

Plankton Modelling and CLAW

Roger Cropp¹ and John Norbury²,

¹ Centre for Environmental Systems Research, Griffith University, Brisbane, Australia.

² Mathematical Institute, University of Oxford, 24-29 St Giles, Oxford, UK.

The CLAW hypothesis postulates a central role for dimethylsulphide (DMS) in the regulation of climate and invokes a plethora of biological, chemical and physical processes that interact to produce a climatic effect. None of these processes are well understood. Although some ice core data reveals the close coupling between biogenic sulphate aerosols and climate variation,^[1] little compelling empirical evidence supporting the existence of a CLAW effect has come to light in the 20 years since its publication. The recent Fourth Assessment Report of the IPCC considers CLAW contributes “a small negative climate feedback to global warming”.^[2] So why has CLAW persisted in the face of such faint praise?

Once produced in the ocean, the small proportion of DMS that makes it into the atmosphere is subject to a myriad of physical and chemical processes on its way to forming a cloud condensation nuclei and influencing climate. However, the influence of CLAW as a climate regulator is predicated on changes in DMS supply to the atmosphere, rather than changes in atmospheric processes, and DMS is a product of ocean plankton. The dynamics of marine plankton ecosystems are determined by both their internal (largely nonlinear) relationships and their response to external forcings; understanding such complex adaptive systems requires the use of process-based models. A common property of many DMS models is that they are typically slaved to their associated ecosystem models: – the DMS dynamics they predict are completely determined by the dynamics of the ecosystem models.^[3] Understanding the marine plankton ecosystem models that drive the DMS models is therefore central to any attempt to simulate the climatic influence of the CLAW hypothesis.

Since the publication of the first simple models of marine biogenic DMS production by Gabric et al.^[4] and Lawrence^[5] the number and complexity of DMS models has increased dramatically. Where the model of Gabric et al.^[4] was a zero-space-dimensional unforced ecosystem model with five biotic variables, one nutrient, and two sulphur species, current models with five trophic guilds may have within those guilds up to five phytoplankton functional types, three zooplankton and three bacteria, as well as five nutrients, four detrital compartments and three sulphur species, and may be forced by high resolution, one- or three-space-dimensional ocean models^[6-8]. While the coupling of these ecosystem models to global ocean models is essential if the potential for CLAW to mediate climate change is to be evaluated, several issues remain unresolved along the path to this goal.

The first issue cuts to the very core of ecological modelling – how much can we rely on what these models tell us? Ecosystem models attempt to encapsulate the most important

processes in ecosystems, but the plethora of different ecosystem formulations and process representations are testament to the lack of consensus on what the important processes are and how they should be represented. While various process formulations are intended to emphasise different ecosystem concepts (i.e. nutrient limited feeding, density dependent grazing, competition, etc), little hard evidence exists to identify the “correct” formulations, and those used may merely represent the preference of the model builder. Compounding this is a paucity of knowledge specifying the values that the parameters that define these processes should take. While several comprehensive data sets enabling plankton ecosystem models to be calibrated in specific scenarios exist, only a few global data sets exist to facilitate the calibration of global ecosystem models. The most comprehensive of these are derived from climatologies of satellite measurements (i.e. SeaWiFS chlorophyll concentration and photosynthetically active radiation, AVHRR sea surface temperature), the least comprehensive are interpolated from sparse *in situ* measurements (i.e. aqueous DMS and nutrient concentrations, mixed layer depths).

The second issue is fundamental to all high-dimension nonlinear models, a descriptor that is certainly appropriate to all but the very simplest ecosystem models; how do these models respond to change? Central to climate modelling are predictions that things will change – in the case of plankton, sea surface temperatures and mixed layer depths will change; in response, we could expect succession in plankton communities. This means that the poorly known ecosystem parameter values in our somewhat arbitrary processes will change, and in high-dimension nonlinear systems this can lead to a multitude of behaviours that are fundamentally different to the initial behaviours that were so carefully tuned to replicate observed dynamics. The uncertainty over the ‘correct’ representation of processes compounds this problem – changing the formulation of just one term in a model can fundamentally change some aspects of the behaviour of the system, sometimes while leaving others unchanged. Understanding and predicting these potential behaviours in complex models is difficult; analysis even of the now comparatively simple Gabric et al.^[4] model ventures into regions where nonlinear dynamical systems theory is sparse and numerical methods with their inherent uncertainties must be used.

Two further issues are specific to plankton ecosystem models and these are essentially the pragmatic issues that currently constrain the utilisation of global models that could be used to test CLAW. One is that plankton ecosystem models often perform poorly when reproducing chlorophyll dynamics in the tropical and sub-tropical oceans – while most models can reproduce the mean annual concentration reasonably well, few if any can reproduce the temporal dynamics of the chlorophyll signal. Further, in the context of DMS modelling, few models can explain the ‘DMS summer paradox’, observed again in low latitude waters, where DMS concentrations are high in summer but chlorophyll concentrations are low^[9]. In contrast, almost all models can reproduce both chlorophyll and DMS dynamics in high latitude (>40°) waters where seasonal forcings of light, mixed layer depth and temperature have comparatively large amplitude. In these regions phytoplankton bloom dynamics appear to be determined by the generic theory proposed by Sverdrup^[10] and DMS concentrations are in phase with chlorophyll concentrations. While it is often assumed that chlorophyll dynamics at low latitudes are determined by as-yet poorly understood nutrient dynamics,^[11] the failure of models to reproduce DMS

dynamics at low latitudes appears to be an attribute of the generic structure common to most current DMS models.

As noted above, DMS models are typically slaved to the ecosystem models that drive them. The precursor of DMS, dimethylsulphoniopropionate (DMSP) is produced by phytoplankton (whereas DMS is an ecosystem product), so model DMS dynamics are always closely associated with phytoplankton dynamics. Hence, models produce DMS predictions that are temporally correlated with chlorophyll, contrary to the observed DMS summer paradox. However, Sunda et al.^[12] observed in laboratory experiments that phytoplankton boosted their intracellular DMSP concentration and their DMSP to chlorophyll ratios in response to oxidative stressors such as solar UV radiation (as well as CO₂ or Fe limitation and others). In a subsequent analysis of field data Vallina and Simo^[13] suggested light was highly correlated with DMS in the ocean. A recent model by Vallina et al.^[14] incorporating this effect reproduces the DMS summer paradox, effectively ushering in a new generation of DMS models that include time-dependent forcings and are therefore not necessarily slaved to their ecosystem dynamics.

So why has CLAW persisted for twenty years despite empirical evidence of its influence and theoretical understanding of its mechanism being so slowly elucidated? An obvious rationale is that, despite the IPCC's (perhaps premature) conclusion that CLAW produces a minor climate effect, many researchers still consider that the true potency of CLAW in the climate story has yet to be revealed. There may also be a deeper perception that CLAW could be a litmus for a class of complex adaptive systems that have developed in, and are important to, the Earth System. Explicating the dynamics and properties of CLAW, and perforce the ecosystems that drive it, could ultimately be a key aspect of human understanding of the systems that support life on Earth. In developing models to facilitate our understanding of CLAW we should seek simple, robust, universal, dynamical models that have the potential to evolve as external factors change. These models must be able to capture the significant temporal and spatial variation of phytoplankton populations, the foundation of life in the oceans and CLAW. Even if CLAW ultimately turns out to be irrelevant to contemporary climate change, it may well leave a fundamentally important legacy to our perceptions of how the world works, and to the way we need to do science in order to understand it.

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