

Blooms of *Synechococcus*

**An analysis of the problem worldwide and possible
causative factors in relation to nuisance blooms in
the Gippsland Lakes**

A report prepared for the Gippsland Task Force by

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Introduction

This report has been prepared for the Gippsland Task force in response to a major bloom of the cyanobacterium *Synechococcus* in the Gippsland Lakes system during late 2007, persisting into April 2008.

The Gippsland Lakes are a system of coastal lagoons situated in southwest Victoria, about 200 km east of Melbourne and are important for recreational, tourism and commercial activities. Considerable modifications to the Lakes' catchments have occurred since European settlement, including the creation of a permanently open entrance to Bass Strait in 1889. This environment, which was once a freshwater lake, is now a more saline, high nutrient region. Salinity varies from 0.5-10‰ in Lake Wellington, though Lake Victoria with 4-17‰ in surface waters overlying 7-25‰ in bottom waters, to Lake King, where bottom waters can be at full salinity (36‰) and surface waters reach 26‰ (Webster et al. 2001). Other changes in water quality have occurred, with recurring blooms of the cyanobacterium *Nodularia spumigena* being of major concern. There have been four major bloom events since 1995 (all dominated by *N. spumigena*), after only one significant bloom in the previous 20 years (Van Buynder et al. 2001).

In November 2007, however, a major bloom of another cyanobacterium, *Synechococcus* sp, appeared and this persisted until early April 2008. The appearance of *Synechococcus* in the Gippsland Lakes system is a departure from previous observations and as a result, this report was commissioned by the Gippsland Task Force to provide background and insights into the event. .

This report is intended to:

- Provide background information on the biology of *Synechococcus* and its occurrence in blooms around the world,
- Use the literature to suggest environmental factors that may be involved in triggering and modulating blooms of this organism,
- Make inferences as to possible triggers for the bloom in the Gippsland Lake system,
- Make recommendations, as far as possible, on management and/or monitoring strategies in relation to *Synechococcus* blooms in the future.

Background information on the genus *Synechococcus*:

Photosynthetic, oxygen-evolving prokaryotes are extremely important primary producers in the world's oceans (Wiesse 1993), where they make a significant contribution to the picoplankton (broadly defined as phytoplankton cells 0.2-2 µm in size). However, despite this, the diversity among this group of organisms is low, and it is represented almost exclusively by the two genera *Synechococcus* and *Prochlorococcus*.

Synechococcus is a genus of cyanobacterium that is distributed widely in the oceans, although there are also some freshwater species. *Synechococcus* is an important organism across all marine environments, where it can be found at concentrations ranging from 5×10^5 to 1.5×10^9 cell L⁻¹, which translates into approximately 7.5 to 12 µg chlorophyll *a* L⁻¹ (Partensky et al. 1999; Moore et al. 1995), although blooms dominated by *Synechococcus* can attain chlorophyll concentrations up to 150 µg chlorophyll *a* L⁻¹ (Ning et al. 2000).

Synechococcus and *Prochlorococcus* have somewhat different ecological niches. *Prochlorococcus* is less ubiquitous, but dominates in equatorial waters with low

nutrient levels. The genus is absent from brackish and well-mixed waters, but can exist at considerable depth in the water column as it is extremely well adapted physiologically to low light conditions (Moore et al. 1995). In contrast, *Synechococcus* can be found in areas where salinity is relatively low (<15-20 PSU) and temperatures are lower (<20°C) than those favouring *Prochlorococcus* (see Paretsky et al. 1999 for a review). It is also more abundant than *Prochlorococcus* in more nutrient-enriched waters.

In some studies, *Synechococcus* has been found as two distinct morphotypes distinguishable by size. In Florida Bay for instance, a size class of larger cells was dominant whenever cyanobacteria reached bloom proportions. This size class was consistently phycocyanin (PC)-rich and cultures have a green tint (Phlips et al. 1999). In the Black Sea, surface blooms of *Synechococcus* were comprised of larger cells than those populations from deep water (Uysal 2000). In contrast to the phycocyanin rich cells, phycoerythrin (PE)-rich isolates have an orange-red tinge (Murrell and Lores 2004). It seems that in some systems (see discussion below and Murrell and Lores 2004) these two strains have different salinity preferences, with the PC-rich strains occurring in salinities <20 PSU, and the ratio of PC:PE-rich cells in a population declining at salinities >20 PSU.

In contrast to many other cyanobacteria, there are few reports of toxins from *Synechococcus*, though cultures of some strains have been reported as being capable of producing compounds with neurotoxic and hepatotoxic effects (Martins et al. 2005). While reports of toxicity in *Synechococcus* blooms are rare, this is largely because investigators have not been attuned to the possibility of this genus producing toxins. We simply do not know how widespread this phenomenon is in *Synechococcus* and it would be important to verify if the strain(s) occurring in the Gippsland Lakes also produce toxins and under what conditions.

Blooms in coastal/estuarine systems throughout the world

Despite its association with open ocean systems, it is becoming increasingly evident in recent years that *Synechococcus* is a significant contributor to algal blooms in tropical and sub-tropical coastal systems, and even appears in temperate waters given favourable circumstances. Significant blooms have been described from Pensacola Bay (Florida) from Florida Bay (Phlips et al. 1999), San Francisco Bay (Ning et al. 2000), the Mediterranean Sea (Agawin et al. 1998; Agawin & Augusti 1997; Perez & Carrillo 2005; Modigh et al. 1996; Bec et al. 2005), the Baltic Sea (Kuosa 1991) and the Black Sea (Uysal 2000). Summaries of the occurrence of *Synechococcus* in a range of marine systems are provided by Perez & Carrillo (2005) and Li (1998). The references cited above also contain information about the relationship of blooms to the physical (light, temperature), chemical (salinity, nutrient levels) and biological factors (grazing) contributing to blooms. These are discussed below.

Environmental factors driving *Synechococcus* blooms

Light

While *Synechococcus* has efficient light harvesting systems, it does not perform as well as *Prochlorococcus* at extremely low irradiance (Moore et al. 1995). Consequently, it is not found at the depths that *Prochlorococcus* can occupy. Nonetheless, cyanobacterial growth in the Mediterranean has been reported to be positively correlated with irradiance (Bec et al. 2005; Modigh et al. 1996), and irradiance should be considered a significant driving force in sustaining

Synechococcus blooms. The genus is certainly tolerant of high light conditions (Phlips et al. 1999)

Nutrients

There are reports of *Synechococcus* being able to fix atmospheric nitrogen (Chow and Tabita 1994), an advantage under the low nutrient conditions in which it is often found. Unlike some species of cyanobacteria which fix N₂ in specialised cells called heterocysts, *Synechococcus* has no cell specialisation and avoids the interference by oxygen in the nitrogen-fixing reactions by carrying out N₂ fixation at night when intracellular O₂ levels are lower and driven down by respiration. In Florida Bay, N₂ fixation has been suggested as a significant factor sustaining blooms of *Synechococcus* (Evans et al. 2006). In the Gippsland Lakes the N:P ratio ranges from 19:1 to 24:1 (Webster et al. 2001) implying that N is not a limiting factor unless there are large inputs of P into the system. The N₂-fixing capacity of *Synechococcus* would thus be unlikely to have a significant impact on bloom formation and persistence unless, as is the case with *Nodularia* blooms, P inputs increased and N became limiting.

However, *Synechococcus* is also found in regions with elevated inorganic nutrients, especially nitrogen. Mesocosm experiments in the Laguna Madre of Texas showed that ammonium addition stimulated growth of *Synechococcus* in mixed populations (Buskey et al. 2003), although Ning et al. (2000) found increased picoplankton populations along a decreasing nutrient gradient in San Francisco Bay. *Synechococcus* is also found in highly eutrophic waters in the Gulf of Naples (Modigh et al. 1996) and is also capable of utilizing dissolved organic nitrogen compounds (DON) such as urea (Glibert et al. 2004). Wawrik and Paul (2004) and Wawrik et al. (2004) have clearly demonstrated the importance of N inputs from the Mississippi River in stimulating algal (including *Synechococcus*) blooms in the Gulf of Mexico.

It is likely therefore that high nitrogen (DON and inorganic N) loadings, together with the elevated levels of other nutrients such as P, in the Gippsland Lakes are contributing to the persistence of *Synechococcus* blooms.

Temperature

Temperature is undoubtedly a very important driver of *Synechococcus* growth. Significant relationships between *Synechococcus* growth rates and biomass accrual have been reported by a number of authors working on a variety of systems (see e.g. Murrell and Lores 2004; Li 1991; Agawin et al. 1998; Ning et al. 2000; Bec et al. 2005). This, combined with the capacity to cope with high light intensity (see above) means that growth is highest in summer and lowest over winter (see Agawin et al. 1998 and references therein; Modigh et al. 1996; Murrell and Lores 2004). Optimal growth of *Synechococcus* in the Mediterranean has been reported at ~24°C with no growth when water temperatures were <11°C (Agawin et al. 1998). Cyanobacterial abundance (dominated by *Synechococcus*) was greatest when water temperatures were 28-30 °C in Pensacola Bay, Florida (Murrell and Lores 2004). The data of Jonathan Smith (pers. comm.) provides good evidence that there is a strong relationship in the Gippsland Lakes between cyanobacterial biovolume and temperature, with lower cyanobacterial numbers as temperatures drop below ~20°C.

Salinity

There are some reports that salinity can be a contributing factor to growth of *Synechococcus*. In the Black Sea, inshore waters with low salinities (≤ 15 PSU) had the lowest *Synechococcus* cell densities (Uysal 2000). For Penascola Bay in Florida, Murrell and Lores (2004) reported that the proportion of phycocyanin-rich to phycoerythrin-rich strains of *Synechococcus* decreased dramatically as salinity changed from ~ 20 PSU to 28 PSU, i.e. PC-rich cells were an order or magnitude higher in abundance in the upper, lower salinity, part of this estuary. Perez and Carrillo (2005) showed a significant decline in picoplankton populations at low (< 5 PSU) salinities compared with higher salinity stations in the Ebro River estuary (Spain). In contrast, Ning et al. (2000) reported weak positive correlations with salinity in the range 20-30 PSU and *Synechococcus* populations in San Francisco Bay at certain times of the year, though in this study such effects were of secondary importance compared to temperature. Given the salinity gradients that exist in the Gippsland Lakes, salinity may be one of the drivers behind the genesis and persistence of *Synechococcus* blooms. However, as discussed above, such effects may well be secondary to those of temperature. *There is evidence that cyanobacterial blooms in the Gippsland Lakes show a strong positive correlation with temperature, but high temperatures will not necessarily lead to elevated Synechococcus numbers if the salinity is low* (Jonathan Smith, pers comm., 'BGA Incident Management Monitoring Summary to Monday 12/05/08', unpublished data of Jonathan Smith).

Grazing

Synechococcus populations frequently show high growth rates in nature. However, extensive blooms are not always found and it is believed that grazing exerts a strong influence on population size. The effects of zooplankton grazing have been demonstrated experimentally in mesocosms by Buskey et al. (2003). Significant grazing pressure has also been reported in studies of *Synechococcus* population in the Bay of Villefranche (NW Mediterranean Sea) (Dolan and Simek 1999) and in the Black Sea (Kuosa 1991). Bloom formation has been suggested to occur when top-down control from grazers breaks down.

Gaps in our knowledge, recommendations for possible management strategies and future research

The review above raises a number of questions regarding the gaps in our understanding about *Synechococcus* autecology, and particularly the determining factors in the onset of *Synechococcus* blooms in the Gippsland Lakes. Unfortunately, the data available *Synechococcus* occurrence in the Gippsland Lakes system is not robust enough to point to causal factors (see below), although it is likely that high temperature and relatively high salinity provide ideal conditions for initiation of the bloom and that the high light in summer and elevated nutrient levels would allow the bloom to persist. Monthly data on biovolume, temperature and salinity provided by Jonathan Smith support these conclusions.

Unfortunately, the data available from Jonathan Smith are based on the total biovolume of algae/cyanobacteria with little specific data on *Synechococcus* abundance (though dominant species are indicated). *Clearly, this is a matter that should be addressed and future monitoring needs to include counts of individual dominant species (or at least genera)*. Without this, little can be done to tease out contributing factors to *Synechococcus* bloom genesis and persistence in the Gippsland Lakes

While there are many indications from the literature of the contribution of different environmental factors to *Synechococcus* growth and blooms in other systems throughout the world, it is clear that different strains may respond differently. This is certainly the case for *Nodularia spumigina* isolated from the Gippsland Lakes and compared to literature data on strains isolated elsewhere (J. Myers, PhD Thesis, Monash University, in preparation). *I would strongly recommend that the Task Force implement research into the autecology of strains of Synechococcus isolated from the Gippsland Lakes, to determine how their growth is regulated by temperature, salinity and nutrient (N and P) levels, and to a lesser extent light.*

The toxicity of *Synechococcus* from the Gippsland Lakes is unknown and this is potentially a significant issue with regard to management and public health issues. *I recommend that the Task Force include some degree of toxicity monitoring of the Synechococcus blooms as they occur, but also suggest that toxicity measurements could be incorporated into the autecological studies recommended above.* Toxin production may be triggered by certain environmental conditions and may not always be constitutive.

Clearly, there is a case for (a) improved monitoring to include numbers of specific genera as well as total biovolume, and (b) autecological studies on strains of Synechococcus specifically isolated from the Gippsland Lakes. The latter would involve, as a minimum, measurements of pigment content, growth rate and final biomass yield in cultures as a function of temperature, salinity and nutrient availability. The issue of toxicity is important because most previous work has assumed a lack of toxin production by this genus, and reports of hepatotoxic and neurotoxic effects from *Synechococcus* cultures originating from other systems are of considerable public health concern. Toxicity studies might be combined with the autecological investigations suggested above.

The bloom event in 2007/2008 was unusual in being dominated by Synechococcus rather than Nodularia. It is difficult to decide on the limited data available if this represents a change of state that will lead to Synechococcus becoming the dominant bloom organism in the future, and the large bloom of this species from late 2007 until April 2008 may have arisen from a unique combination of environmental parameters. If *Synechococcus* blooms are repeated in late 2008, then we might be seeing such a state change. However, unlike *Nodularia*, *Synechococcus* does not produce the resting cells (akinetes) that allow the species to persist under adverse conditions and which act as the 'seed bank' for future bloom events. This means that the capacity for *Nodularia* to bloom in the Gippsland Lake will remain because 'seeds' will remain in the sediments for several years into the future.

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