Are there thermal refugia for coral reefs in the Coral Triangle?

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Motivation

The Coral Triangle (CT) is widely recognized as the center of coral species diversity (Veron, 1995), with high marine productivity that supports the livelihoods of millions of people. About 150 million people live in the Coral Triangle proper, and 100–125 million of these depend strongly on coastal resources (The Nature Conservancy, 2009). The formation of the Coral Triangle Initiative on Coral Reefs, Fisheries and Food Security (CTI-CFF) (Coral Triangle Secretariat, 2009), a consortium of six nations, underlines the importance of protecting the marine ecosystems of the region.

Reports of coral bleaching in the CT are incomplete, but have increased since 1982 (**Table 1**; **Fig. 1A**). The most significant event occurred in 1998, following the strong 1997–1998 El Niño (**Fig. 1B**).

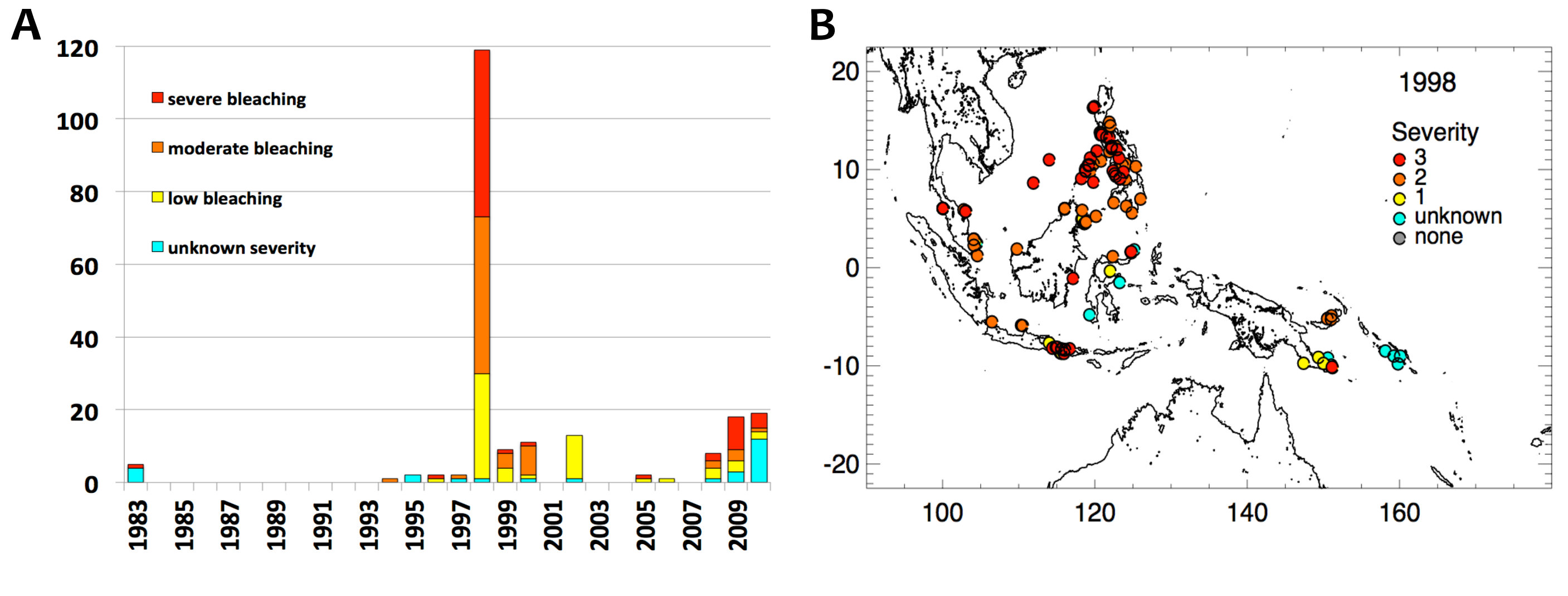
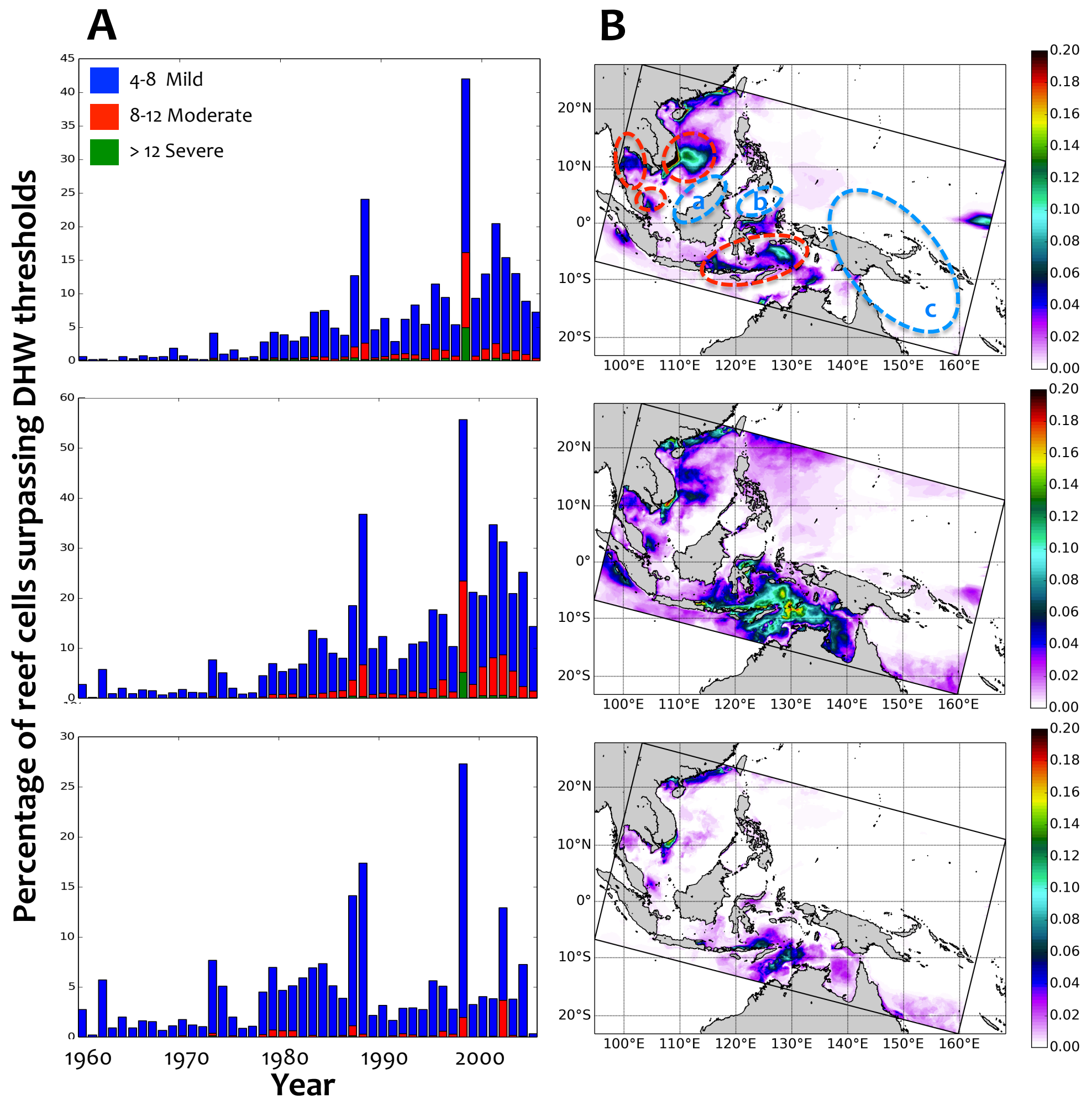


Figure 1. *Historical records of coral bleaching in the Coral Triangle. A. Count of 1x1 deg cells with reported bleaching events. B. Distribution of bleaching events in 1998.*

Table 1. *Summary of bleaching events in the Coral Triangle since 1982 (derived from ReefBase). ENSO data are from the updated Oceanic Niño Index; Climate Prediction Center, NCEP/NOAA (w = weak; m = moderate; s = strong).*

Year	Region	Notes	El Niño	La Niña	La Nada
1982	No bleaching reports within CT region		s		
1983	Indonesian Arch., Seribu Is.	Few reports, single report of severe bleaching (50% of coral)		w	
1984	No bleaching reports within CT region	Note: A few severe bleaching reports from Thailand in Andaman Sea (not CT)		w	
1985					▨
1986			m		
1987			m		
1988				s	
1989					▨
1990					▨
1991			m		
1992					▨
1993					▨
1994	N CT and SE CT: Philippines, N Marianas, East PNG	Few, isolated reports; mod to severe; Note: a few severe reports, Thailand in Andaman Sea & Taiwan (not CT)	m		
1995				w	
1996					▨
1997	N CT: Philippines	Single location; mod. Note: A few mild to severe bleaching reports, Thailand in Andaman Sea (not CT)	s		
1998	**Most of CT**	**Widespread across CT, *except* in N PNG, Solomon Is., and Banda/ Arafura Seas; mod to severe**		m	
1999	Philippines, Palau, Coral Sea	Few scattered reports		s	
2000	Solomon Islands	Multiple locations; May-Jul; mod to sev		w	
2001	N Mariana Islands	Multiple locations; May-Aug; low to sev			▨
2002	Scattered	Scattered locations in CT; low to sev	m		
2003	N Australia	Very few reports; Torres Shelf			▨
2004	Very limited	Very few reports; single location in Philippines with high bleaching intensity (temperature was not elevated)	w		
2005				w	
2006	New Britain Is.	Few reports	w		
2007				m	
2008	N to NW CT: Gulf of Thailand, Philippines	Few reports; low to severe		w	
2009	S to SW CT: Gulf of Thailand, W Borneo, Makassar Strait, Bali, S PNG	Scattered reports; mod to severe	m		
2010				s	
2011	Indonesian Arch.	Two isolated reports; severity unknown		w	
2012					▨

Results: Identifying thermal refugia depends on how thermal stress is determined



Climatology	Threshold
1970–1985	1°C > MMM
1970–1985	2.5σ °C > MMM
20-year rolling	2.5σ °C > MMM

Figure 4. *Bleaching over time and space based on the CT-ROMS hindcast, based on three heat stress methodologies. A. Histogram of bleaching by severity; note differences in scales; B. Return frequency of DHW > 4 over the 1960–2008 time period. Blue and red circles: refuge and exposed regions, respectively.*

See DWH animations for methods 1 and 2 on the laptop

The spatial patterns of the return frequency of thermal stress (**Fig. 4B**) over the 1960–2008 period highlight important differences in the metric used. The 2.5σ °C metric, for example, reflects local conditioning of corals to variations in SST_{max}, such that corals living in stenothermal conditions are more sensitive to increases in SST_{max} (e.g. Banda Sea).

Regardless of the method used, however, some regions experienced higher frequency of stress over the last half-century than others (circles in Fig. 4B, top). Regions with the least stress included W Borneo (a), the Celebes Sea (b), and Solomon and Coral Seas (c).

Note that the 1998 ENSO event (Fig. 3), which strongly affected DHW in the northern half of the CT, is not widely reflected in Fig. 4B, illustrating the uniqueness of the 1998 warming pattern.

For corals that may have adapted/acclimated to the previous 20-year SST_{max} (Fig. 4B, bottom), frequency of thermal stress was considerably less than in the other scenarios.

Methods

Model: A 5-km resolution Regional Ocean Model System was developed for the CT region (CT-ROMS; Castruccio et al. 2013; **Fig. 2**). CT-ROMS sea surface temperatures (SST) were first validated against in situ and satellite-observed SST, and the model was then run in hindcast for the years 1960–2008, using atmospheric forcing from CORE2 (Large and Yeager 2004) and boundary conditions from SODA (Carton et al. 2000).

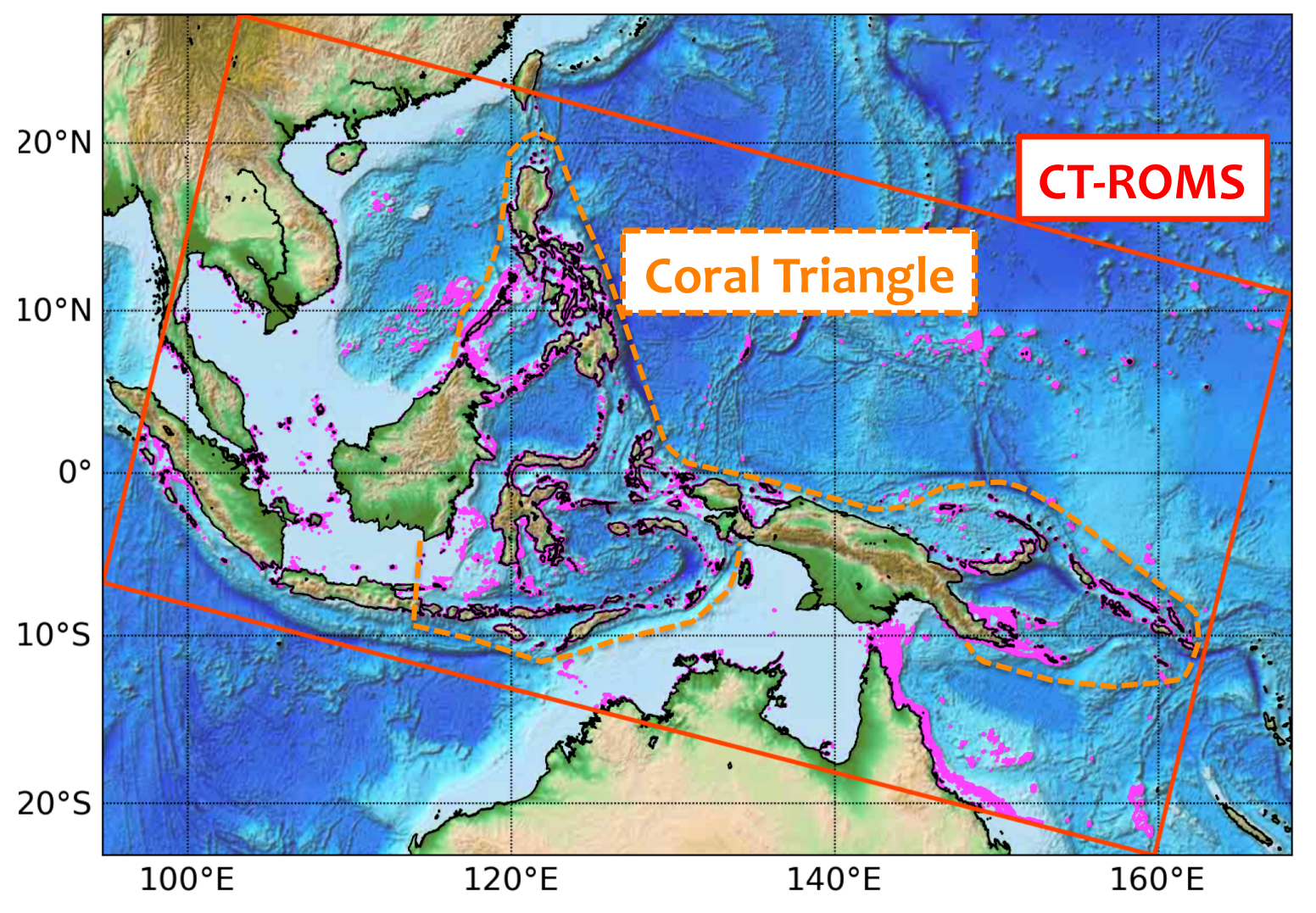


Figure 2. *The Coral Triangle and CT-ROMS domain. Coral reef locations are designated in pink.*

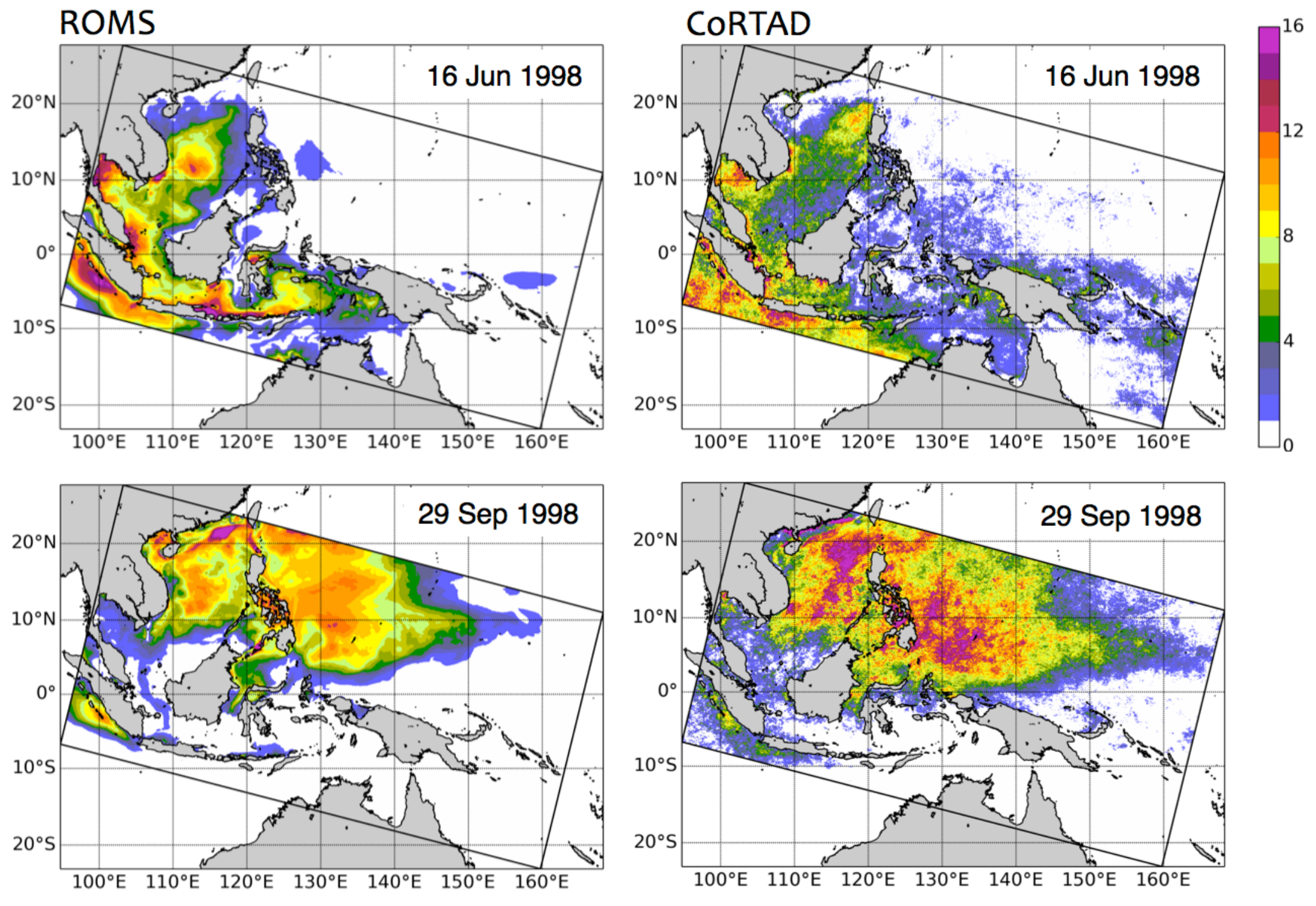


Figure 3. *DHW calculations from CT-ROMS and CoRTAD for the beginning and end of the 1998 bleaching event, using method 2.*

See poster ID 2583 for details about CT-ROMS

Analyses: CT-ROMS temperature output is used to determine heat stress within the CT (**Fig. 3**). Degree heating weeks (DHW) is determined using several methodologies. We compare the results of three DHW methods:

1. Stress threshold = 1 °C above mean monthly maximum (MMM)
2. Stress threshold = 2.5σ °C above MMM
3. As #2 above, but with MMM calculated as a rolling 20-year climatology (simulating the ability to adapt to the average conditions of the previous 20-year period)

We also examine the patterns of temperature stress with depth.

Discussion: Insights into the nature of temperature change

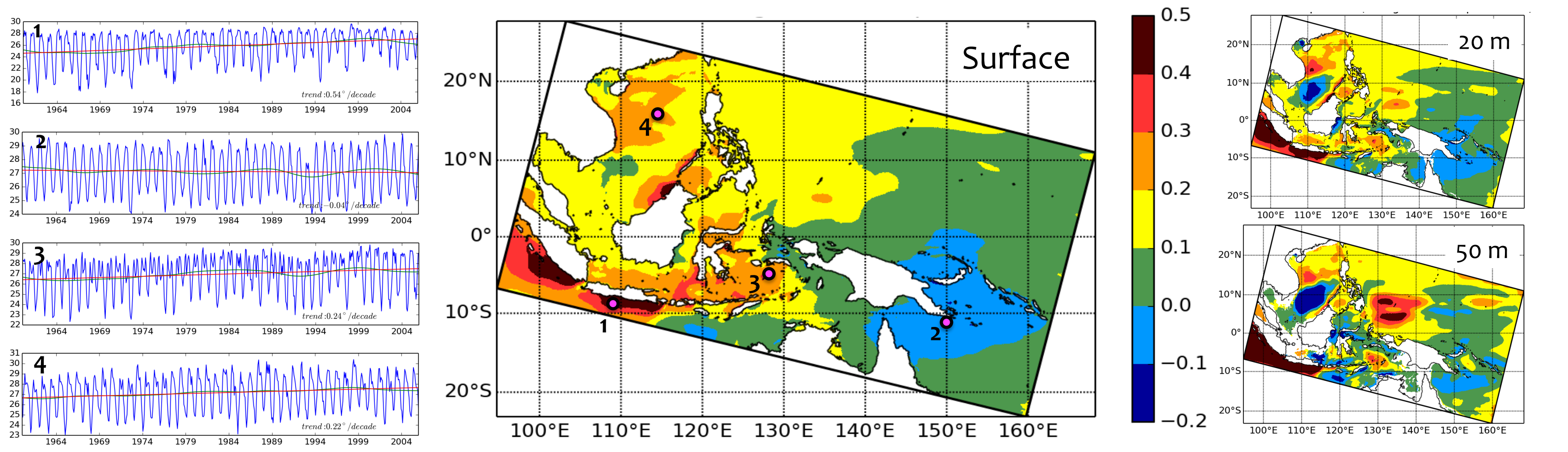


Figure 5. *Trends in CT-ROMS hindcast SSTs (in °C/decade), 1960–2008. Temperature trends at 20 and 50 m depths illustrate how the rates of warming at depth differ from those at the surface. Monthly SST time series are shown for four different locations (left): blue line= monthly SST, green = Hodrick-Prescott filtered SST, red = linear fit of the filtered data.*

Large scale patterns in SST trends (**Fig. 5**) are similar to previous analyses, with high rates of warming in the W/NW regions, and cooling in the E/SE regions. Deeper levels that warm more slowly could provide thermal refugia. Interannual variability in SSTs is largely driven by ENSO and the DMI (**Fig. 6**). K-means clustering (**Fig. 7**) of SST (using mean, min, max) show surprisingly little change in cluster pattern over the last four decades of the 20th Century. Many sharp features persist because of topographic controls on circulation. Notable changes are in upwelling zones and the central regions of the CT.

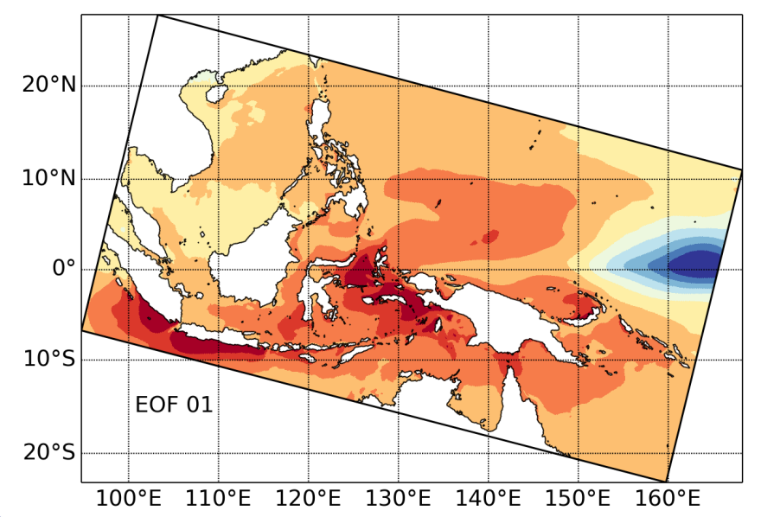


Figure 6. *First EOF of CT-ROMS SSTs for the period 1960–2008. EOF 1 explains 44% of the total variance and is strongly negatively correlated with ENSO (-0.70) and the Indian Ocean Dipole Mode Index (DMI; -0.65).*

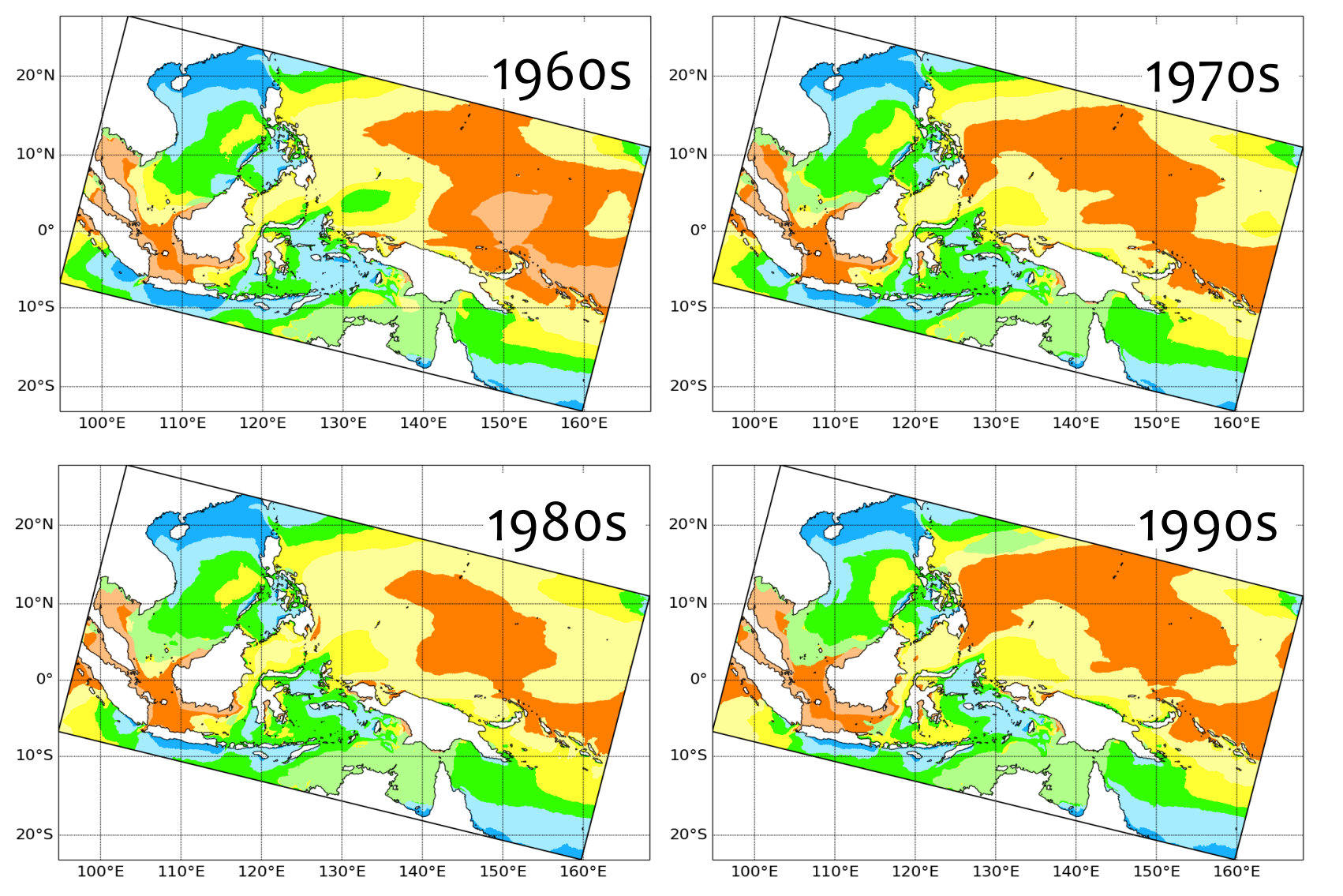


Figure 7. *K-means clustering of CT-ROMS weekly SSTs for each decade.*

Conclusions & Future Work

CT-ROMS simulations permit analysis of the spatio-temporal patterns of heat stress in the Coral Triangle to much greater detail and for longer periods than with observations alone.

The DHW methodology influences thermal stress metrics – and the identification of thermal refugia. The previous 50 years of heat stress within the CT reflects the long term trends of warming in the W and NW regions and slight cooling in E regions. Thermal refugia over this period have been off the west coast of Borneo, the Celebes Sea, and Solomon and Coral Seas. The differences in temperature trends at depth also suggest that deeper reefs could act as thermal refugia during warming events.

CT-ROMS simulations for the 21st Century are now being run using forcing from the Community Earth System Model (CESM 1.0) RCP 8.5. These simulations are being used to determine if the 20th Century patterns will hold in response to further warming, to assess additional factors that affect bleaching (e.g. cloud cover), and to determine the time scales over which refugia persist.

References/Acknowledgements

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