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Technical Note: A proposal for ice nucleation terminology

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Abstract. Terminology dealing with ice nucleation in the atmosphere, in biological systems, and in other areas has not kept pace with the growth of empirical evidence and the development of new ideas over recent decades. Ambiguities and misinterpretations could be seen in the literature. This paper offers a set of definitions for various terms in common use, adds some qualifications, and introduces some new ones. Input has been received on the interpretation of various terms from a fair number of researchers; diverse views have been accommodated with some success. It is anticipated that the terminology proposed here will be helpful both to those who adopt it and to those who wish to explain a different perspective.

1 Introduction

The purpose of this Technical Note is to suggest definitions of terms for use in describing ice nucleation. The suggested list of terms evolved from one originally proposed by the authors to one containing substantial inputs from reviewers and other contributors. Three successive drafts were posted on the discussion page linked to this paper (Vali et al., 2014). Comments by reviewers and others are on the same discussion page, as are responses to those comments. Careful examination of this material makes it clear that there have been different interpretations of some terms and those uses continue to appear in the current literature. The proposed list has evolved, and the introduction of a few new terms has become necessary in order to recognize different perspectives and to allow for the relatively unambiguous presentation of current knowledge. Nonetheless, it is certain that the proposed list of terms will have to be revised, with some terms becoming obsolete or ambiguous, and with the introduction of additional terms to describe new discoveries.

The motivation for revising and expanding on the “Nucleation terminology” article by Vali (1985) is that the progress made in the intervening 30 years has revealed unexpected complexities of heterogeneous ice nucleation and that the terminology applied in discussing these phenomena has not evolved in a consistent and unambiguous way. These problems can be seen in recent literature with overlapping, unclear, and in some cases, contradictory usage of terms describing heterogeneous ice nucleation. More detailed terminology is potentially helpful in eliminating some of the problems and represents a step toward facilitating further progress. The meanings of scientific terms evolve with time. A concise summary of all the various interpretations attached to given terms by a broad spectrum of researchers at any given time is not possible. Even so, a set of definitions can perhaps be agreed upon for present usage, acknowledging that future definitions will diverge to various degrees. However, it can be hoped that the stated definitions will serve, at a minimum, to allow for more concise identification of possible deviations from them.

With the aforementioned ideas in mind, the first version of the terminology was posted in *Atmospheric Chemistry and Physics – Discussions* in August 2014. Reviews of and comments on this paper indicated support for the need to clarify the usage of controversial terms and included many suggestions for changes and improvements. Based on those inputs, a second draft was posted in February 2015 and a further exchanges of views followed. A third draft was posted on 5 May 2015. Along with the second and third drafts, responses were listed on specific points made by the reviewers and in comments. All of this material is contained on the interactive discussion page (Vali et al., 2014) for this paper. The reviewers of the discussion paper were two anonymous referees and Dr. T. Koop. The authors of the interactive comments were C. A. Knight, R. Jaenicke, Z. Kanji on behalf of the Lohmann Ice Nucleation Group at ETH Zurich; H. Wex on behalf of S. Augustin-Bauditz, H. Bieligk, T. Clauss, S. Hartmann, K. Ignatius, L. Schenk, F. Stratmann, J. Voigtländer from the Cloud-group at the Institute for Tropospheric Research, TROPOS; D. Niedermeier on behalf of D. Ciochetto, C. Gurganus, R. Shaw and Y. Wang at Michigan Technical University; B. Murray and A. Bogdan.

Heterogeneous ice nucleation is the main focus of the terminology proposed here as it is the topic where recent developments revealed most need for clarifications of concepts. Homogenous ice nucleation and terms common to both types of nucleation are included only for the sake of completeness and no significant changes from accepted practice are proposed.

Following the naming of entries, a brief definition is given in italics. Additional details are provided in the paragraph(s) that follow in normal font. Cross references to other entries are given by section numbers.

2 General

2.1 Phases of water

> *Within the range of normal atmospheric conditions water can exist in three different phases, namely vapor, liquid and ice.*

The thermodynamically stable phase is defined by the existing pressure and temperature, as usually depicted in a phase diagram. A metastable state arises when conditions change from those corresponding to one stable phase to those corresponding to another. The first formation of the new stable phase from the metastable state is a nucleation event.

2.2 Ice nucleation

> *The first appearance of a thermodynamically stable ice phase*

The ice phase can be initiated in environments of supersaturated vapor (deposition nucleation) or supercooled liquid water (freezing nucleation). In this context, supersaturated vapor and supercooled water refer to the existence of these conditions on scales considerably larger than that of the ice embryo (Sect. 2.3). Nucleation means the first development of the bulk phase, i.e., an embryo larger than the critical size (Sect. 2.3.2), within these environments.

2.3 Embryo or germ

> *Thermodynamically unstable aggregate of water molecules in a structure that favors further development into stable ice*

In the metastable states, clusters of the stable phase form. Molecular fluctuations lead to decay or growth. For small embryos, decay is more likely than growth. The probability of growth increases as the embryo approaches critical size.

2.3.1 Embryo size

> *The size of an ice embryo expressed either as the number of water molecules making up the ice-like structure, or the linear dimension of the embryo, or the radius of curvature of its surface toward the metastable phase*

2.3.2 Critical embryo size

> *The size at which the probability of growth of an embryo becomes equal to the probability of decay*

The critical size is the point of metastable equilibrium. With minimal additional increase in size, growth becomes energetically more favorable and nucleation can take place.

3 Homogeneous ice nucleation

> *Ice nucleation without any foreign substance aiding the process*

3.1 Homogeneous deposition nucleation and homogeneous ice nucleation from water vapor

> *Ice nucleation from supersaturated vapor, without any foreign substance aiding the process*

Deposition nucleation is the formation of ice directly from water vapor. Because of the very high supersaturation required for the homogeneous deposition nucleation of ice, it is not observed in the atmosphere or in other natural systems. However, there is evidence for homogeneous ice nucleation from water vapor via processes that involve the intermediate step of homogeneous condensation of liquid, or an amorphous phase, at supersaturations below that required for deposition (Murray and Jensen, 2010).

3.2 Homogeneous freezing nucleation

> *Ice nucleation within a body of supercooled liquid without any foreign substance aiding the process*

3.3 Homogeneous nucleation rate coefficient

> *The probability, or observed frequency, of ice nucleation events in unit volume of supercooled liquid or supersaturated vapor within a unit of time*

Table 1. List of symbols (with CGS units indicated).

A	Total surface area of ice nucleating particles (INPs) in a sample unit (cm^2)
f	Fraction of samples frozen (Sect. 4.5)
$J(T)$	Nucleation rate (probability of freezing) per unit time as a function of temperature (s^{-1})
$J_\mathrm{s}(T)$	Nucleation rate coefficient; per unit time and per unit surface area of INPs ($\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$)
$J_\mathrm{m}(T)$	Nucleation rate coefficient; per unit time and per unit mass of INPs ($\mathrm{g}^{-1}\,\mathrm{s}^{-1}$)
$J_\mathrm{v}(T)$	Homogeneous nucleation rate coefficient, per unit time and per unit sample volume (Sect. 3) ($\mathrm{cm}^{-3}\,\mathrm{s}^{-1}$)
$J_\mathrm{site}(T)$	Nucleation rate on a specific site (Sect. 4.7.2) (s^{-1})
$k(T)$	Differential nucleus spectrum; number of sites active within a 1 °C interval at T per unit sample volume ($\mathrm{cm}^{-3}\,{}^\circ\mathrm{C}^{-1}$)
$K(T)$	Cumulative spectrum, or integrated volume density of active sites : number of sites active above T per unit sample volume (cm^{-3})
$n_\mathrm{s}(T)$	Surface density of sites (number per unit surface area of INPs) active above T (cm^{-2})
N_U	Number of samples units in which no nucleation event has taken place
N_F	Number of samples frozen
N_0	Total number of samples in an experiment
R	Freezing rate per unit time (s^{-1})
S	Supersaturation
t	Time (s)
T	Temperature (°C)
T_c	Characteristic temperature for a nucleating site (°C)
V	Volume of sample unit (cm^3)
CNT	Classical nucleation theory
INP	Ice nucleating particle

Classical nucleation theory (CNT) relates the nucleation rate coefficient to the properties of the liquid and the net rate at which molecules are added to the ice embryos. Empirically, the nucleation rate is determined from the frequency of events as a function of supersaturation or temperature: $J_\mathrm{v} = -\frac{1}{V} \cdot \frac{1}{N_\mathrm{U}} \cdot \frac{\mathrm{d}N_\mathrm{U}}{\mathrm{d}t}$, using N_U to denote the number of sample units in which no nucleation event has taken place by time t, and V to denote the total volume observed[1]. Here the subscript "v" is added to the usually employed symbol J in order to focus on the fact that the homogeneous nucleation rate coefficient refers to unit volume of vapor or liquid and to distinguish it from similar expressions for heterogeneous nucleation. It is recommended to use the symbols $J_\mathrm{v}(S)$ and $J_\mathrm{v}(T)$. The quantity J_v has dimensions of $\mathrm{L}^{-3}\,\mathrm{t}^{-1}$ (CGS units of $\mathrm{cm}^{-3}\,\mathrm{s}^{-1}$).

While the concept of freezing rate (Sect. 4.6) has not been applied so far in the literature on homogeneous ice nucleation, it is a valid representation of experimental results or of predictions for both homogeneous and heterogeneous ice nucleation. For homogeneous nucleation, the freezing rate is directly proportional to the nucleation rate coefficient and the volume of the sample units: $R = J_\mathrm{v} \cdot V = -\frac{1}{N_\mathrm{U}} \cdot \frac{\mathrm{d}N_\mathrm{U}}{\mathrm{d}t}$.

In practice, it is not always possible to ensure that all sample units are free of ice nucleating particles (INPs) so that the apparent freezing rate observed may lead to an incorrect value for J_v; in such a case the observed freezing rate has to be seen as the sum of various contributions (e.g., Koop et al., 1997).

4 Heterogeneous ice nucleation

> *Ice nucleation aided by the presence of a foreign substance so that nucleation takes place at lesser supersaturation or supercooling than is required for homogeneous ice nucleation*

4.1 INP, INM, INE, etc.

> *Ice nucleating particle (INP), molecule (INM), entity (INE), material, substance, object, item, unit, or other, that is assumed to be the agent responsible for observed heterogeneous nucleation*

Because of the variety of substances and forms that can be responsible for heterogeneous ice nucleation, it is impractical to have a single designation that covers all possibilities while being sufficiently informative. It is suggested that authors refer to the specific nucleating agent in each particular case in the manner most appropriate for the system studied. The form of the designation IN, plus a third letter, may be helpful enough for effective communication. The term "nucleator" is also used as a general reference to an object whose presence is responsible for observed ice nucleation.

Reference to an INP (or an equivalent) does not, in general, specify the composition of the particle, but describes

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[1] Definitions of symbols are given in Table 1.

the unit that carries the nucleating substrate. A number of different terms have been used in the literature for this. For decades, the terms "ice nucleus" and "ice nuclei" were used almost exclusively with reference to atmospheric aerosol that could initiate ice, that is, individual particles, each of which resulted in the formation of one ice crystal. While it was recognized that only a specific location on the particle surface is actually where ice begins to form, the entire particle was referred to as the ice nucleus. This led to confusion. The concept of a "site" appeared in the literature to narrow the identification of an ice nucleus. With the advent of ice nucleation studies on systems other than clouds, also including biological substances (bacteria, fungi, etc.), usage has become more confusing as focus has expanded to nucleation by entities other than aerosol particles. In all, the term "ice nucleus" has become both overused and vague. For atmospheric applications, or more generally, when dealing with many separate entities, it is more appropriate to use ice nucleating particle (INP) or the other forms listed above to refer to individual units, and to use the plural INPs or other forms to refer to a collection of them. Since ice nucleation is more complicated than condensation nucleation, due to the different modes it can follow, using "ice nuclei" in the general sense similarly to "condensation nuclei" is overly ambiguous and can be misleading.

4.2 Site

> *Preferred location for ice nucleation on an INP, or equivalent*

Direct experimental evidence for deposition nucleation (e.g., Mason, 1957; Anderson and Hallett, 1976) points to the role of specific locations on surfaces which promote nucleation with greater effectiveness than other locations. Similar evidence is available with freezing nucleation in terms of repeated freezing of samples at nearly the same temperatures, but this evidence is less direct than for deposition where the locations can be visually identified. Sites are thought to arise due to non-uniform surface properties of INPs that result in different binding energies to water molecules and incipient ice structures. Sites are considered to be important for both deposition and freezing nucleation. Observed nucleation on, or within, a sample is understood to be due to the most effective site found in it. Sites of various effectiveness are assumed to occur on the surfaces of most materials. In principle, sites have identifiable properties distinct from the assumed spontaneous formation of embryos at some unpredictable location on a surface.

4.3 Site density

> *The number of sites causing nucleation per unit surface area of the INP, or equivalent as functions of temperature or supersaturation; the quantitative measure of the abundance of sites of different ice nucleating effectiveness*

A number of different methods have been used in the literature to quantitate the frequency of occurrence of different temperatures or supersaturations at which ice nucleation has been observed and/or modeled. Most of these descriptions are direct representations of measurements. Time is considered an implicit factor specific to each experiment, i.e., the singular approximation (Sect. 4.7.1) is applied.

The density of sites is the number of sites per unit surface area of INPs that have caused nucleation by the time some supercooling temperature or supersaturation is reached. Connolly et al. (2009) and Niemand et al. (2012) used "integrated site density", and Hoose and Möhler (2012) used INAS (ice nucleation active site density) to refer to this quantity. The quantity is designated as $n_\mathrm{s}(T)$, or $n_\mathrm{s}(S)$, with dimension of L^{-2} (CGS units of cm^{-2}).

Interpreting the results of freezing experiments with subdivided sample units (e.g., particles randomly distributed into liquid volumes), the number concentrations of sites are defined (Vali, 1971) as the differential (k) and cumulative (K) nucleus spectra: $k(T) = \frac{1}{V\cdot(N_0 - N_\mathrm{F}(T))}\cdot\frac{\mathrm{d}N_\mathrm{F}(T)}{\mathrm{d}T}$ and $K(T) = -\frac{1}{V}\cdot\ln(1-\frac{N_\mathrm{F}(T)}{N_0})$. Site density with reference to surface area and the cumulative nucleus spectrum, for freezing, are related as $K(T) = n_\mathrm{s}(T)\cdot A$.

The foregoing descriptions assume that the nucleation rate is equal to zero at temperatures higher (supersaturations lower) than the characteristic temperature (supersaturation) of the site and equal to infinity beyond that. Thus, these definitions rely on the singular description (Sect. 4.7.1) with T_c for each site replaced by the observed freezing temperature T.

Marcolli et al. (2007) used contact angle as a surrogate to express site effectiveness. That idea was further developed by Welti et al. (2012) in the α-pdf model. Niedermeier et al. (2011, 2014) constructed the Soccer Ball Model to describe the distribution of sites of different effectiveness. Hartmann et al. (2013) modeled the distribution of sites among sample units. In these cases, the site density is represented using distributions of parameters in the CNT formulations of the nucleation rate coefficient thereby linking these models to the stochastic description (Sect. 4.8.1 and 4.8.2), while allowing the characterization of sites of different effectiveness to be included.

Site frequency distributions should always include some indication of the timescale of the experiment being interpreted. This allows various experiments to be compared more effectively.

4.4 Modes of heterogeneous ice nucleation

> *Distinctions in the mode of nucleation made on the basis of the process envisaged to lead to nucleation*

Definitions of nucleation modes were given by Vali (1985) with a focus on atmospheric processes. Several of the definitions given below broaden and alter those definitions.

4.4.1 Deposition nucleation

> *Ice nucleation from supersaturated vapor on an INP or equivalent without prior formation of liquid*

It is difficult to ascertain whether or not ice nucleates from (supersaturated) vapor without any liquid forming. Similar to the homogeneous case, deposition nucleation may have a transitory stage in which liquid is present but does not develop to a macroscopic, observable quantity. It has also been theorized that condensation in voids and cavities followed by freezing can account for many observations that appear to be deposition (Marcolli, 2014), but this process is better viewed as freezing followed by depositional growth. Observations of what is believed to be deposition nucleation need to focus critically on identifying the details of the process.

4.4.2 Freezing nucleation

> *Ice nucleation within a body of supercooled liquid ascribed to the presence of an INP, or equivalent*

Further specifications of modes are as follows:

Immersion freezing refers to ice nucleation initiated by an INP, or equivalent, located within the body of liquid.

Contact freezing is initiated by an INP, or equivalent, at the air–water interface as the INP comes into contact with the liquid, or forms at an air–liquid–particle triple interface.

This process is defined as separate from immersion freezing because of empirical evidence that some INPs are more effective in this mode than when immersed in liquid (Shaw et al., 2005). There is as of yet no definite method for how to distinguish this mode from immersion freezing. Some laboratory evidence points to a difference depending on whether the particle is inside of or outside of the liquid; this is described as inside-out versus outside-in nucleation. In the atmosphere, pre-activated particles may cause freezing when coming into contact with supercooled liquid droplets.

Condensation freezing is defined as taking place when freezing is initiated concurrently with the initial formation of liquid on a cloud condensation nucleus (CCN) at temperatures below the melting point of ice. This was envisaged as a possible sequence in clouds but evidence for its existence is minimal. Whether condensation freezing on a microscopic scale, if it occurs, is truly different from deposition nucleation, or distinct from immersion freezing, is not fully established. Hence, the use of this term requires added circumspection.

Other modes of freezing nucleation reported in the literature are electro-freezing, evaporation freezing, mechanical shock freezing and collision freezing. Evidence available at this time does not permit general definitions to be established for these processes.

4.5 Fraction frozen

> *The ratio of the cumulative number of sample units frozen at T to the original number N_0: $f = \frac{N_\mathrm{F}}{N_0}$, with N_F given as either a function of time or of temperature*

The frozen fraction represents the results of experiments with sample units drawn from the same original volume. It can be used when the sample units are gradually cooled or when held at a fixed temperature. Similar quantities can be readily defined for nucleation modes other than freezing.

4.6 Freezing rate

> *Expresses the results obtained from an experiment in which the freezing of a number of sample units is observed*

The freezing rate is expressed as a function of the number of sample units frozen at time t: $R = \frac{1}{N_0 - N_\mathrm{F}(t)} \cdot \frac{\mathrm{d}N_\mathrm{F}(t)}{\mathrm{d}t}$. The freezing rate for a given T is given in units of inverse time, e.g., s^{-1}. The freezing rate function is a direct description of empirical observations with distributed samples and can be used both for experiments in which the samples are steadily cooled and others in which the temperature is held constant. The freezing rate is related to the time derivative of the frozen fraction (Sect. 4.5): $R = \frac{1}{1 - f(t)} \cdot \frac{\mathrm{d}f(t)}{\mathrm{d}t}$. The freezing rate for any particular sample is dependent on the volumes of the sample units and on the INP content (site density or nucleus spectrum) of the liquid. It is also influenced by dissolved substances. For polydisperse sample volumes, the freezing rate should be specified separately for each volume range.

For homogeneous nucleation, the freezing rate is usually called nucleation rate. In the stochastic description of heterogeneous nucleation, the terms freezing rate and nucleation rate are interchangeable, but using freezing rate makes it clearer that one refers to observed frequencies of events and not to the more abstract rate coefficient or site nucleation rate (Sect. 4.7.2).

Some overlap exists in the use of the term freezing rate between discussing nucleation of sample units and talking about growth of ice. The distinction has to be clarified explicitly if not evident from the context.

4.7 Site-specific descriptions/models

4.7.1 Singular description (time independent)

> *Description/model of observed nucleation events for a population of sample units containing INPs (or equivalents) and assuming that the preferred sites have a spectrum of different nucleating*

> *abilities; also referred to as the deterministic description of ice nucleation; no time dependence is taken into account*

This description is based on evidence that points to sites having well-defined, albeit not perfectly stable, potentials for promoting nucleation. Each site is then characterized by the temperature, or supersaturation, at which it is observed to nucleate ice for a given mode. For freezing, a characteristic temperature T_c is used to specify the effectiveness of the site or INP. The time history of the sample is not taken into account. In that sense, the singular description is often called deterministic. The singular description is expressed quantitatively by site density or by nucleus spectra (Sect. 4.3).

4.7.2 Site nucleation rate

> *Expresses the probability per unit time that nucleation takes place on a given site of an INP (or other) involved*

Site nucleation rate, J_site, is a function of temperature (for freezing) and other factors reflecting the nature of the nucleating site. The term is adopted from the description of homogeneous nucleation according to which nucleation rate refers to an observed volume or ensemble of drops. Applied to a site, the term has a narrower focus but the same meaning, i.e., the probability of nucleation within a time interval.

In cases where data fit the stochastic model (Sect. 4.8.1 and 4.8.2), i.e., all INP surface areas (or masses) appear to be entirely equivalent in their ability to nucleate ice, the nucleation rate coefficient $J_\mathrm{s}(T)$ replaces the site nucleation frequency J_site as the relevant quantity.

Site nucleation rate has the dimension of inverse time (CGS units of s^{-1}).

4.7.3 Time-dependent site-specific descriptions/models

> *Descriptions that encompass definitions of site density distributions (Sect. 4.3) and account for the time dependence of freezing nucleation*

Each site is assumed to be defined by its characteristic temperature and by the site nucleation rate associated with it (Vali and Stansbury, 1966, VS66; Vali, 2014). The abundance of sites of different characteristic temperatures is specified by some characterization of the site density (Sect. 4.3) such as the nucleus spectra. The site nucleation rate is defined in Sect. 4.7.2.

The singular description (Sect. 4.7.1) is an approximate solution in which the site nucleation rate is assumed to be a step function from 0 to ∞ at T_c.

The site nucleation rate function may depend on the value of T_c and is thus designated as $J_{\mathrm{site},T_\mathrm{c}}(T)$. The characteristic temperature T_c for each site (Sect. 4.3) is defined by the temperature at which the nucleation rate J_site has an arbitrarily chosen value C: $J_{\mathrm{site},T_\mathrm{c}}(T_\mathrm{c}) = C$. A convenient choice is $C = 1\,\mathrm{s}^{-1}$. Empirical evidence points to J_site being a steep function of temperature (similarly to homogeneous nucleation). Empirical determination of J_site has only been approached indirectly (e.g., Vali, 2008; Wright and Petters, 2013) since multiple examples of sites with the same T_c are not identifiable a priori. Theoretical guidance is limited by the lack of detailed knowledge about the nature of ice nucleating sites.

4.8 Stochastic description/model

> *Description/model of the frequency of nucleation events in a population of sites, or of sample units, which have equal probability for nucleation within a period of time*

4.8.1 Stochastic description

This description assumes that there are large numbers of sites of equal effectiveness on the surfaces of INPs, and interprets observations in terms of a nucleation rate coefficient, i.e., the freezing rate per unit surface area or per unit mass. Thus, this description employs $J_\mathrm{s}(T)$ with units of $\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$, and $J_\mathrm{m}(T)$ with units of $\mathrm{g}^{-1}\,\mathrm{s}^{-1}$. Empirical values of $J_\mathrm{s}(T)$ are obtained from $R(T)$ via $J_\mathrm{s}(T) = \frac{R(T)}{A}$. If the number of sites of the same effectiveness per unit surface area is $n_\mathrm{S}(T)$ then $J_\mathrm{s}(T) = n_\mathrm{s}(T) \cdot J_\mathrm{site}(T)$, where $J_\mathrm{site}(T)$ is the site nucleation rate (probability of nucleation) for given parameters. From these values of $J_\mathrm{s}(T)$, the site density n_s can be derived if $J(T)$ is taken from theory (e.g., CNT) or is independently determined.

As mentioned in Sect. 4.7.2, the heterogeneous nucleation rate coefficient can be applied to cases where all INP surface areas appear to nucleate ice with equal effectiveness. In other cases the site nucleation rate J_site should be used.

4.8.2 Stochastic description for multi-component systems

The foregoing description (Sect. 4.8.1) is valid when all sites are considered identical. This case is termed the single component model in Broadley et al. (2012) and Herbert et al. (2014). Sites of different effectiveness are considered in the multi-component stochastic models (MCSMs). The essence of this approach is to allow for different site characteristics by varying critical parameters (usually the contact angle) in the CNT formulation of the nucleation rate coefficient and assuming some frequency distribution for that parameter. Variations of this approach have been presented by Marcolli et al. (2007), Niedermeier et al. (2011, 2014), Welti et al. (2012) and Ekman (2015) among others. In these formulations, sites are characterized by their frequency, say $n_{\mathrm{s},i}$, and a corresponding function $J_{\mathrm{s},i}$, using the second subscript, i, to indicate assignment to a specific value of the contact angle (or other parameter). In effect, this is very similar to the time-dependent site-specific description (Sect. 4.7.3) with a theory-based nucleation rate coefficient instead of J_{site} and an assumed, or fitted, frequency distribution instead of an empirical one (Sect. 4.3).

4.8.3 Comparison of stochastic and site-specific descriptions

While the CNT-derived nucleation rate coefficient in the stochastic description (Sect. 4.8.1) and the site nucleation rate in the site-specific description (Sect. 4.7.3) arise from the same need to describe the probability of nucleation, different underlying assumptions are incorporated in these two descriptions. To apply the stochastic description to a given data set, the function J_{s} is assumed to have finite values over the range of observed freezing temperatures in the sample. For the site-specific description, the function J_{site} is assumed to rise very rapidly over a narrow range of temperatures and the spread in observed freezing temperatures is ascribed to differences in the effectiveness of sites. The two descriptions lead to divergent predictions about the time dependence of nucleation (Vali, 2014; Herbert et al., 2014). This time dependence can not be determined from a single continuously cooled experiment with a sample, but requires more elaborate tests.

The multi-component (and similar) descriptions (MCSM; Sect. 4.8.2) present a view similar to the time-dependent site-specific description (VS66; Sect. 4.7.3). The degree of similarity is determined by the range of temperatures over which the nucleation rate coefficients $J_{\mathrm{s},i}(T)$ for species i assume empirically relevant values in the MCSMs in comparison with the range of $< 1\,^{\circ}\mathrm{C}$ for the site nucleation rate $J_{\mathrm{site}}(T)$ in VS66.

4.9 Aqueous solutions

Dissolved substances in water change the equilibrium phase boundaries and influence ice nucleation.

In many atmospheric and other natural systems, dissolved materials are present in water and alter the conditions for ice nucleation. The magnitudes of the changes in freezing rates depend on the type and concentration of the solute. Water activity has been shown to provide a good representation of these dependences for homogeneous freezing nucleation and several heterogeneous systems (Koop et al., 2000; Knopf and Alpert, 2013). Modifications of INP surfaces by some solutes may introduce additional changes in heterogeneous freezing nucleation rates J_{s} or J_{site} (e.g., Reischel and Vali, 1975; Wex et al., 2014).

4.10 Pre-activation and memory effects

The mode or efficacy of observed nucleation may be influenced or altered by the previous temperature/humidity history of the INP, or equivalent.

Experiments have shown that prior exposure to low temperature or high humidity, or a combination of both, leads to enhanced activity in comparison to what the INP or equivalent would exhibit otherwise. Such effects may introduce ambiguity in the diagnosis of the mode of activity (Sect. 4.4) in laboratory experiments or in atmospheric or other natural systems. Certain INP characteristics (composition, configuration, surface properties) may favor such effects. Explanations of the effects focus on the potential for cracks, pores and other features on surfaces to retain ice even under conditions where bulk ice would be unstable.

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