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Static Energy Deserves Greater Emphasis in the Meteorology Community

Daniel R. Chavas and John Peters

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ABSTRACT: Potential temperature and static energy are both useful quantities for understanding our atmosphere, yet static energy receives much less attention in weather science relative to climate science. Bridging this conceptual gap is important, as there is a pressing need for our communities to work together to understand and predict changing weather patterns in a warming world. Here we provide evidence for this gap in usage in American Meteorological Society journal publications and in introductory textbooks. We then describe key benefits of static energy for explaining basic concepts in atmospheric science. We encourage scientists and educators unfamiliar with static energy to familiarize themselves with the concept and consider incorporating it into their science and teaching.

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Corresponding author: Daniel R. Chavas, dchavas@purdue.edu
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AFFILIATIONS: Chavas—Department of Earth, Atmospheric and Planetary Sciences, Purdue University, West Lafayette, Indiana; **Peters**—Department of Meteorology and Atmospheric Science, The Pennsylvania State University, State College, Pennsylvania

Why does an air parcel cool as it rises adiabatically?

A cornerstone of most undergraduate and graduate meteorology curricula is the topic of how properties of air change when moved within our atmosphere and when heated or cooled. The canonical introductory-level example is an air parcel rising adiabatically through the atmosphere. A dry air parcel will cool at the "dry adiabatic lapse rate," which is 9.8 K km^{-1} on Earth.

But why conceptually does a parcel cool at this rate? The standard explanation is that the parcel's pressure decreases as it rises, and as a result it expands and cools. This explanation is commonly augmented using the conservation of potential temperature. Yet the dry adiabatic lapse rate describes how temperature changes with height, not pressure, which leaves a conceptual gap in our explanation. This gap is filled by considering conversions between different forms of static energy: sensible energy[1] is exchanged with gravitational potential energy. The term "static energy" refers to the nonkinetic component of the total energy of air, and it is used widely because kinetic energy is typically much smaller than static energy in our atmosphere and so is often neglected.

[1] We use the general term "energy" to match the other forms of energy discussed here and to be consistent with the widely used term "static energy" that is the focus of our discussion. Formally, this term is an enthalpy (an energy-like state variable). This quantity is also commonly though imprecisely referred to as "sensible heat" (American Meteorological Society 2023b).

Static energy is a close cousin to potential temperature, with both thermodynamic variables long established in the scientific literature as fundamental for understanding our atmosphere going back to the 1970s (Betts 1974). Each variable offers unique insights into the physics of air owing to their distinct physical foundations and conservation properties (Bohren and Albrecht 1998; Romps 2015; Peters et al. 2022). Hence, static energy and potential temperature complement one another, and together they offer a deeper understanding of our atmosphere.

As we show below, static energy is used widely in the climate community, yet it is much less prevalent in the weather community. This represents a core conceptual gap between the weather and climate communities that hinders our field's ability to solve urgent scientific and societal problems at the weather–climate interface.

Our goal is to help bridge this gap: encourage scientists and educators unfamiliar with static energy to familiarize themselves with the concept and consider incorporating it into their science and teaching. Below we provide evidence for this gap in usage in journal publications and introductory textbooks and discuss its significance. We then describe key benefits of static energy for explaining basic concepts in atmospheric science in a manner that is valuable to both the introductory student and the established scientist. We avoid getting bogged down in technical details, for which the reader is referred to relevant references provided in the text below.

Usage of static energy in weather and climate science

While potential temperature is used widely throughout our field, static energy is commonly used in climate science but much less so in weather science. To quantify this, we use the American Meteorological Society online publication title/abstract search tool

(https://journals.ametsoc.org/browse; accessed 12 April 2023) for all publications during the period 1988–2022 (Fig. 1). In *Journal of Climate*, the term "potential temperature" is 1.8 times more common than "static energy" (12,262 entries; 1,745 with "potential temperature"; 950 with "static energy"). This contrast is much larger in the weather-focused journals: in *Monthly Weather Review* "potential temperature" is 13 times more common (7,755; 3,113; 240), and in *Weather and Forecasting* it is 17.4 times more common (2,943; 608; 35).

This disparity in usage extends to introductory meteorology textbooks, too. Here we explore the inclusion of static energy across several commonly used textbooks, as well as its application to the dry adiabatic lapse rate. Among textbooks at the broader introductory level that do not require advanced math (calculus), conceptual insights from energy are not common. Four broad weather-focused introductory texts—*Meteorology Today: An Introduction to Weather, Climate, and the Environment* (Ahrens 2021), *Practical Meteorology: An Algebra-Based Survey of Atmospheric Science* (Stull 2015), *The Atmosphere: An Introduction to Meteorology* (Lutgens and Tarbuck 2015), and *Weather: A Concise Introduction* (Hakim and Patoux 2021)—do not mention static energy, and they explain the dry adiabatic lapse rate solely in terms of changes in pressure. In contrast, the prominent introductory climate physics book *Global Physical Climatology* (Hartmann 2015) introduces both potential temperature and static energy. Meanwhile, among introductory textbooks that use advanced math, a few do introduce the concept at varying degrees of detail. The prominent introductory meteorology textbook *Atmospheric Science: An Introductory Survey* (Wallace and Hobbs 2006) derives the dry adiabatic lapse rate from static energy (p. 77), though the conceptual explanation is mentioned only briefly in a separate discussion (p. 86). *Fundamentals of Weather and Climate* (McIlveen 1991) does not discuss static energy. *A First Course in Atmospheric Thermodynamics* (Petty 2008) mentions static energy only briefly and separately from the dry adiabatic lapse rate. At the advanced level, *Atmospheric Thermodynamics* (Bohren and Albrecht 1998) provides a delightfully detailed conceptual and mathematical introduction to the dry adiabatic lapse rate in terms of static energy (p. 109). *Atmospheric Convection* (Emanuel 2005) lacks this conceptual explanation but is comprehensive in its coverage of both potential temperature and static energy. Overall, while an introduction to

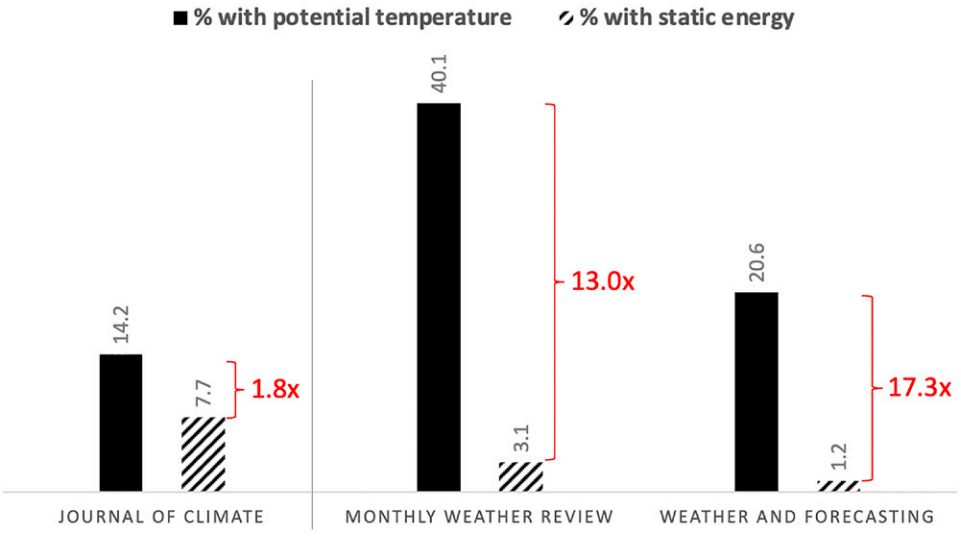

Fig. 1. Percentage of papers whose title or abstract contain the term "potential temperature" (solid bar) and "static energy" (hatched bar) and their factor difference (red) in three top American Meteorological Society journals for all papers published during the period 1988–2022. *Journal of Climate* is a climate-focused journal, while *Monthly Weather Review* and *Weather and Forecasting* are weather-focused journals. Data taken from AMS Journals online search tool (https://journals.ametsoc.org/browse; accessed 12 April 2023).

static energy can be found in certain advanced textbooks (and in the scientific literature), most introductory texts, particularly weather-focused ones, do not mention static energy or do so with relatively little emphasis or conceptual application.

There are likely valid historical reasons for the much greater prevalence of static energy within climate science. Practically, there is deep historical precedent for calculating potential temperature from observational data given that pressure can be readily measured directly whereas altitude could not prior to the advent of GPS (Stith et al. 2018), which has driven its broader usage. Physically, climate entails longer spatial and temporal scales for which the atmosphere is close to hydrostatic balance. Moreover, the climate is commonly analyzed via energy budgets composed of the transfers of energy due to incoming and outgoing radiation at the top of the atmosphere, energy fluxes between the surface and atmosphere, and internal transport of energy by atmospheric and oceanic circulations (Lorenz 1955; Hartmann 2015; Peixoto and Oort 1992). Energy budgets help us understand the global-mean climate, its spatiotemporal variability, and its response to climate change (Manabe and Strickler 1964; Budyko 1969; Miyawaki et al. 2022). Meanwhile, potential temperature has long been applied to understand both small-scale processes such as deep convection, owing to its strong conservation properties, and large-scale atmospheric dynamics such as baroclinic instability (Pedlosky 1979).

The key question though is not why this contrast in terminology exists, but whether it is important to address. In this case, this contrast reflects a significant conceptual gap between the weather and climate science communities. Given that these are foundational thermodynamic quantities for our science, this gap is arguably a difference not just in methodology but in language. If we speak different languages, we lose the ability to communicate and learn from one another, which can lead to fragmentation within our field that can slow scientific progress (Balietti et al. 2015; Chu and Evans 2021). Yet there is a pressing societal need for the weather and climate communities to work together closely. We need to understand how extreme weather, such as heat waves, hurricanes, and tornadoes, is changing with climate change, a topic that integrates weather and climate by definition. Similarly, subseasonal-to-seasonal forecasting of impactful weather is a critical area of research at the interface between weather and climate (Mariotti et al. 2018; Robertson et al. 2018). Closing this conceptual gap can help us to solve these important problems.

Practical benefits of static energy

Static energy offers several benefits for better understanding how our atmosphere works that are valuable for both scientists and educators. Below we illustrate these benefits in part by contrasting with potential temperature. We emphasize, though, that both quantities have distinct scientific value and should be considered fully complementary.

Energy is tangible. Energy is a tangible quantity that even the layperson is deeply familiar with. Each of us at some point adds gasoline to fuel our car, lights a fire to stay warm, pedals a bike to move it forward, eats food to function in our daily lives, and even may feel "energized" when doing activities such as yoga or exercise. This intuition extends to specific forms of energy even if the layperson does not explicitly think about the physical terminology. We know it takes energy to propel ourselves or other objects forward (kinetic energy); we know it takes energy to lift objects upward against gravity (potential energy); we can sense with our fingers that coffee is hot and ice cream is cold (sensible energy); and we expect to feel cold when we step out of the shower and water quickly evaporates off of our skin (latent energy). Finally, the units of energy, the joule (J), can be related to everyday objects such as a 60-W light bulb, which uses 60 J of energy every second, or a 1,000-W microwave.

The introductory undergraduate or advanced high school student brings even greater intuitive familiarity. A first course in physics introduces the student to the simple math of conversions among different forms of energy. The most basic example is the falling object: students are often asked to predict how fast the object will be going after falling a certain distance based on the conversion from potential energy to kinetic energy. Similar classic applications of energy conversions in physics classes include the motion of a swinging pendulum and a roller coaster. Such tangible applications are readily amenable to interactive hands-on and online activities to further deepen understanding (Wieman et al. 2010; Ateş and Eryilmaz 2011; Vollmer and Möllmann 2012). These introductory concepts of energy conversions for solid objects can also be applied to a gas. Doing so provides an opportunity to tap into a student's intuitive understanding of energy when we teach atmospheric science.

In contrast, potential temperature tends to be more conceptually complex. The purpose of translating an absolute temperature to a reference pressure is not obvious on its own. The utility of potential temperature is tied to its conservation under adiabatic displacements (Wallace and Hobbs 2006, p. 78), a property that is intimately related to entropy. Indeed, potential temperature is the "meteorologist's entropy" (Bohren and Albrecht 1998, p. 157): our field uses the term "isentropic" to indicate constant potential temperature, a term used interchangeably with "adiabatic" (American Meteorological Society 2023a). However, explaining the meaning of entropy in a tangible fashion has long befuddled scientists and science educators (Ben-Naim 2008; Ribeiro et al. 2021). Mathematically, entropy is proportional to the natural logarithm of potential temperature (Wallace and Hobbs 2006, p. 96; Emanuel 2005, p. 120; Bohren and Albrecht 1998, p. 157), which feels odd given that quantities inside of logarithms are typically expected to be unitless. Moreover, entropy itself has the units of joules per kelvin ($J\ K^{-1}$), which does not have a tangible everyday analog. Despite this conceptual complexity, potential temperature is undoubtedly an essential variable in atmospheric physics. The ability to consider both potential temperature and static energy together offers deeper insight than considering one alone.

Energy "buckets." Static energy is especially convenient because of its mathematical simplicity: it is a sum of different forms of energy. Each form is a "bucket" of energy that can simply be added up.

Dry static energy is the sum of potential energy and sensible energy, i.e.,

$$D = gz + C_p T. \tag{1}$$

Because the gravitational acceleration g and the specific heat capacity of air C_p are approximately constant, dry static energy is a linear combination of geopotential height above mean sea level z and temperature T. Moist static energy adds the latent energy associated with water vapor, i.e.,

$$M = gz + C_p T + L_v q_v. \tag{2}$$

Because the specific latent heat of vaporization L_v can be taken as approximately constant, moist static energy is a linear combination of height, temperature, and water vapor mass fraction q_v (i.e., specific humidity). Note that the latent energy of freezing can also be included in a similar manner, though it is often neglected for simplicity.[2]

[2] This is done by further adding the term $-L_f q_i$, with water ice mass fraction q_i and specific latent heat of fusion L_f (also approximately constant). This yields a quantity sometimes referred to as frozen moist static energy (FMSE; Bretherton et al. 2005). While it may seem odd that the latent energy of ice is negative, this is because the latent component of moist static energy represents phase changes relative to liquid water. Conceptually, the latent energy of water vapor is positive, as condensation of vapor to liquid releases sensible energy (exothermic), while the latent energy of water ice is negative, as melting of ice to liquid absorbs sensible energy (endothermic). The choice of reference phase is arbitrary though: for example, liquid water static energy (and its liquid water potential temperature counterpart) is defined relative to the vapor phase, with a negative latent energy of liquid water term in lieu of a positive latent energy of water vapor term; see Emanuel (2005, 121–123).

Since our atmosphere is nearly in hydrostatic balance, dry and moist static energy are closely analogous to dry and equivalent potential temperature, respectively. To illustrate this, vertical profiles of dry static energy and dry potential temperature, and their moist counterparts, from an example sounding are shown in Fig. 2. Their vertical structures are very similar. A key benefit of static energy is that its profiles may be further decomposed into component energies as shown in Fig. 2f. Doing so offers a direct physical pathway to consider the sources and sinks of each individual form of energy for the atmosphere. In contrast, potential temperature is a nonlinear combination of temperature and pressure, which does not allow for this simple decomposition into separate forms. Equivalent potential temperature exacerbates this problem by incorporating water vapor nonlinearly, too.

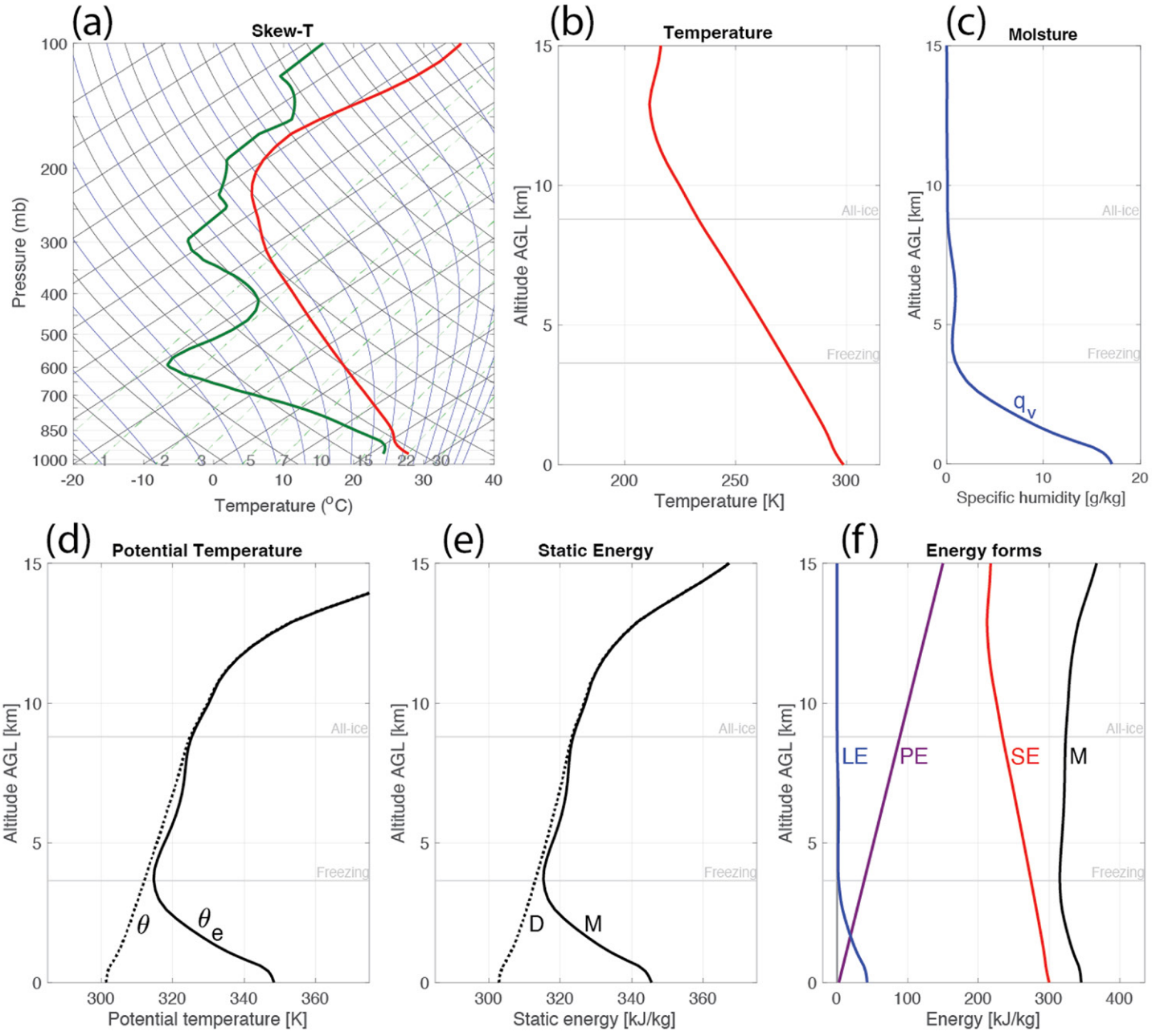

Fig. 2. Vertical structure of an example sounding. (a) Skew *T* diagram; vertical profiles of (b) temperature; (c) water vapor mass fraction (specific humidity); (d) dry and equivalent potential temperatures; (e) dry and moist static energies; (f) decomposition of moist static energy into its different forms of energy: potential energy (PE), sensible energy (SE), and latent energy (LE). Sounding is from Chavas and Dawson (2021). Surface geopotential height at sounding location is 277.4 m.

Energy conversions. Many basic processes that change the properties of air can be thought of simply as a conversion from one form of energy to another—from one bucket to another—while the sum total is conserved.

We return to our question posed at the outset: what does the dry adiabatic lapse rate mean? The dry adiabatic lapse rate is given by

$$\Gamma_d = -\left.\frac{dT}{dz}\right|_d = \frac{g}{C_p}. \tag{3}$$

As noted above, the standard explanation is that an air parcel expands and cools as its pressure decreases and is derived from the first law of thermodynamics. Changes in pressure are then converted to changes in height via the hydrostatic balance equation to yield Γ_d, but this step loses conceptual insight into its meaning. Alternatively, we can rewrite the equation for Γ_d as $g\,dz = -C_p\,dT$ to produce meaning: a *conversion from sensible energy to potential energy*. As a parcel ascends, its potential energy increases ($dz > 0$), and thus its sensible energy decreases—it cools ($dT < 0$). The reverse is true for adiabatic descent. The dry adiabatic lapse rate emerges from assuming a parcel rises while its dry static energy D is conserved. This adiabatic process exchanges sensible energy and potential energy. Both the height-based (energy) and pressure-based (potential temperature) explanations are valuable, and using both together yields deeper insight into this core concept.

A second canonical concept taught in introductory atmospheric science courses is that of "latent heat release" due to condensation of water. The conversion from latent energy to sensible energy can be understood mathematically by assuming moist static energy M remains constant [Eq. (2)]: when condensation occurs (q_v decreases), the latent energy decreases as it is converted to sensible energy (T warms); the reverse is true for evaporation. This process exchanges sensible energy and latent energy. This conceptual explanation has a tangible analog that is accessible at an introductory level. Humans sweat because the sensible energy from our skin is used to evaporate the water, which cools off our bodies. We put ice in our drinks because the sensible energy of the surrounding liquid is used to melt the ice, which cools off the drink. Both examples represent a conversion between sensible energy and latent energy. In this case, these processes are direct physical analogs to phase changes occurring in our atmosphere. Such tangible, real-world experiences can be used to explain these seemingly intangible concepts in cloud physics to a new student, or even a layperson.

Finally, if a parcel is saturated as it rises adiabatically through the atmosphere, both of the above energy conversions—dry adiabatic cooling and latent heat release—occur simultaneously. This outcome leads to the moist adiabatic lapse rate, which emerges from assuming a parcel rises while its moist static energy stays approximately constant. Figures 3a and 3b show an example of how the temperature and water content of an air parcel change as it rises adiabatically from the surface. The conversions from potential energy to sensible energy and from latent energy to sensible energy are shown in Fig. 3c. Note that this logic extends naturally to freezing too if the latent energy of freezing is included.[3] Doing so enables consideration of energy conversions due to condensation or freezing separately within different layers (warm, cold mixed phase, cold ice only) as shown in Fig. 3.

[3] During freezing (q_i increases), the latent energy also decreases ($-L_f q_i$ becomes more negative) as it is converted to sensible energy (T warms). When deposition occurs, such as in the homogeneous freezing regime (<−40°C), both latent energy conversions occur simultaneously.

Hence, the complicated process of a moist air parcel ascending through the atmosphere can be explained in terms of multiple successive stages, each characterized by combinations of energy conversions occurring simultaneously. This energy bucket view helps provide

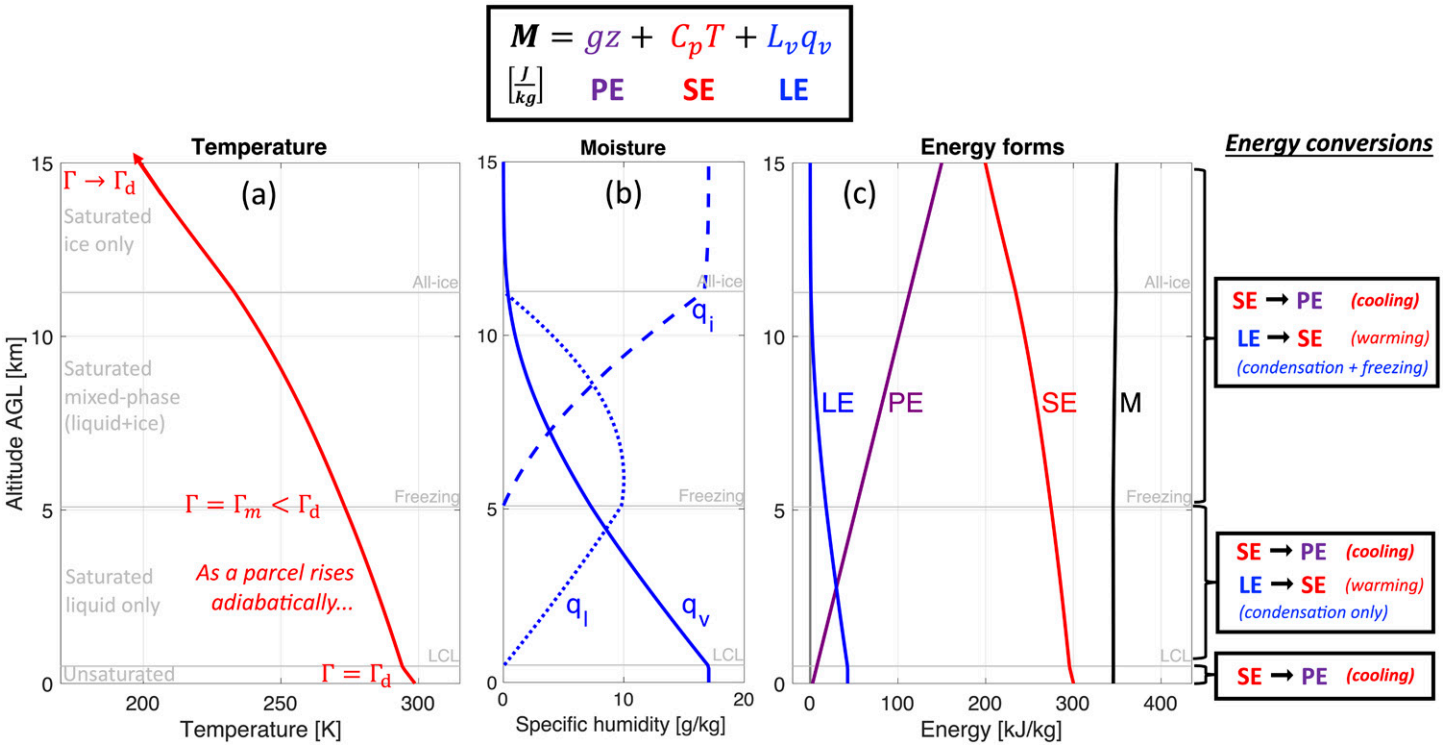

Fig. 3. An example of the cooling of a parcel rising adiabatically from near the surface and its interpretation in terms of conversions among different forms of static energy. Vertical profiles of (a) temperature; (b) water vapor, liquid, and ice mass fractions; (c) moist static energy and its constituent forms: potential energy (PE), sensible energy (SE), and latent energy (LE). Conversion among energy components within unsaturated, warm saturated, and cold (mixed-phase and ice-only) saturated layers are denoted on the right, with dominant term in boldface font. Parcel temperature and mass fractions in (a) and (b) are calculated by lifting the near-surface parcel from Fig. 1 using the adiabatic parcel algorithm of Peters et al. (2022) with total water mass conserved throughout ascent. Energies in (c) are calculated using constant coefficients [Eq. (2) and top of figure] as described in the text (and hence do not include the latent energy of freezing).

conceptual understanding: when two or more forms of energy conversion occur at the same time, they may be considered separately and their effects simply added together. This level of conceptual understanding is not accessible through potential temperature alone.

Ultimately, both variables have complementary scientific value, as they possesses distinct physical foundations and conservation properties. Formally, for adiabatic ascent, potential temperature is conserved except for sources from irreversible processes (e.g., when nonequilibrium mixed-phase condensate is present); moist static energy is conserved except for a sink due to buoyancy (Romps 2015). For full technical treatment of moist static energy, the approximations used in defining Eq. (2), and its conservation in a rising air parcel with comparison to potential temperature, the reader is referred to Peters and Chavas (2021) and Peters et al. (2022), which build on the work of Betts (1974), Bohren and Albrecht (1998), and Romps (2015).

Link to CAPE. Finally, we note briefly that static energy takes the same unit as another core concept in meteorology: convective available potential energy (CAPE). For an undilute lifted parcel, CAPE is defined as the vertical integral of its positive buoyancy, which depends on a difference in temperature (i.e., sensible energy) between a parcel and its environment. Hence, CAPE is intimately linked to static energy and its variation with height (Emanuel 2005; Randall 2012; Li and Chavas 2021; Wang and Moyer 2023), which is somewhat obscured by the use of log pressure as the vertical coordinate of a skew T–log$p$ thermodynamic diagram. Moreover, the generation of a buoyant updraft is associated with another energy conversion: from static energy (specifically sensible energy) to vertical kinetic energy.

Thus, static energy can also be intuitively linked to the kinetic energy of updrafts that produce the precipitation and thunderstorms studied by our field. For technical treatment of the conservation of total energy for a buoyant parcel, including the effects of background pressure perturbations, the reader is referred to Peters and Chavas (2021).

Conclusions

Static energy offers unique insights that, alongside potential temperature, can help both scientists and educators better explain basic concepts in atmospheric science. It is worthy of greater emphasis particularly within the weather community. Bridging this conceptual gap between the weather and climate communities is important, as there is an urgent need for our communities to work closely together to understand and predict how weather and its societal impacts are changing in a warming world.

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Data availability statement. The data and code used to generate the figures in the manuscript are available at https://doi:10.4231/TJK1-HS57 (Chavas and Peters 2023). Python code to calculate properties of a lifted parcel following the algorithm of Peters et al. (2022) is available at https://doi.org/10.6084/m9.figshare.22040807.v2 (Peters 2023).

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