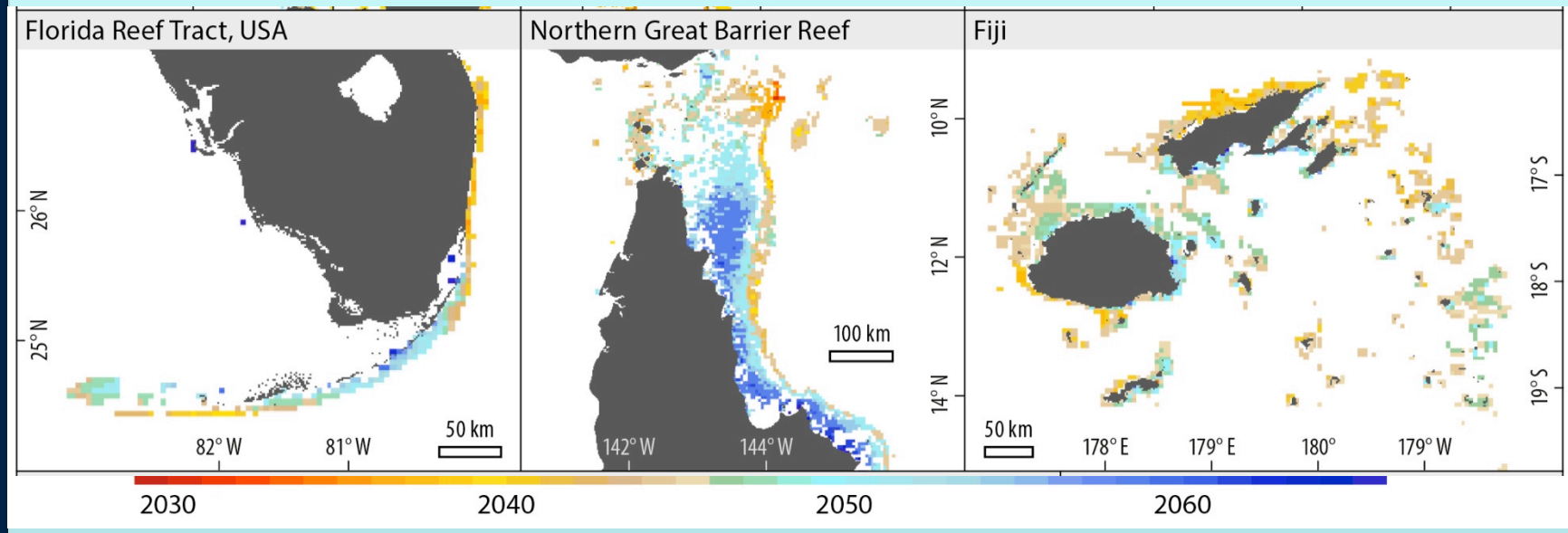


- Initial downscaling work has spawned a variety of research efforts including:
  - Bluefin and Skipjack Tuna habitat change
  - Biogeochemical process changes
- Future applications include impacts of:
  - Slowed Florida Current on sea level rise
  - Increased thermal stratification on hypoxia along TX-LA shelf
  - Warm water on hurricane intensification
  - Summer season warming on N. Gulf of Mexico ecosystems – to be explored using ultra-high resolution model

NOAA/CRCP: S.-K. Lee, Y. Liu
AOML: R. van Hooidonk & SEFSC: J. Lamkin, B. Muhling

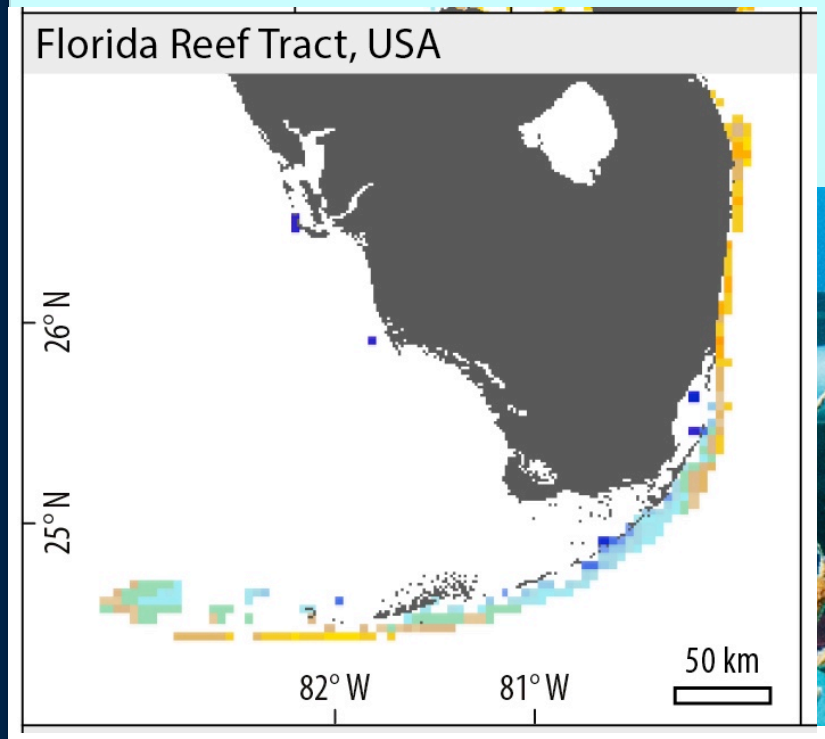
Modeling Reef Futures Using a High Resolution Modular Ocean Model – Ruben van Hooidonk

- Statistically downscaled projections of the timing of the onset of annual severe bleaching (>8 DHW) conditions under RCP8.5.
- These exemplify the high local-scale (10's of km) variation seen in projected in most locations.
- Data available from CRW

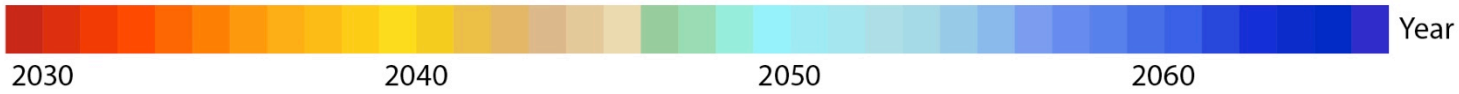


Modeling Reef Futures Using a High Resolution Modular Ocean Model – Ruben van Hooidonk

- Working with Coral Program-funded FL nurseries to maximize long term survival



- Computing resources an issue due to large file sizes



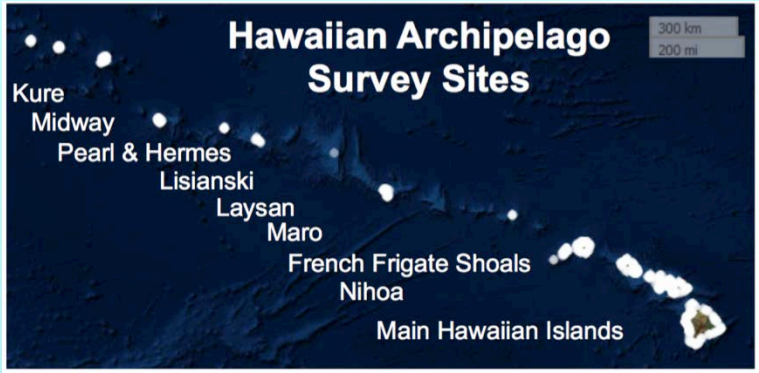
NOAA Coral Reef Conservation Program

Environmental Monitoring of Coral Disease and Bleaching in the Hawaiian Islands – Bernardo Vargas-Angel et al.

- Develop and populate comprehensive database of coral disease observations
- Use these to develop products to predict disease from satellite-SST

HAWAII CORAL DISEASE (HICORDIS) DATABASE

- **286,071 coral colonies surveyed on 1,819 transects at 660 sites between 2005 and 2015**
- **60 species from 22 genera with 21 health conditions.**



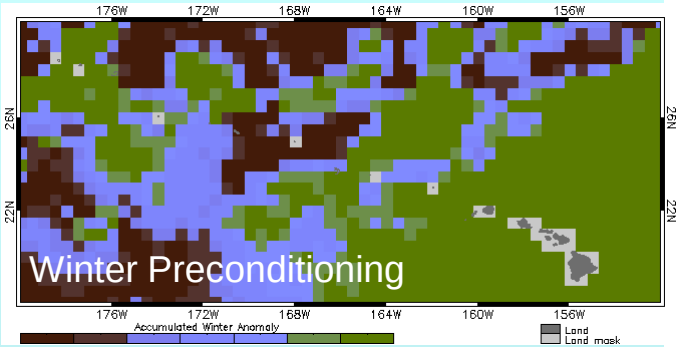
- Could be expanded elsewhere (Caribbean has data sharing issues)

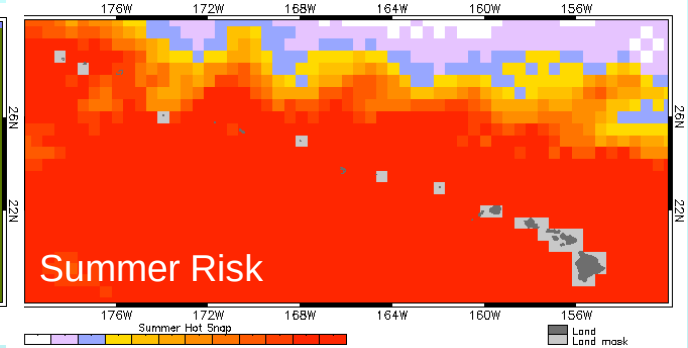
NOAA Coral Reef Conservation Program

Environmental Monitoring of Coral Disease and Bleaching in the Hawaiian Islands – Bernardo Vargas-Angel et al.

- Products available from CRW

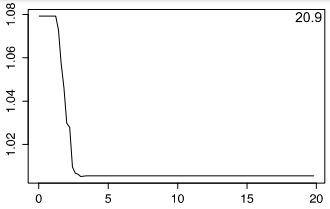
SST-BASED OUTBREAK RISK TOOLS: Metrics from winter (left) and summer (right) temperatures of 2015 contribute to the assessed outbreak risk for various coral diseases.





Cool **Mild** **Warm** **Low** **Moderate** **High**

PRODUCT EVALUATION: Boosted Regression Tree analysis revealed distinct relationships for different diseases. *Caldwell et al. 2016*



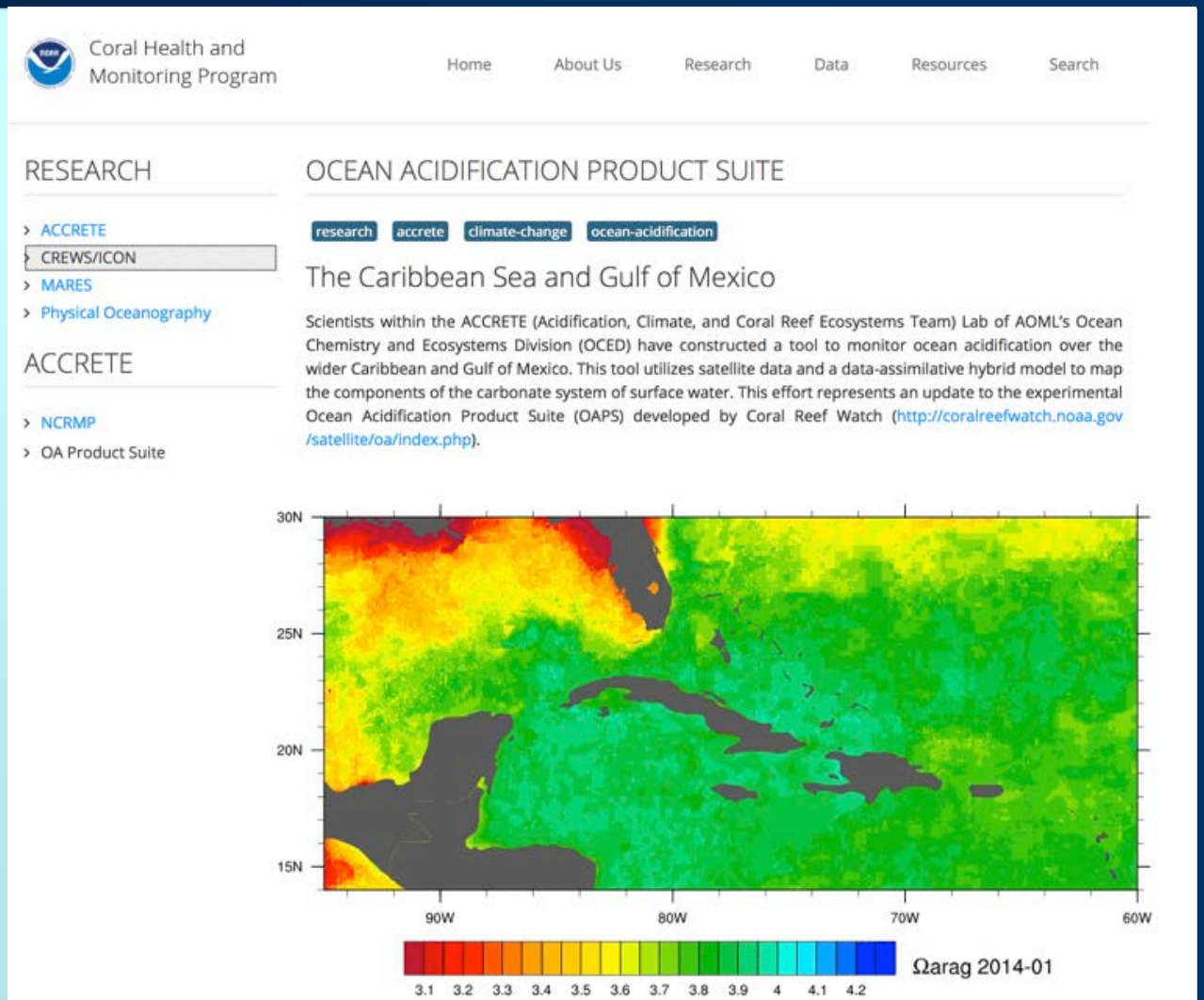
***Montipora* Coral Density** **Winter Condition** **Summer Hot Snap**

- Further support sought from NASA, led by UH PhD student

NOAA Coral Reef Conservation Program

Monitoring Ocean Acidification from Space in the Pacific – Ruben van Hooidonk

- OAPS developed by CRW updated and ported to AOML
- Working to calibrate for Pacific



Climate Goal II: Modeling and Forecasting

Summary:

- Coral Program-supported remote sensing and modeling have become the go-to products for scientists and managers across all US jurisdictions and worldwide
- They have guided planning, monitoring, and action by marine resource managers
- Confidence in NOAA's predictive ability has enhanced NOAA credibility working with resource users

Climate Goal II: Modeling and Forecasting

From Coral Managers' Survey:

Items needing improvement/missing:

- Continued increase in resolution
- Actual sea level products, incorporating ENSO
- Wave and surface current prediction
- Nutrient detection
- Turbidity plumes in nearshore
- Localized data in modeling
- Coastwatch data alongside CRCP products
- Coral Disease forecasting

Climate Goal II: Modeling and Forecasting

Addendum:

Publication List since 2010

Questions?

Climate Goal II: Modeling and Forecasting

Publication List from Coral Reef Watch since 2010

I. Coral Reef Watch Data Products:

- Liu, G.; Chen, M.; Eakin, C.M.; Kumar, A.; De La Cour, J.L.; Geiger, E.F.; Heron, S.F.; Skirving, W.J.; Tirak, K.V.; Strong, A.E.; Gomez, A.M. (2016). **Noaa Coral Reef Watch's Probabilistic Seasonal-scale Coral Bleaching Thermal Stress Outlook System For Informing Management Decisions**. *Proceedings of the 13th International Coral Reef Symposium*, Honolulu, HI, 19-24 June 2016.
- De La Cour, J.L.; Eakin, C.M.; Liu, G.; Geiger, E.F.; Heron, S.F.; Skirving, W.J.; Tirak, K.V.; Gomez, A.M.; Strong, A.E. (2016). **Application Of Noaa Coral Reef Watch's Near-real-time Satellite And Model-based Decision Support System To Local Coral Reef Management**. *Proceedings of the 13th International Coral Reef Symposium,* Honolulu, HI, 19-24 June 2016.
- Geiger, E.F.; Eakin, C.M.; Liu, G.; De La Cour, J.L.; Heron, S.F.; Skirving, W.J.; Tirak, K.V.; Strong, A.E. (2016). **No Reef Left Behind: Using And Interpreting Noaa Coral Reef Watch's 5-km Regional Virtual Stations For Monitoring Bleaching Stress**. *Proceedings of the 13th International Coral Reef Symposium,* Honolulu, HI, 19-24 June 2016.
- Skirving, W.J.; Burgess, T.F.; Liu, G.; De La Cour, J.L.; Enríquez, S.; King, H.M.; Gomez, A.M.; Strong, A.E.; Dove, S.; Hoegh-Guldberg, O.; Eakin, C.M.; Heron, S.F.; Geiger, E.F.; Tirak, K.V.; Iglesias-Prieto, R. (2016). **From Mesocosm Experiments To Satellites: Implementing The Light Stress Damage Product Suite For Tracking Coral Photosystem Health**. *Proceedings of the 13th International Coral Reef Symposium,* Honolulu, HI, 19-24 June 2016.

Climate Goal II: Modeling and Forecasting

Publication List from Coral Reef Watch since 2010, continued

I. Coral Reef Watch Data Products:

- Strong, A.E.; Wang, M.; Eakin, C.M.; Geiger, E.F.; Warner, R.A.; Skirving, W.J.; Liu, G.; Heron, S.F.; Tirak, K.V.; Ondrusek, M.; Hernandez, W.J.; Cardona-Maldonado, M.; Armstrong, R.A.; De La Cour, J.L. (2016). **New Viirs Satellite Ocean Color Products For Management Of Land-based Sources Of Pollution Over Coral Reefs**. *Proceedings of the 13th International Coral Reef Symposium*, Honolulu, HI, 19-24 June 2016.
- Johnston, L.; Heron, S.F.; Johnson, S.; Okano, R.; Benavente, D.; Iguel, J.; Perez, D. I.; Liu, G.; Geiger, E.F.; De La Cour, J.L.; Eakin, C.M. (2016). **Validation Of Reef-scale Thermal Stress Satellite Products For Coral Bleaching Monitoring**. *Proceedings of the 13th International Coral Reef Symposium*, Honolulu, HI, 19-24 June 2016.
- Caldwell, J.M.; Heron, S.F.; Eakin, C.M.; Donahue, M.J. (2016). **Application Of Satellite Sst-based Coral Disease Outbreak Predictions For Hawaii**. *Proceedings of the 13th International Coral Reef Symposium*, Honolulu, HI, 19-24 June 2016.
- Clark, S.J.; Heron, S.F.; Eakin, C.M.; Brainard, R.E.; Oliver, T.A.; Geiger, E.F. (2016). **Improving Thermal Stress Representation On Oceanographically Diverse Pacific Reefs Using A Combination Of In Situ And Satellite Data**. *Proceedings of the 13th International Coral Reef Symposium*, Honolulu, HI, 19-24 June 2016.

Climate Goal II: Modeling and Forecasting

Publication List from Coral Reef Watch since 2010, continued

I. Coral Reef Watch Data Products:

- Eakin, CM, Liu G, Gomez AM, De La Cour JL, Heron SF, Skirving WJ, Geiger EF, Tirak KV, Strong AE (2016). **Global Coral Bleaching 2014-2017: Status and an Appeal for Observations**. *Reef Encounter 43* 31(1): 20-26.
- Heron, S.F.; Johnston, L.; Liu, G.; Geiger, E.F.; Maynard, J.A.; De La Cour, J.L.; Johnson, S.; Okano, R.; Benavente, D.; Burgess, T.F.R.; Iguel, J.; Perez, D.; Skirving, W.J.; Strong, A.E.; Tirak, K.; Eakin, C.M. (2016). **Validation of Reef-scale Thermal Stress Satellite Products for Coral Bleaching Monitoring**. *Remote Sensing* 8(1): 59, doi: 10.3390/rs8010059.
- Mohammed, S.S.; Heron, S.F.; Mahabir, R.; Clarke, R.M. **Performance Evaluation of CRW Reef-Scale and Broad-Scale SST-Based Coral Monitoring Products in Fringing Reef Systems of Tobago**. *Remote Sensing* 8(1): 12, doi: 10.3390/rs8010012.
- Heron, SF, Liu G, Eakin CM, Skirving WJ, Muller-Karger FE, Vega-Rodriguez M, De La Cour JL, Burgess TFR, Strong AE, Geiger EF, Guild LS, Lynds S (2015). **Climatology Development for NOAA Coral Reef Watch's 5-km Product Suite**. *NOAA Technical Report NESDIS 145*. NOAA/NESDIS. College Park, MD. 21pp.
- Liu, G, Heron SF, Eakin CM, Muller-Karger FE, Vega-Rodriguez M, Guild LS, De La Cour JL, Geiger EF, Skirving WJ, Burgess TFR, Strong AE, Harris A, Maturi E, Ignatov A, Sapper J, Li J, Lynds S (2014). **Reef-scale Thermal Stress Monitoring of Coral Ecosystems: New 5-km Global Products from NOAA Coral Reef Watch**. *Remote Sensing* 6(11): 11579-11606, doi:10.3390/rs61111579.

Climate Goal II: Modeling and Forecasting

Publication List from Coral Reef Watch since 2010, continued

I. Coral Reef Watch Data Products:

- Heron, SF, Liu G, Rauenzahn JL, Christensen TRL, Skirving WJ, Burgess TFR, Eakin CM, Morgan JA (2014). **Improvements to and Continuity of Operational Global Thermal Stress Monitoring for Coral Bleaching**. *J. Operational Oceanography* 7(2): 3-11.
- Liu, G, Heron SF, Eakin CM, Rauenzahn JL, Geiger EF, Skirving WJ, Burgess TFR, Strong AE (2014). **NOAA Coral Reef Watch's Next-Generation 5 km Satellite Coral Bleaching Thermal Stress Monitoring**. *Reef Encounter 40* 29(2): 27-29.
- Liu, G., J.L. Rauenzahn, S.F. Heron, C.M. Eakin, W.J. Skirving, T.R.L. Christensen, A.E. Strong, J. Li (2013). **NOAA Coral Reef Watch 50 km Satellite Sea Surface Temperature-Based Decision Support System for Coral Bleaching Management**. *NOAA Technical Report NESDIS 143*. NOAA/NESDIS. College Park, MD. 33pp.
- Lucas, E.Y., A.E. Strong (2013). **Product Development Plan for the Next Generation of Satellite Remote Sensing Products for NOAA Coral Reef Ecosystem Management Activities**. *NOAA Technical Report NESDIS 142B*. NOAA/NESDIS. Silver Spring, MD. 69pp.
- Eakin, C.M., G. Liu, M. Chen, A. Kumar (2012). **Ghost of bleaching future: Seasonal Outlooks from NOAA's Operational Climate Forecast System**. *Proceedings of the 12th International Coral Reef Symposium*, Cairns, Australia, 9-13 July 2012.

Climate Goal II: Modeling and Forecasting

Publication List from Coral Reef Watch since 2010, continued

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- Liu, G, C.M. Eakin, J.L. Rauenzahn, T.R.L. Christensen, S.F. Heron, J. Li, W. Skirving, A.E. Strong, T. Burgess (2012). **NOAA Coral Reef Watch's Decision Support System for Coral Reef Management**. *Proceedings of the 12th International Coral Reef Symposium*, Cairns, Australia, 9-13 July 2012.
- Strong, A.E., E.Y. Lucas, C.M. Eakin, J. Rauenzahn, P. Chang, A. Ignatov, G. Liu, E. Maturi, L. Miller, W. Pichel, W.J. Skirving, M. Wang (2012). **Enhanced Satellite-Remote Sensing for Coral Reef Management: Next Decade.** *Proceedings of the 12th International Coral Reef Symposium*, Cairns, Australia, 9-13 July 2012.
- Strong, A.E., G. Liu, W. Skirving, C.M. Eakin (2011). **NOAA's Coral Reef Watch Program from satellite observations**. *Annals of GIS* 17(2): 83-92, doi: 10.1080/19475683.2011.576266.
- Heron, S.F., B.L. Willis, W.J. Skirving, C.M. Eakin, C.A. Page, I.R. Miller (2010). **Summer Hot Snaps and Winter Conditions: Modelling White Syndrome Outbreaks on Great Barrier Reef Corals.** *PLoS One*. 5, e12210. (doi:10.1371/journal.pone.0012210)

II. Bleaching Events:

- Eakin, C.M.; Gomez, A.M.; Hodgson, G.; Vevers, R.; De La Cour, J.L.; Liu, G.; Geiger, E.; Heron, S.F.; Skirving, W.J.; Tirak, K.V.; Strong, A.E. (2016). **Two Years And Counting: Monitoring And Documenting The Ongoing Global Coral Bleaching Event (2014-2016 And Beyond)**. *Proceedings of the 13th International Coral Reef Symposium,* Honolulu, HI, 19-24 June 2016.

Climate Goal II: Modeling and Forecasting

Publication List from Coral Reef Watch since 2010, continued

II. Bleaching Events:

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