A metrological approach to a coral reef bleaching alert system

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Introduction to Coral Bleaching

Corals rely on an endosymbiotic relationship with unicellular algae. These dinoflagellate algae (genus *Symbiodinium*), collect light and via photosynthesis, transfer energy to the coral. Coral bleaching refers to the dramatic loss of the *Symbiodinium* population that inhabits coral tissues, leaving the coral polyps transparent, which makes the underlying white calcium carbonate skeleton visible. This occurs when the symbiosis breaks down under any stressful condition capable of pushing the symbiosis beyond its limits of stability. Mass coral bleaching refers to bleaching at scales of an entire reef system (hundreds to thousands of kilometres) and is a recent phenomenon that first started in the early 1980s. It is caused by large scale sea temperature anomalies where the temperature becomes too warm. In the face of increased mass coral bleaching due to climate change (Eakin, et al., 2005; Heron, et al., 2016; Skirving, et al., 2019), tools that allow coral reef managers, scientists and stakeholders to monitor the extent and severity of coral bleaching are becoming more and more important. Some information comes from in situ bleaching surveys, which are important in understanding the biological details, but they only cover a limited area. The use of freely available satellite products (which can cover all reefs) to monitor heat stress now enables one of the most important global coral bleaching monitoring tools that exist today. For the past two decades, the most widely used satellite heat stress monitoring tools have been developed and served by the National Oceanic and Atmospheric Administration's (NOAA) Coral Reef Watch (CRW) program. CRW relies heavily on satellite-based sea surface temperature (SST) products to provide a wide range of coral stress metrics for use by coral reef managers, scientists, and other stakeholders. Its Degree Heating Week (DHW) flagship product, which is based on satellite SST anomalies relative to a climatology, provides a measure of accumulated heat stress and has been shown to be a strong predictor of mass coral bleaching (Eakin, et al., 2005; Heron, et al., 2016; Skirving, et al., 2019). The climatology used is based on the Maximum Monthly Mean (MMM) which is the maximum of the 12 monthly means calculated over 1985 to 2012 (Skirving, et al., 2000). Although the DHW product has been slowly developed over the past two decades, one thing that is missing is a thorough description of the myriad of uncertainties both on the SST side and on the biology side (which determines the thresholds used for bleaching detection). This poster represents the first attempt at a complete description of uncertainties associated with the calculation and calibration of the DHW coral bleaching product.

Coral Bleaching Alert Uncertainty Tree: Current SST Methodology

Following on from the application of metrology to satellite data for both historic and modern sensors (for a current overview see, for example, the poster "QA4EO framework and a metrological approach to FRMs, FDRs and TDPs", Woolliams *et al.* this conference) we have constructed a preliminary uncertainty tree for the coral bleaching alert system (see Figure 1). It can be split into two main sections. The top half corresponds to the current operational system based on 5km satellite SST data derived from Level 4 analyses from a range of satellite sensors (both polar and geostationary). The left-hand side (top half) is related to the real time SST data while the right-hand side (top half) corresponds to the baseline climatology and derivation of the MMM per pixel/location. The two sides are then combined to provide the HotSpot and DHW estimate used for the bleaching alert system. In terms of the underlying error effects for the original satellite SST data (derived from the level 1 radiance data), the likely effects are relatively well understood in broad terms, though the exact details for different sensors and SST retrieval methodologies are less well known as only a few instruments have had any detailed metrological analyses performed. Also, in terms of the Level 4 (analysis) data, where multiple instruments are combined and data gaps filled, the associated uncertainties and error correlations have not been fully scoped to date. Possible issues include uncertainties in regions with a lot of gap filling (due to persistent cloud) and there may also be temporal correlations as many Level 4 analyses use background data derived from previous days as part of their processing. Finally, there is also the issue of the DHW value which uses a threshold-based methodology, so the associated uncertainties may not be strictly Gaussian in nature. In conclusion, there are still many effects and uncertainties to be understood from the current operational bleaching alert system even before the addition of effects due to coral biology (the lower part of the uncertainty tree, see next section).

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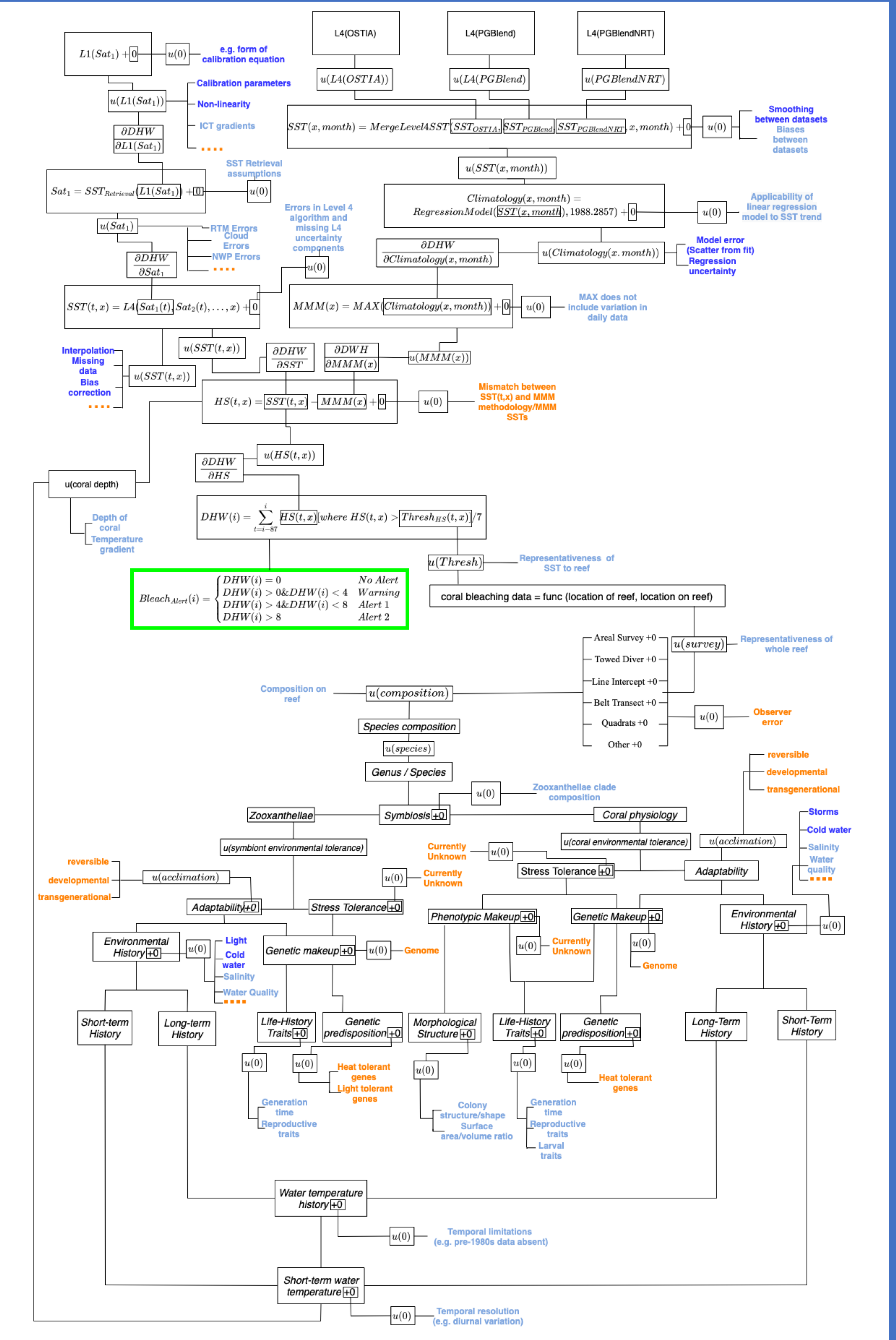

Figure 1: Coral Bleaching Alert Uncertainty Tree. The top half relates to the satellite-based DHW product and the lower half refers to the in situ bleaching surveys that are used to calibrate the use of DHW for monitoring bleaching. The coloured text shows the possible error effects driving the uncertainties with the different colours representing estimates of knowledge of those effects Dark blue corresponds to effects that are reasonable well known, light blue corresponds to effects which we don't know yet but can potentially estimate and orange corresponds to effects where we may not be able to characterise in detail or at all. For the biological tree we have not yet included sensitivity coefficients as how to calculate them needs to be understood.

Uncertainty Within the Biology of Coral Bleaching

The lower part of the uncertainty tree describes uncertainty with regards to coral biology which is used to calibrate the DHW product for use as a coral bleaching predictor. Biological uncertainty in the responses of corals to heat stress is diverse and ever-present. The ability of a coral reef to cope with excess SST (actually the excess temperature at the depth of the coral) is highly dependent on the species composition of that reef and different coral genera have varying capacities to handle thermal stress. While one coral species may begin to bleach at a DHW > 3, a coral only a few meters away could remain tolerant to stress up to a DHW of 6 or more. This is because varying coral physiology among genera provide different phenotypic and genetic characteristics that can make them more or less well-suited to handling heat stress. The morphological structure of a coral colony can also have significant implications for how likely it is to bleach under elevated heat stress conditions. Genera such as *Acropora*, which have very high surface area to volume ratios, are more likely to suffer high levels of bleaching compared to those with lower surface area to volume ratios, such as in *Porites* spp. Further, the horizontal area that a colony covers can also affect stress levels and recovery, as the amount of sunlight corals are exposed to is important in both bleaching and recovery. Different coral species also have variable levels of plasticity in relation to environmental change. Short-term SST conditions can influence the acclimation potential within the lifespan of that coral, and long-term SST conditions can provide corals with the capacity for transgenerational acclimation, and therefore an increased potential for genetic adaptation. The other aspect of coral biology that leads to uncertainty is the symbiosis with their zooxanthellae, *Symbiodinium*. The various clades of *Symbiodinium* have different thermal tolerances. Depending on the community mix of *Symbiodinium* present, a coral host is capable of shuffling the available clades into different roles, changing the dominant symbiont type to a more heat resistant one. These examples highlight the myriad of uncertainties in quantifying coral bleaching assuming an accurate, objective bleaching measurement of every coral on a reef. However, in situ coral bleaching data relies on subjective visual assessments of the level of bleaching which includes bleaching from all forms of stress, even those that only cause individual colonies or individual reefs to bleach (i.e. not mass bleaching). These stressors include: anomalous temperature (both hot and cold), anomalous increasing levels of light, anomalous levels of salinity (both high and low), reduction in water quality (e.g. heavy metals), diseases and more (Skirving, et al. 2017). Additionally, partial loss of coral pigmentation can occur during acclimation to high-light conditions or low nutrient availability. Seasonal changes in the number of symbionts and/or in symbiont pigmentation can also lighten coral colour (Skirving, et al., 2017). These processes can often be confused on a visual assessment, but this should be avoided as they do not result in a dysfunctional effect on the symbiotic relationship. Since coral reefs are large complex structures, in situ surveys use sampling techniques (often a single transect in a single location and depth on each reef), which are then assumed to be representative of the entire reef which is almost certainly never the case. Also, since the global data set from in situ surveys used by CRW is sourced from hundreds of providers, the variation of sampling techniques is huge (e.g. ranging from in situ observations of a single coral colony through to aerial surveys). The uncertainties within the "ground truth" data used in the development of CRW's DHW product may then have larger total uncertainties than the satellite products. Nevertheless, understanding and quantifying the uncertainty in the in situ coral bleaching data will contribute greatly to our understanding of the uncertainty within the biological processes of coral bleaching.

Recommendations

We have shown a first attempt to understand uncertainties present in coral bleaching alert systems using an uncertainty tree which for the first time includes both observational and biological processes. As can be seen, the range of different uncertainties is large and often not well understood, particularly for the biological processes. Work on some aspects of the problem will help and some starting recommendations are:

- Continued improvement in understanding SST uncertainties including on climatologies.
- Since heat stress on corals is a continuous phenomenon, it is important to quantify uncertainties related to gap filling in satellite-based L4 SST products
- Modelling biological uncertainties may be the only non-destructive way to quantify many of the biological uncertainties of coral bleaching and should be pursued
- A better understanding of biological adaptation is necessary if we are to quantify uncertainty with predictions of future climate change effects.
- More consistent standards should be set for coral bleaching survey methodologies.
- This study provides glimpse into the possible future of metrology as it increasingly important to merge biological uncertainties (with no strict measurement equations and yet to be determined sensitivity coefficients) with the uncertainty of physical phenomenon.