



## Introduction to the Themed Section: 'Revisiting Sverdrup's Critical Depth Hypothesis' Introduction

### Revisiting Sverdrup's critical depth hypothesis

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Published more than 60 years ago in this Journal, the article in which Sverdrup proposed the concept of critical depth to explain the initiation of the spring bloom in the North Atlantic has accrued an exceptionally large number of citations and continues to be cited more than 50 times per year. The framework provided by Sverdrup has now been applied, adapted, and tested across many aquatic systems worldwide. Datasets have been collected; models have been built on the framework: these studies have generated new insights into phytoplankton dynamics and interesting debates on the relative importance of the various factors responsible for phytoplankton blooms. This article theme set presents some of the most recent efforts to discuss and test Sverdrup's critical depth hypothesis using a diverse set of approaches, ranging from controlled experiments to field observations as well as numerical and analytical models. The set of papers celebrates an elegant and powerful hypothesis that has had long-lasting influence. It is to be expected that it will also stimulate future research, adding even more to our understanding of one of the most fundamental processes in biological oceanography.

**Keywords:** bloom onset, light attenuation, mixed layer, mixing depth, phytoplankton, primary production, stratification, turbulence.

#### Background

More than 60 years ago, [Sverdrup \(1953\)](#) published an article in this Journal laying down the theoretical framework for analysing spring phytoplankton bloom initiation in the North Atlantic. It inspired a generation of oceanographers, and continues to do so to this day. In a world where it has become fashionable to cite the most recent author to advance an idea, rather than the first, Sverdrup's article remains one of the most cited publications in the field (see below). This is a testament to its importance.

What is the secret of its longevity? Probably, the answers to this question would be as varied as the backgrounds and interests of the scientists to whom it might be posed, but we will try to list a few aspects that we find important. First of all, Sverdrup provided a rigorous, mathematical formalism to concepts and observations that had been aired before (e.g. [Gran and Braarud, 1935](#)), thereby making it possible to test hypotheses regarding phytoplankton blooms in a quantitative way. Although he addressed the specific case of spring blooms, the model presented by Sverdrup was built on the broad and strong general principle of mass balance for

phytoplankton in a layer of the water column, such that the model was readily applicable to the study of any type of phytoplankton dynamics just about anywhere. The model, which is deceptively simple, is rich in potential applications, providing a master class on how to construct a general model and how to simplify it for a specific case: that of the spring bloom initiation in the North Atlantic. The simplifications led to an analytic result that provided insights into the processes that determine spring blooms. Even in the current oceanographic era when numerical modelling is the norm and the aspiration, analytic solutions remain the method of choice for interpretation of model solutions.

It is useful to recognize the two distinct parts of the critical depth concept that Sverdrup introduced: the first part, that uses the principle of conservation of mass in a layer of the water column to study net change in phytoplankton concentration, is axiomatic, and may be recognized as a theory that cannot be violated: it provides the framework for constructing details of a model. The second part, which identifies the major factors responsible for the formation of blooms, belongs more in the realm of hypotheses that can be tested. And, the model has been tested, again and again.

When authors have criticized the Sverdrup model, most of the criticisms have been levelled at the specific case with which Sverdrup chose to illustrate his model, pointing to additional processes or different parameterizations that might have been invoked to render the model more suitable for situations and locations not considered, or perhaps not relevant, to the particular case Sverdrup studied. In so doing, some authors overlooked a deeper message in Sverdrup's paper: biological dynamics in the ocean can be described by rigorous equations based on first principles (in this case, the principle of mass balance) to yield original results testable by observations at sea. It was a revolutionary view when the paper was published. In our opinion, the paper remains a thing of beauty, as useful now as it was then, whose importance matures as one or another criticism makes us realize how easily the Sverdrup model can be adapted to a variety of situations.

The paper introduced a biological depth horizon—the critical depth—that has remained arguably the most important reference depth for the study of phytoplankton dynamics, on a par with the mixed layer depth (or mixing depth) in the physical domain and euphotic depth in the optical domain. Importantly, Sverdrup brought the biological and the physical reference depths in juxtaposition, and discussed the implications. In this regard, his was among the first models to explore biological–physical interactions in the ocean. The work has also led to interesting discussions on the nuances that differentiate a mixed layer from an actively mixing layer [see Franks (2015)], which helped explain apparent contradictions that seemed to violate the very foundations of the concept of critical depth: instances when biological fields appeared to show vertical structure in a surface layer notwithstanding that the physical properties indicated a deeper mixed layer. Interestingly, in such instances, one might argue that vertical profiles of some easily measured biological or bio-optical properties could provide excellent measures of mixing depth, in the absence of direct measurements of turbulence. One might also argue that such studies, discussing apparent contradictions between biological and physical fields, have provided impetus to physical oceanographers to delve deeper into processes that govern the development and evolution of mixed layer and mixing layers, to assess which of these would be more appropriate for interpretation of biological processes.

### Quantifying the impact of Sverdrup (1953)

The bibliographic database Web of Science (WoS), Thomson Reuters, was used to trace the influence of Sverdrup (1953) in the literature. Sverdrup's publications are not indexed as primary literature in the WoS. Therefore, citations to the articles from the indexed literature were traced using the WoS's cited reference search in which the author names and publication year are used to identify cited references. We searched for citations to "HU Sverdrup 1953" in journals that are indexed in WoS from 1945 onwards. The searches were carried out in April 2015. The retrieved citing publications were analysed according to bibliographic parameters such as publication year, journal, and nationality of citing authors. A quantitative bibliometric analysis does not yield any information about the reasons why an article or author's work continues to be cited. To provide more insights into that question, we conducted a citation context analysis by analysing the textual passages in which Sverdrup (1953) is referred to in the citing documents [*sensu* Small (1982)]. We made an arbitrary choice to look only at citing articles that in turn have been highly cited. Using this approach, we were able to assess the influence of Sverdrup's work on other high impact publications within the field. We limited the

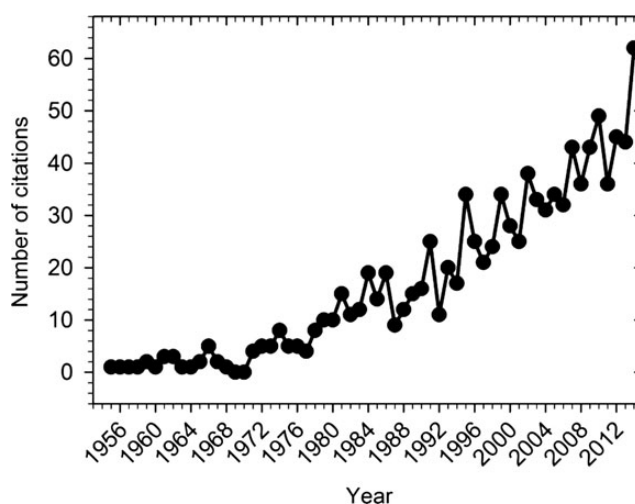
study to the top 20 articles, all of which have been cited >200 times. Thus, the context analysis should be considered illustrative rather than systematic.

In total, 1082 unique citations of Sverdrup (1953) were identified (including citations from 1953 to April 2015). Those articles have themselves been cited >43 000 times. The top five highly cited articles that refer to Sverdrup (1953) have accrued between 488 and 881 citations themselves. Google Scholar listed 1543 cites to Sverdrup (1953).

The number of citations has increased over time, with Sverdrup (1953) currently being cited an impressive 30–60 times per year (Figure 1). Very few publications, in any field, attain total citation numbers as high as this and the current citation rate is exceptional for a 62-year-old scientific publication. The typical scientific article is poorly cited the first year after publication; and a citation peak is reached ~3 years after publication, followed by decreasing citedness (Aksnes, 2003). In oceanographic research, the rise typically takes longer, although it rarely reaches a level anywhere near as high as has Sverdrup (1953). Aksnes (2003) defined different temporal citation patterns of highly cited articles. One category, termed "delayed rise, no decline", is characterized by a relatively slow rise in citation frequencies and a stable or increasing citation level thereafter. The citation curve of Sverdrup (1953) resembles this category of highly cited articles (Figure 1). Such a citation pattern indicates that Sverdrup (1953) reports research—concepts—theories that are of continuing interest to researchers.

When interpreting the citation life cycle of Sverdrup's work, it must be noted that there has been a large increase in the overall volume of research in marine science since 1953. Thus, the number of articles that could cite Sverdrup (1953) is much larger today than in the past. However, this does not account for the rise in citations to Sverdrup (1953), since they have risen from ~2–5 per year before 1980 to >30 per year since 2000, an increase that is much greater than the overall growth in marine science publications during the same period (i.e. a factor of ~3).

Garfield (1977) identified 15 reasons why a particular article might be cited. At least two of them seem particularly relevant for Sverdrup (1953): paying homage to pioneers and identifying original publications in which an idea or concept was discussed. The second, more specific type of referencing, "identifying original



**Figure 1.** The absolute number of citations to Sverdrup (1953) per year (1953–2014).



the articles. Typically, the introduction of a scientific article is structured as a progression from the general to the particular and often starts with references to the more general or basic works within a field. Consistent with this, references to Sverdrup (1953) are often found at the beginning of the text. Moreover, there are several instances of the work having been the basis for other notable hypotheses in marine science, for example Cushing's match–mismatch hypothesis, “The hypothesis assumed that during the spring peak, plankton production followed Sverdrup's (1953) model, and that during the autumn peak the same principles applied, but in reverse—spring and autumn are the periods of mixing or weak stratification” (Cushing 1990, p. 251, lines 8–11). In another example, Platt *et al.* (2003a, b) found it illuminating to place their model on phytoplankton biomass and residual nitrate in the mixed layer in the context of Sverdrup's critical depth. They pointed out that, if environmental conditions remain stable, changes in phytoplankton concentration will draw the critical depth towards the mixed layer depth, and the maximum biomass that can be attained will be dictated by the mixed layer depth and the bio-optical properties of the system: a bio-optical homeostasis that guards against runaway blooms (Sathyendranath and Platt, 2007). More recently, the concept of bloom initiation timing has been placed into the more general topic of plankton phenology under a changing climate (e.g. Ji *et al.*, 2010).

It is worth noting that teachers still use Sverdrup's work to stimulate student engagement and discussion of topical issues in biological oceanography. A paper that emerged from such a course (Fischer *et al.*, 2014) points out that Sverdrup's model provided a framework against which new observations could be compared with garner new insights into the functioning of the marine ecosystem.

### The articles in this theme set

The papers that make up this theme set of the *ICES Journal of Marine Sciences* provide a cross section of the various types of research that are still stimulated by Sverdrup's work. New datasets from both field observations of many different regional oceans, along with theoretical analyses based on different types of models, are included.

Franks (2015) points out that we may have sometimes been lax in “testing” Sverdrup's carefully laid-out critical depth hypothesis. Step by careful step, he lays out the different physical processes that have a potential influence on phytoplankton dynamics, and discusses the associated scales and their implications for bloom formation. Lewandowska *et al.* (2015) focus on the importance of phytoplankton traits such as growth rates, photoadaptation to low light, nutrient kinetics, and grazing resistance for the formation of phytoplankton blooms.

Different types of models are used to examine various aspects of bloom dynamics associated with the critical depth hypothesis. Enriquez and Taylor (2015) use a theoretical approach to explore the contrasting roles of wind mixing and surface heating on the timing of spring blooms. Levy (2015) uses a nitrogen–phytoplankton–zooplankton simulation model that is run with varying degrees of complexity in how the biological and physical processes are expressed in the model to examine conditions under which one process or another has a dominant role in dictating bloom formation. Lindemann *et al.* (2015) use a Lagrangian model that follows a population of individual cells to illustrate the importance of plasticity of phytoplankton physiological rates in determining phytoplankton community structure and dynamics.

Regional coverage and spatial scale of the studies in this theme set is also broad. Smith and Jones (2015) examine phytoplankton

growth in the Ross Sea in the context of the critical depth criterion and wind mixing, and conclude that periods of calm, favouring shallow mixed layers interspersed with deep wind mixing events favoured accumulation of high biomass in the mixed layer. Brody and Lozier (2015) use *in situ* data from the Labrador Sea and the North Atlantic to study blooms, and conclude that the transition of oceanographic conditions in Spring from buoyancy-driven to wind-driven mixing conditions marks the onset of blooms. Llorca *et al.* (2015), Sallée *et al.* (2015), and Thomalla *et al.* (2015) focused their work on understanding bloom dynamics in the Southern Ocean. Marra *et al.* (2015) use mooring data from the Iceland Basin in the North Atlantic and from the central Arabian Sea to study factors that determine bloom dynamics and conclude that changes in water column stratification were important at all mooring sites as a factor responsible for bloom formation. Cole *et al.* (2015) examine bloom-favouring processes at the basin scale in the North Atlantic, and contrast them with the Southern Ocean and the North Pacific. Aksnes (2015) studied the coastal waters off Norway, pointing out the importance of water clarity, unrelated to phytoplankton concentration, in dictating the light environment in the surface layers and hence bloom dynamics. Fieldwork at small-scales is presented by Diehl *et al.* (2015) who studied the onset of blooms in a controlled mesocosm experiment in a lake. Walter *et al.* (2015) examine the potential effects of temperature and light during deep convection on phytoplankton growth, using laboratory experiments on growth of a single species of phytoplankton (*Thalassiosira weissflogii*).

The articles comprising this theme set, and the many relevant articles cited by them, attest to the great progress that oceanography has made since the days of Sverdrup. Some of the discussions of today, for example surrounding parameterization of the physical conditions that dictate bloom dynamics, or over the intricacies of phytoplankton growth and loss terms, would not have been possible in the days of Sverdrup. Technologically as well, we have made great strides, with moorings, drifters, gliders, and satellites generating huge quantities of data. Modelling has also developed rapidly as computing power has increased and become readily available to researchers. And yet, the simple concept of critical depth still provides the underpinning for many efforts to understand the ephemeral world of phytoplankton.

The breadth of oceanographic regions and oceanographic processes investigated in this theme set within the framework of Sverdrup's critical depth hypothesis, the new theoretical developments presented, the innovative observational technologies brought to bear on the problem, and the variety of laboratories and countries engaged in the investigations, all bode well for the continued influence of Sverdrup's work on the oceanographic community.

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