WHAT IS A WIND SLAB? A REVIEW OF VARIABLE DEFINITIONS IN RESEARCH AND PRACTICE

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ABSTRACT: Despite widespread use in both research and practice, the definition of the term wind slab varies throughout snow and avalanche literature. Publications from as early as the 1930s recognized the role of wind in transporting snow and creating slabs, but acknowledged that the process was poorly understood. Though our understanding of formation processes has advanced, definitions of the term wind slab remain inconsistent. Some definitions focus on physical properties of the slab and snow grains, while others focus on formation. Different definitions are not necessarily mutually inclusive of each other. Associated terms such as wind skin and wind crust, while often used in practical situations, are only infrequently and vaguely defined in avalanche literature. Inconsistent definitions pose challenges for both practitioners and researchers. In avalanche forecasting, inconsistent definitions can hinder communication, which can lead to the application of inappropriate mitigation or avoidance strategies. From a scientific perspective, it is important to accurately and consistently define terms in order to effectively conduct and communicate research. This review paper addresses the varied definitions of the term wind slab and other associated terms. In doing so, it also summarizes how our understanding of wind influence on snow has evolved. Examining both historic and modern uses of the term wind slab can help us form consistent definitions, not just for wind-related terms, but perhaps for other avalanche problem types as well.

KEYWORDS: Wind Slab, Avalanche Problems, Avalanche Problem Types, Review Article

1. INTRODUCTION

The term “wind slab” (Figure 1) has been widely adopted by the avalanche industry and is used in daily communications at many operations. Despite widespread use, wind slab definitions vary between different documents and resources. This can be partially attributed to how our understanding of wind slab formation has changed over time. However, commonly used modern definitions of the term wind slab still differ. Using one definition over another can lead to instances where neighbouring operations, or even coworkers, disagree on what exactly constitutes a wind slab. Recent research has shown that even when working from the same definition, the term wind slab is applied differently by different operations (de Leeuw & Birkeland, 2023; Hordowick, 2022). From a practical perspective, inconsistent definitions hinder communication, which could lead to the application of inappropriate mitigation strategies. From a scientific perspective, consistent definitions are crucial in order to effectively conduct and communicate research. Though a large body of research exists on the use of avalanche problem types (Horton et al., 2023), inconsistencies in definitions of the term wind slab persist.

Figure 1 – A wind slab on the lee side of a slope.

This paper reviews our industry’s current understanding of “wind slab” and summarizes the different definitions found in research papers and technical documents. It also summarizes early wind slab research to build context for our modern understanding of wind transport and wind slab formation processes. By examining both historic and modern uses of this term we can improve our ability to understand varied interpretations. This helps us to more easily address practical issues associated with inconsistent communication of avalanche problems in workplaces and academic settings. While this paper focuses on wind slabs, inconsistency has been noted across all nine avalanche problem types used in North America (Hordowick, 2022), and the five

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used in Europe (Techel et al., 2018). Collecting and reviewing different definitions and interpretations of the term wind slab could help us to move towards more consistent definitions for all avalanche problem types.

2. A BRIEF HISTORY OF OUR UNDERSTANDING OF WIND SLAB FORMATION

The term wind slab dates back to at least the 1930s, where Gerald Seligman (1936) (Figure 2) described wind slabs as “the most insidious of all avalanches” (p. 160) (Table 1). Seligman recognized the role of wind transport in slab formation, and noted that wind slabs formed on downwind slopes. He further differentiated between a wind slab and what he called a wind skin, which he observed on upwind slopes and considered to be an indicator of snowpack stability. Upon further reflection, Seligman noted the difficulties in differentiating between a wind skin and a sun crust, and recognized he may have confused the two. He wrote multiple chapters addressing wind slabs and wind skins in his 1936 book “Snow Structure and Ski Fields.” These early records show that that the terms wind slab and wind skin have long been part of the avalanche lexicon, and that wind has long been considered an important factor in avalanche formation.

Figure 2 – Gerald Seligman and a colleague investigating the snowpack. Seligman published the earliest extensively recorded theories of wind slab formation.

Early theories of wind slab formation proposed that warm wind would thaw surface snow grains, which would subsequently freeze back together forming a slab (Seligman, 1936). In later years, Antarctic researchers proposed that the upward migration of water vapour in the snowpack contributed to this melt-freeze process (Benson, 1967) (Table 1). Melting was also used to describe the rounded shape of snow grains in a wind slab (Seligman, 1936). Seligman posited that heat from friction during saltation would melt the sharp corners of dendritic grains, resulting in the smaller and rounder grain shapes noted in wind slab layers. We now instead attribute this rounding to mechanical fragmentation during the saltation process,. (Colbeck, 1991; Comola et al., 2017). In 1947, Seligman proposed the process of “riddling” where small grains fill gaps between larger grains in a wind slab. This parallels our current understanding of snow layer properties, where smaller grains pack more closely together than large grains, forming denser layers with relatively more inter-grain bonds per unit area, leading to increased hardness (Colbeck, 1991, 1998). Although our understanding of the specific processes has changed, early researchers understood that grain metamorphism driven by the wind was often responsible for slab formation, and thus avalanche formation.

As avalanche research and mitigation became more prevalent in North America, practitioners continually recognized wind as an important factor in avalanche formation. In 1954, Monty Atwater (1954) suggested that wind action was “the most important and versatile of all” ten contributing factors to avalanches (p. 30) (Table 1). Ron Perla’s later study on Atwater’s ten factors confirmed that wind speeds were positively correlated with avalanche hazard (1970), and Martinelli's 1971 study provided evidence that stronger winds produced harder slabs (Table 1). In 2004, Roger Atkins listed wind slabs as one of the major categories in his avalanche characterization checklist, with five different avalanche regimes involving wind slabs. In Europe, Mair and Nairz (2013) recognized “cold, loosely packed new fallen snow plus wind” as one of ten avalanche danger patterns. The avalanche problem types commonly used now, both the Conceptual Model of Avalanche Hazard in North America (Statham et al., 2018), and the European Avalanche Warning Services’ Types of Avalanche Problems (2022), grew out of this early work on classifying avalanche types. Though the exact definitions may have changed over the years (Table 1), wind has long recognized as a contributory factor in avalanche formation.

3. MODERN DEFINITIONS

3.1 Wind Slab

Most wind slab definitions (Table 1) are based on either physical properties or formation processes. The International Classification of Seasonal Snow on the Ground (ICSSG) (Fierz et al., 2009) uses physical properties, stating that wind slabs are “thicker, often dense layers, usually found on lee slopes” composed of “closely packed and well-sintered particles” (Table 1). The European Avalanche Warning Services (EAWS) on the other hand, defines wind slab through its formation process, stating that “wind slabs are formed when loose snow in near-surface layers is transported and deposited by wind" (European Avalanche Warning Services, 2022) (Table 1). The Conceptual Model of Avalanche Hazard uses both approaches, defining a wind slab as a "cohesive slab of locally deep, wind deposited snow," but also describing the processes of mechanical fragmentation and subsequent deposition (Statham et al., 2018) (Table 1). Research papers, whether on snow avalanches or Arctic snow, often create their own definitions of the term wind slab which are appropriate for their specific research goals (Table 1). While other definitions exist, the three main definitions outlined above have been widely adopted and are the definitions most commonly used by avalanche professionals.

Despite the similar wording and understanding demonstrated in each of the three definitions, there are slight differences which can lead to different interpretations of a physical slab on the ground. In practical situations, the term wind slab can overlap with both storm slab and persistent slab in North America, or both new snow and persistent weak layer in Europe (de Leeuw & Birkeland, 2023). Although considered discrete options, in reality there is considerable overlap between different avalanche problem types (Statham et al., 2018). The newest version of the Canadian Avalanche Association's Operational Guidelines and Recording Standards (OGRS) (Canadian Avalanche Association, 2024) addresses this concern by explicitly stating that a wind slab consist of "primarily surface snow (redeposition) but may also include some falling snow (preferential deposition)" (Figure 3) (Table 1). The EAWS definitions consider both falling and surface snow transported by the wind to result a wind slab (European Avalanche Warning Services, 2022). This inconsistency could allow for what may be classified as a storm slab in North America to be classified as a wind slab in Europe. Many operations may have their own adaptation of wind slabs and storms slabs, whether consciously or not. Similarly, many operations have internal guidance for when to turn a surface slab problem, such as a wind slab, into a persistent slab problem. For example, the National Avalanche Center in the USA suggests three days (National Avalanche Center, n.d.), though this is not always considered a hard and fast rule. Although most members of the avalanche industry know how to recognize and mitigate a wind slab appropriately, definitions remain inconsistent, especially where avalanche problems overlap.

Figure 3 – A situation where wind is actively transporting both falling snow (preferential deposition), and surface snow (redeposition) at the same time.

3.2 <u>Wind Crust</u>

The term wind crust and the similar term wind skin are used in practical situations but are rarely defined in literature or technical documents. A definition of wind crust does exist in the ICSSG, where it is defined exactly as a wind slab, but is said to be "thinner" and "irregular" by comparison (Fierz et al., 2009). For research purposes de Leeuw (2003) defined the term wind skin as formed through the same depositional process as a wind slab and with the same physical properties, but less than 1 cm thick. Despite the lack of formal definition, the terms wind crust and wind skin appear in ISSW papers (eg. Adams & Brown, 1998), public resources (eg. Avalanche.Org, n.d.), educational literature (eg. American Avalanche Institute, 2023), and online blogs and articles (eg. Costa, 2019). Though lacking a formal definition, the terms wind crust and wind skin are used by avalanche professionals and in avalanche communication.

4. CONCLUSION

Our understanding of wind slabs and their formation processes has changed over time, but our current definitions generally recognize a wind slab as existing on lee slopes and being composed of small, rounded grains deposited by the wind. Though the term wind slab is commonly used by practitioners and researchers, there remains inconsistency in exactly how a wind slab is defined. Much of this inconsistency stems from situations where the definition of a wind slab overlaps with a different avalanche problem type. The terms wind skin and wind crust are also used in writing and conversation between avalanche professionals but are only vaguely defined in literature. A summary of the different definitions of the term wind slab (Table 1) can help us to understand where discrepancies exist, and potentially move towards a singular coherent definition that applies to and is useable by all audiences.

Table 1 – Wind slab definitions and proposed processes of formation from a selection of literature, sorted by date of publication.

Publication	Wind Slab Definition	Proposed Process of Formation
Seligman, 1936	"A snow deposit which has been packed tough… by wind agency [with a] high proportion of regularly rounded ice grains," (Seligman, 1936, p.164).	Through the process of wind packing, which is "a special form of firnification accelerated by a wet wind " (Seligman, 1936, p.200).
Seligman, 1947	Does not define wind slab explicitly.	Through wind packing, as well as "riddling" which occurs when smaller grains "shake themselves into spaces between [larger] grains" (Seligman, 1947, p.124-125).
Atwater, 1954	A "slab is a type of wind packed snow which commonly forms on lee slopes" (Atwater, 1954, p.26).	Wind is "essential to the formation of a slab in ways which we do not yet completely understand" (Atwater, 1954, p.31).
Benson, 1967	Hard and fine-grained, and one of "the extreme end products of diagenetic processes" (Benson, 1967, p.1040)	Due to the movement of saturated air in snow which creates necks between grains. Wind accelerates this process by depositing snow grains with low vapour pressure between them.
Martinelli, 1971	"Wind action… toughens the snow and often leads to slab formation" (Martinelli, 1971, p.1). "Initial hard slab" describes snow with a density and strength increase that occurs soon after deposition.	"Initial hard slab appears to require high winds, low temperatures, and a high drift ratio," drift ratio being a comparison of snow available for transport in start zones to measured precipitation. This occurs "either during snowfall or during the transport and redeposition of old snow" (Martinelli, 1971, p.26)
Colbeck, 1991	"…thicker layer of wind hardened snow" (Colbeck, 1991, p.83).	"Wind breaks the ice particles into smaller shards…. Because of their small size and movement of air by the wind, they round off and sinter quickly" (Colbeck, 1991, p.83).
Zhang et al., 1996	"Hard, wind-packed layer" (Zhang et al., 1996, p.2076).	Did not propose a method of formation.
Massom et al., 2001	"A medium to high density surface layer" (Massom et al., 2001, p.422) which can be soft to very hard.	"Wind… mechanically fragments and compacts the snow" (Massom et al., 2001, p.417).
McClung & Schaerer, 2006	"Most slabs consist of cohesive wind-deposited or well-bonded old snow" (McClung & Schaerer, 2006, p.95).	"… as snow is redistributed, the particles become broken and abraded as they impact the snow surface, …these small fragments, upon deposition, become tightly packed and rapidly produce a slab-like texture…" (McClung & Schaerer, 2006, p.35).
Clifton et al., 2006	"Increased deposition of snow on lee slopes" (Clifton et al., 2006, p.592).	Particles are moved "both from the surface and the snow which has not yet reached the ground" (Clifton et al., 2006, p.592).
DeWalle & Rango, 2008	"A densified, dry-snow layer at the snowpack surface" (DeWalle & Rango, 2008, p.54) formed by wind.	"Formed due to … deposition and packing of broken crystals of blowing snow" (DeWalle & Rango, 2008, p.54)
Fierz et al., 2009	"Thicker, often dense layers, usually found on lee slopes" composed of "small, broken or abraded, closely packed and well-sintered particles" (Fierz et al., 2009, p.15).	"Packing and fragmentation of wind transported snow particles that round off by interaction with each other in the saltation layer" (Fierz et al., 2009, p.15).
Haegeli et al., 2010	"Consist of snow crystals broken into small particles and packed together by the wind… created on lee slopes" (Haegeli et al., 2010, p.1). Vary from medium to very hard, and often have a "pillowed" shape.	"Form when there is sufficient wind to transport falling snow or surface snow" (Haegeli et al., 2010, p.1). Formation depends on wind speed, duration of wind event, and snow available for transport.
Sommer et al., 2017	The result of wind packing.	Through wind packing, which is "the process of snow hardening under the influence of wind" (Sommer et al., 2017, p.950)

Sommer, 2018	"Hard layers of well-sintered snow" (Sommer, 2018).	"Wind-packing of snow." (Sommer, 2018).
Statham et al., 2018	"Cohesive slab of locally deep, wind deposited snow" (Statham et al., 2018, p.675).	"Wind transport of falling snow or soft surface snow. Wind action breaks snow crystals into smaller particles and packs them into a cohesive slab" (Statham et al., 2018, p.675).
Thompson & Kelly, 2021	"Small, wind-fractured fragments in a hard-packed, high-density layer" (Thompson & Kelly, 2021, p.1123).	As a result of "aeolian and thermodynamic snowpack processes" (Thompson & Kelly, 2021, p.1123).
American Avalanche Association, 2022	"A dense layer(s) of snow formed by wind deposition" (American Avalanche Association, 2022, p.62).	Through the process of wind deposition
European Avalanche Warning Services, 2022	Defined by process of formation	"Wind slabs are formed when loose snow in near-surface layers (new snow or old snow) is transported and deposited by wind" (European Avalanche Warning Services, 2022, "Wind Slab" section)
N. de Leeuw, 2023	"A snow layer of locally deep, dense, and hard snow, composed of small rounded grains, and formed by the transport and deposition of snow by wind." (de Leeuw, 2023, p. 10)	Transport and deposition of snow by wind, including both preferential deposition and redeposition.
Canadian Avalanche Association, 2024	"Cohesive slab of locally deep, wind deposited snow." (Canadian Avalanche Association, 2024, p. 52)	"Wind transport of primarily surface snow (i.e., redeposition) but may also include some falling snow (i.e., preferential deposition). Wind action breaks snow crystals into smaller particles and packs them into a cohesive slab…."

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