Question: Is it possible to have of different levels of bleaching?

(*) Bleaching defined as the **decrease** in zooxanthellae density **regardless of level of whitening**. However **[2] stated that most *Montastrea* species start to look tan or white when the densities of the zooxanthellae fall bellow 0.5 x 10^6 cell/cm^2**
(**) There are no measurements of the same coral colony before bleaching, so the reference for unbleached corals is unbleached corals at proximity or in other locations (sometimes measured at different time of the year) or healthy corals.
(***) Measurement of temperature prior bleaching: it's sometime annual mean, sometime experimental control. **MMMax** stands for Mean of Monthly Maximum (which is used as a reference for the conventional way of measuring thermal stress: DHW, DHM), it was not always given in the papers, so unless stated, we provide the value that could be used for this measure (it is chosen within the reported ranges and/or for which zooxanthellae density were measured, the reference symbiont density should be changed accordingly).

Bleached Corals (*) Compared to unbleached Corals

e.g. Symb density	Bleaching T (°C)	Symb. density	Pre-bl T (°C) (***)	Methods	Reference
Visual signs of bleaching 0.26 x 10^6 (*Acropora*) 0.17 x 10^6 (*Pocillopora*) No visual signs of bleaching 0.7 x 10^6 (*Acropora*) (cell/cm^2)	30.8 (monthly mean in June 2007) Increased 0.848°C/months since January 2007 (+2.2°C compared to annual mean)	Visual signs of bleaching 10%, 11%, 28%, 16% No visual signs of bleaching 52%, 47%, 55%, 69% (resp. *Acropora, Pocillopora, Porites and Favia*)	28.6 **(26.9, 29.8)** annual mean **(ranges)** Between 2000-2008 **MMMax ≈ 29.8**	***In situ*** ecological surveys & SST from remote sensing (NOAA) (2007 bleaching event)	**[1] (**)** **Site:** **Nansha Islands South China Sea**
Low densities (Fig. 1) (1-2 m depth) 1.5 x 10^6 (*Acropora P.*) 0.9 x 10^6 (*Acropora C.*) 2.5 x 10^6 (*M. Faveolata*) 1 x 10^6 (*M. annularis*) Around July every year	30 - 32 (1-2 m depth) (My estimations from Fig. 6, of the mean around July every year)	Peak densities (Fig.1) (1-2 m depth) 3.5 x 10^6 (*Acropora P.*) 1.5 x 10^6 (*Acropora C.*) 5 x 10^6 (*M. Faveolata*) 3.5 x 10^6 (*M. annularis*) Around January every year	26 - 27 (1-2 m depth) (My estimations from Fig 6, of the annual mean temperature between 1996-1999) **MMMax ≈ 29**	3-4 years (1995-1999) *In situ* seasonal monitoring of 5 species of reef corals (most samples were collected from the same colony)	**[2]** **Site:** **Bahamas and Florida Keys (~CAR)**
Low densities (Fig. 1) (3-4 m depth) 2 x 10^6 (*M. Faveolata*) 1 x 10^6 (*M. annularis*) Around July every year	30 - 31 (3-4 m depth) (My estimations from Fig. 6, of the mean around July every year)	Peak densities (Fig. 1) (3-4 m depth) 5 x 10^6 (*M. Faveolata*) 3 x 10^6 (*M. annularis* Around January every year	26 - 27 (3-4 m depth) (My estimations from Fig 6, of the mean temperature between 1995-1999)	... ...	**[2]** ... ...
Low densities (Fig. 1) (13 m depth) 1 x 10^6 (*Acropora C.*) 2 x 10^6 (*M. Faveolata*) 1.5 x 10^6 (*M. annularis*) Around July every year	**Our** SST forcing is calculated between 0-5 m depths regardless of coral location. Thus we can use the values the 2 previous rows	Peak densities (Fig. 1) (13 m depth) 1.5 x 10^6 (*Acropora C.*) 2.5 x 10^6 (*M. Faveolata*) 2 x 10^6 (*M. annularis*) Around January every year	We can use the values the 2 previous rows	... ...	**[2]** ... ...
M. annularis **[3]** 100% minus 86% *Agaricia lamarcki* **[3]** 100% minus 57%	+ 0.5 – 1.0 warmer than unbleached corals (inferred from difference in $\delta^{18}O$) **[3]**			Analysis of bleached and unbleached corals (6 m depth) **[3]** (1987 bleaching event)	**[3]** **Site:** **Caribbean (CAR)**
M. annularis **[4]** **(tab 1)** Light 0.2-0.4 x 10^6 med. 0.6-0.7 x 10^6	Not reported	*M. annularis* **[4]** **(tab 1)** Dark 1 – 1.4 x 10^6	Not reported	(12 -15 m depth) **[4]** (Documents the recovery 1988 - 1889)	**[4]**
Analysis (Bleached) 0.131 x 10^6 (*S. pistillata*) 0.394 x 10^6 (*Se. hystrix*) Exp. (4 days) 0.46 x 10^6 (*S. pistillata*) 0.2 x 10^6 (*S. pistillata*) 1.5 x 10^6 (*Se. hystrix*) 0.4 x 10^6 (*Se. hystrix*)	Not reported Exp. (non-continuous) 30 32 30 32	Analysis (Normal-looking) 0.446 x 10^6 (*S. pistillata*) 2.107 x 10^6 (*Se. hystrix*) Exp. (4 days) 0.5 x 10^6 (*S. pistillata*) 1.75 x 10^6 (*Se. hystrix*)	Not reported Exp. (control) 27 **MMMax ≈ 30**	Analysis of bleached corals collected in the field and laboratory experiments (6m depth)	**[5] (**)** **Site:** **Lizard Island (GBR)**

Exp. (15 days) *A. millepora* 0.75 (DR), 0.9 (NKI) 0.40 (DR), 0.2 (NKI) 0 (DR), 0 (NKI), 0.5 (MI)	Exp. (computer controlled) 30 31 32 (I do not consider the transplants)	Initial/Before exp. (x 10^6 cell/cm^2) 1.2 (DR) 1.4 (NKI) 1.8 (MI) Exp. (control) 0.9 (DR), 1.5 (NKI & MI)	Mean summer (Dec-Feb) at location 28.3 ± 0.5 (at DR) 27 ± 0.5 (at NKI) 29.2 ± 0.45 (at MI) Exp. (control) 27.5 **MMMax ≈ upper limit of summer**	Transplantation from NKI and DR to MI and experimental manipulation	**[6]** **Site:** **GBR**
Exp. (3 days) *Goniastrea aspera* 100% minus 35% = 75% of zooxanthellae is remaining in the coral	33.03 – 33.81 (Range for the elevated temperature)		28.51 – 29.77 (Range for median ambient temperature) **MMMax ≈ 29.77**	Experiment on *Goniastrea aspera* **(Andaman Sea)** **(SEA)**	**[7]** **Site:** **South east tip of Ko Phuket, Thailand,**

Bleached Corals (*) Compared to unbleached Corals

e.g. Symb density	Bleaching T (°C)	Symb. density	No Bl. T (°C)	Methods	Reference
Acropora formosa 100% minus (65 – 66%) with visual signs 100% minus (44 - 48%) no visual signs	34 (reef flat) 32 (reef slope) (+2°C of daily average over 1 week)	Compared to zooxanthellae measured in December 1994 (considered “normal” level)	30 (reef slope) (Daily average 1993-1994) **MMMax ≈ 30**	Analysis of bleached and unbleached corals (bleaching event January 1994) *Acropora formosa* (5-6 m depth)	**[8]** **Site:** **Magnetic Island (GBR)**
Exp. (7 days) 0.8 x 10^6 cell/cm^2 0.7 x 10^6 cell/cm^2 0.3 x 10^6 cell/cm^2	Exp. (non-continuous) 24 28 30	Initial 1.2 x 10^6 cell/cm^2	Initial conditioning 24 **MMMax ≈ 28**	Experiment on *Galaxea fascicularis* (1-1.5 m depth)	**[9]** **Site:** **Okinawa, Japan**
< 0.1 x 10^6 cell/cm^2 (Bleaching: Oct-Dec 1993) Low densities (Fig. 2A) 0.7-1.5 x 10^6 cell/cm^2 (Spring-summer October-April)	**The author stated that the variation in zoox density is better explained by season than by temperature or solar radiation.** Maximum exceeding 30°C in Summer 30.8°C in April 1994, **so we could estimate a summer mean of (30+30.8)/2 = 30.4**	High densities (Fig. 2A) 2-3 x 10^6 cell/cm^2 (Autumn-winter May-September)	**The author stated that the variation in zoox density is better explained by season than by temperature or solar radiation.** Minimum was 22.8°C in August 1993, **so we could estimate an annual mean of (30.8+22.8)/2 = 26.8** **MMMax ≈ 30**	6-years field study August 1991 – March 1997. Weekly data collection *Acropora formosa* (1-2 m depth)	**[10]** **Site:** **Mauritius**
Pocillopora verucosa: 0.3 x 10^6 cell/cm^2 *Acropora samoensis:* 0.15 x 10^6 cell/cm^2 *Acropora subulata:* 0.4 x 10^6 cell/cm^2	29.5 - 30	Healthy corals 1 - 5 x 10^6 cell/cm^2 (Drew 1972)	27.5 (My estimation of the mean between 1991-1994 Fig. 2) **MMMax ≈ 28.5**	Reports of mass-bleaching in April 1994 (5-16 m depth)	**[11] (**)** **Site:** **Moorea French Polynesia**
Exp. (Fig. 3 day 0) *Porites divaricata:* 0.5 x 10^6 cell/cm^2 *Porites astreoides:* 1 x 10^6 cell/cm^2 *Orbicella faveolata:* 0.35 x 10^6 cell/cm^2	Exp. (bleached) 31.48 ± 0.20	Exp. (Fig. 3 day 0) *Porites divaricata* 1.1 x 10^6 cell/cm^2 *Porites astreoides* 2.3 x 10^6 cell/cm^2 *Orbicella faveolata* 1.2 x 10^6 cell/cm^2	Exp. (control/non-bleached) 30.66 ± 0.24 **MMMax ≈ 30.5** (Although the author reported 29°C it's better to use this value to have a more precise zoox density)	Experiment on corals collected at 3-8 m depth 15 days experiement + up to 11 months recovery on reef	**[12]** **Site:** **Caribbean (CAR)**
Exp. (Fig. 2 & 4) Respectively at → *Montastrea annularis:* 0.5, death (use 0.1) *Montastrea cavernosa:* Not significant *Agaricia lamarcki:* 0.5, death (use 0.1) *Agaricia agaricites:* 0.5, death (use 0.1) x 10^6 cell/cm^2	Respectively at 32, 34 (Some corals did not survive during the whole experiment, I report at the end of experiment and indicate coral death)	Exp. (Fig. 2 & 4) Resp. at control & MMMax *Montastrea annularis* 1.6, 2 *Montastrea cavernosa* 0.3, 0.5 *Agaricia lamarcki* 0.95, 0.75 *Agaricia agaricites* 1.1, 0.8 x 10^6 cell/cm^2	Exp. (control) 26 ± 1 (also ambient seawater temperature) **MMMax ≈ 30** **(also considered in experiment)**	Experiment on Corals collected at 14-16 m depth 52 – 60 hour experiment	**[13]** **Site:** **Caribbean (CAR)**

Bleached Corals (*)		Compared to unbleached Corals			
e.g. Symb density	Bleaching T (°C)	Symb. density	No Bl. T (°C)	Methods	Reference
Exp. (Fig. 2) (4, 8 weeks) Gulf of Panama exp(1.6), exp(1.3) = 4.31 exp(1), exp(-0.2) = 1.77 exp(-2), death = 0.135 Gulf of Chiriqui exp(2.1), exp(2) = 7.77 exp(1.8), exp(1.2) = 4.68 x 10^6 cell/cm^2	Respectively Gulf of Panama 28.44 (± 0.04) 29.61 (± 0.03) 31.68(± 0.04) Gulf of Chiriqui 27.89 (± 0.08) 30.37(± 0.07)	Ambient (Fig. 2) Gulf of Panama exp(1.6), exp(1.5) = 4.71 Gulf of Chiriqui exp(2.4), exp(2.2) = 10.02	Ambient Gulf of Panama 27.87 (± 0.04) **MMMax ≈ 28.44** Gulf of Chiriqui 26.21 (± 0.07) **MMMax ≈ 27.89**	10 weeks experiment on *Pocillopora damicornis* from 2-5 m depth (major reef-building coral in the tropical eastern Pacific) I report average at 4 & 8 weeks (if corals survived)	**[14]** **Site:** **Gulf of Panama/ Chiriqui** **(~ CAR)**
From fig 5 (25, 50 days) *Pocillopora damicornis:* mean(5, 1) = 4 *Pocillopora elegans* mean(8, 3) = 5.5 *Porites lobata* mean(8, 4) = 6 *Pavona clavus* mean(9, 5) = 7 *Pavona gigantea* mean(8, 5) = 6.5 x 10^6 cell/cm^2	Heated for 50 days at (30-31°C) (I report average symbiont density after 25 and 50 days heating, approximately averaged within 2months)	From fig 5 *Pocillopora damicornis:* 8 *Pocillopora elegans* 16 *Porites lobata* 14 *Pavona clavus* 15 *Pavona gigantea* 11 x 10^6 cell/cm^2	Ambient sea temperature (27-29°C) (I report average symbiont density after 25 and 50 days ambient, approximately averaged within 2months) **MMMax ≈ 29**	Experiment on corals collected from 4-6m depth, heated for 50 days at (30-31°C) then returned to ambient sea temperature (27-29°C) for 25 days (simulating El Niño effect)	**[15]** **Site:** **Gulf of Panama** **(~ CAR)**
Fig 9 & text October 1997 (Uva) *Pavona clavus, P. elegans, P. damicornis:* 0.01 x 10^6 cell/cm^2 March 1998 (Uva) *P. damicornis:* 0.5 x 10^6 cell/cm^2 *P.elegans:* 0.8 x 10^6 cell/cm^2 *Porites lobata:* 0.7 x 10^6 cell/cm^2	July-Oct 1997 (Fig. 5 Uva and text) 30-31 March-July 1998 (Fig. 5 Uva and text) 29-31	Fig 9 & text October 1997 (Uva) *Pavona clavus: 1; P. elegans: 10; P. damicornis: 10* x 10^6 cell/cm^2 March 1998 (Uva) *P. damicornis:* 10 x 10^6 cell/cm^2 *P.elegans:* 10 x 10^6 cell/cm^2 *Porites lobata:* 5 x 10^6 cell/cm^2	1997-2000 (Uva) (Fig 6- SST 2m depth) annual 27.5-28.5 **MMMax ≈ 29**	Observation of bleaching and mortality of zooxanthellate corals during the 1997-98 El Niño (I report the symbiont density of bleached corals and of normal looking corals only for Uva Island because SST measurement was not clear for Jicarón)	**[16]** **Site:** **Panama & Ecuador (Uva, Jicarón)** **(~ CAR)**
Fig. 6 mean of pale & fully bleached *Goniastera aspera:* 3 x 10^6 cell/cm^2 *G. retiformis:* 6 x 10^6 cell/cm^2 *Favites abdita:* 1.5 x 10^6 cell/cm^2 *Coeloseris mayeri:* 4 x 10^6 cell/cm^2 *Go. pandoraensis:* 1 x 10^6 cell/cm^2 *Galaxea fascicularis:* 8 x 10^6 cell/cm^2	Fig 1a + text (Corals begin to bleach in May 30-30.5	Fig. 6 Pigmented sample *Goniastera aspera:* 10 x 10^6 cell/cm^2 *G. retiformis:* 11 x 10^6 cell/cm^2 *Favites abdita:* 9x 10^6 cell/cm^2 *Coeloseris mayeri:* 18 x 10^6 cell/cm^2 *Go. pandoraensis:* 18 x 10^6 cell/cm^2 *G. fascicularis* (control): 12 x 10^6 cell/cm^2	Fig 1a 28.5 **MMMax ≈ 29.5**	Analysis of coral collected in the field (1991 Bleaching event)	**[17]** **Ko Phuket Thailand** **(SEA)**
Fig 4a + text *Goniastera aspera:* 5.52 x 10^6 cell/cm^2	Fig 1 + text 28.81	Fig 4a + text *Goniastera aspera:* 7.4 x 10^6 cell/cm^2	Fig 1 + text 28.18 **MMMax ≈ cannot estimate**	Analysis of coral collected in the field	**[18]** **Ko Phuket Thailand** **(SEA)**

Bleached Corals (*) Compared to unbleached Corals

e.g. Symb density	Bleaching T (°C)	Symb. density	No Bl. T (°C)	Methods	Reference
In text 2.7 x 10^6 cell/cm^2	Summer July-October Not reported	In text 5.2 x 10^6 cell/cm^2 Pre-bleaching density (May 2008) 3.2 x 10^6 cell/cm^2 Post-bleaching density (May 2010) 8.3 x 10^6 cell/cm^2	Winter (December-February) Not reported	Analysis of corals *Orbicella faveolata* collected from 2-4 depth (Documenting recovery from October 2009 bleaching)	**[19] Puerto Morelos, Mexico (~CAR)**

- **[1] Shu et al. 2011**. Assessment of coral bleaching using symbiotic zooxanthellae density and satellite remote sensing data in the Nansha Islands, South China Sea. **Chinese Science Bulleting** (It was recently renamed Science Bulletin and is part of Springer)
  NOTE: I think this article is well written. However, they suggested that corals showing no visual signs of bleaching were in the initial stage of bleaching.
- **[2] Fitt et al. 2000**. Seasonal patterns of tissue biomass and densities of symbiotic dinoflagellates in reef corals and relation to coral bleaching. **Limnology and Oceanography.**
  NOTE: "On the basis of results of this study, we hypothesize that all reef corals worldwide exhibit similar seasonal cycles"
- **[3] Porter et al. 1989.** Bleaching in Reef corals: Physiological and stable isotopic response.
- **[4] Fitt et al. 1993.** Recovery of the coral *Montastrea annularis* in the Florida Keys after the 1987 "bleaching event".
- **[5] Hoegh-Guldberg, Ove and Smith, G. Jason. 1989.** The effect of sudden changes in temperature, light and salinity on the population density and export of zooxanthellae from the reef corals *Stylophora pistillata* Esper and *Seriatopora hystrix* Dana. **Journal of Experimental Marine Biology and Ecology**.
  NOTE: This study highlighted the difference between the 2 definitions of "bleaching": "Originally, coral bleaching referred to the loss of brown pigment by corals (Yonge & Nichols, 1931b). More recently, bleaching has been taken to be synonymous to the loss of zooxanthellae by corals (Refs) despite the fact that bleaching (by the original definition) has been reported to occur when zooxanthellae lose photosynthetic pigment rather than leave corals photo-adapting to high light conditions (Porter et al, 1984)". Particularly, this study (and other studies they compare their work with) shows that high light exposure causes loss of zooxanthellae pigments and high temperature causes lose of zooxanthellae density. **Therefore we can justify our use of zooxanthellae expulsion in our model of bleaching by stating that we are only dealing with temperature induced bleaching.**
- **[6] Berkelmans, Ray and van Oppen, Madeleine J. H. 2006.** The role of zooxanthellae in the thermal tolerance of corals: a 'Nugget of hope' for coral reefs in an era of climate change. **Proceedings of the royal society B**
  NOTE: MI refers to Magnetic Island, NKI refers to North Keppel Island and DR refers to Davies Reef
- **[7] Brown, B. E. and Dunne, R. P. 2008.** Solar radiation modulates bleaching and damage protection in a shallow water coral. **Marine Ecology Progress Series.**
- **[8] Jones, Ross J. 1997.** Changes in zooxanthellar densities and chlorophyll concentrations in corals during and after a bleaching event. **Marine Ecology Progress Series.**
- **[9] Bhagooli, R and Hidaka, M. 2002.** Physiological responses of the coral *Galaxea Fascicularis* and its algal symbiont to elevated temperatures**. Japanese Coral Reef Society.**
- **[10] Fagoonee, I. et al. 1999.** The dynamics of Zooxanthellae populations: A long-term study in the field. **Science.**
  NOTE: similar to conclusions of [2], "These bleaching events are likely to be part of a constant variability of zooxanthellae density caused by environmental fluctuations superimposed on a strong seasonal cycle abundance"…"The time series of zooxanthellae density over the study period is shown Fig. 1. The mean density was 1.7 x 10^6 cell/cm^2 (SD = 2.4 x 10^6 cell/cm^2), comparable to densities of 1 x 10^6 to 2 x 10^6 previously reported (10, 11)**".**
- **[11] Hoegh-Guldberg, Ove and Salvat, B. 1995.** Periodic mass-bleaching and elevated sea temperatures: bleaching of outer reef slope communities in Moorea, French Polynesia**. Marine Ecology Progress Series.**
- **[12] Levas, Stephen et al. 2018.** Long-term recovery of Caribbean corals from bleaching. **Journal of Experimental Marine Biology and Ecology.**
- **[13] Fitt, W. k. and Warner, M. E. 1995.** Bleaching Patterns of Four Species of Caribbean Reef Corals. **The Biological Bulletin.**
- **[14] Glynn, P. W. and D'Croz, L. 1990.** Experimental evidence for high temperature stress as the cause of El Niño-coincident coral mortality. **Coral Reefs.**
- **[15] Hueerkamp, C. et al. 2001.** Bleaching and recovery of five eastern pacific corals in an El Niño-related temperature experiment. **Bulletin of Marine Science.**
- **[16] Glynn, P. W. et al 2001.** Coral Bleaching and Mortality in Panama and Ecuador during the 1997-1998 El Niño-Southern oscillation event: Spatial/temporal Patterns and comparisons with the 1982-1983 event. **Bulletin of Marine Science.**

- **[17] Brown et al. 1995.** Mechanisms of bleaching deduced from histological studies of reef corals sampled during a natural bleaching event. **Marine Biology.**
- **[18] Brown et al. 1999.** Seasonal fluctuations in environmental factors and variations in symbiotic algae and chlorophyll pigments in four Indo-Pacific coral species. **Marine Ecology Progress Series.**
- **[19] Kemp et al. 2014**. Community dynamics and physiology of *Symbiodinium* spp. Before, during and after a coral bleaching event. **Limnology and Oceanography.**