Processes other than mergers can also contribute to differences in the AM content between galaxies and their halos. One likely relevant factor is that the minority of baryons that end up in galaxies, relative to the cosmic baryon fraction, is not necessarily representative of the majority of halo baryons. The fraction of baryons found in galaxies peaks at ∼0.2 for Milky Way–mass halos and is as low as $\lesssim 10^{-3}$ for dwarf galaxies and for central galaxies in massive clusters (e.g., Behroozi et al. 2019). Another possibility is that the sAM of gas accreting through the CGM is not strictly conserved but rather experiences exchanges with other components.

2.2.3. Gravitational versus gas pressure torques. We do not yet have a detailed understanding of AM transport in the CGM, but several mechanisms can contribute. Danovich et al. (2015) decomposed the total Lagrangian torque on gas elements into three components, $\boldsymbol{\tau} = \mathrm{d}\boldsymbol{l}/\mathrm{d}t = \boldsymbol{\tau}_\Phi + \boldsymbol{\tau}_P + \boldsymbol{\tau}_s$, where $\boldsymbol{l}$ is the AM vector, $\boldsymbol{\tau}_\Phi = -\rho \boldsymbol{r} \times \nabla\Phi$ is the torque due to gravitational forces, $\boldsymbol{\tau}_P = -\boldsymbol{r} \times \nabla P$ is the torque due to pressure gradients, and $\boldsymbol{\tau}_s = -\boldsymbol{l}\nabla \cdot \boldsymbol{v}$ corresponds to viscous stresses. The viscous stress term is negligible in the ideal hydrodynamics limit. **Figure 6*c*** compares $\log q$ radial profiles for gravitational and pressure torques acting on cold gas for simulated halos at $z \sim 1.6$–3.2 from Danovich et al. (2015), where $q_{\Phi,P} \propto |\boldsymbol{\tau}_{\Phi,P}|/|\boldsymbol{l}|$. The results indicate that the torques on cold streams are dominated by gravity rather than gas pressure. These gravitational torques are sourced by anisotropies in the matter distribution, ranging from large-scale structure to central disks, which tend to align the infalling gas. It would be valuable to extend this kind of analysis to other regimes in the future. For example, the relative importance of gravitational torques versus pressure torques could be very different for hot gas, which tends to be more spherical in geometry and in approximate hydrostatic equilibrium throughout the halo. It would also be worthwhile to quantify the effects of magnetic fields on AM transport in the CGM. Magnetic fields play a key role in transporting AM in accretion disks around young stars and black holes, but their effects on AM exchanges in the CGM have not yet received attention to our knowledge.

After baryons are accreted by galaxies, gravitational torques due to asymmetric features in the potential (e.g., spiral arms, bars, or massive clumps) can strongly affect the AM distribution within galaxies, such as by forming central bulges (e.g., Shlosman et al. 1989). This would also contribute to differences between the AM of galactic components relative to what may be expected from strict conservation of AM inherited from the halo. Overall, AM acquisition and exchange processes in the CGM remain relatively understudied and more work on this topic would be highly valuable.

2.3. Galactic Winds

Galactic winds are commonly observed and are an essential ingredient of modern galaxy-formation theories. In most galaxies, these outflows are understood to be primarily driven by energy and/or momentum produced by massive stars, including via SNe (e.g., Chevalier & Clegg 1985) and/or radiation pressure (e.g., Murray et al. 2005). In galaxies with luminous AGNs, galactic winds can also be powered by accretion onto massive black holes (e.g., Faucher-Giguère & Quataert 2012, and references therein). Here, we focus on outflows powered by star formation. In current models, these outflows are critical to suppress star formation in galaxies up to $\sim L_\star$ by either ejecting gas from the ISM before it has time to turn into stars or preventing CGM gas from accreting onto galaxies in the first place (Somerville & Davé 2015, Naab & Ostriker 2017). However, because they originate on small scales and their driving mechanisms are not yet fully understood, the properties of galactic winds remain highly model dependent. Therefore, we limit our discussion below to general concepts and results that are useful for understanding the impact of galactic winds on the CGM, and vice versa, rather than the detailed predictions of specific models.

Figure 7 summarizes some key properties of galactic winds in simulations. One salient feature is that galactic winds are multiphase. This multiphase structure is clearly observed in

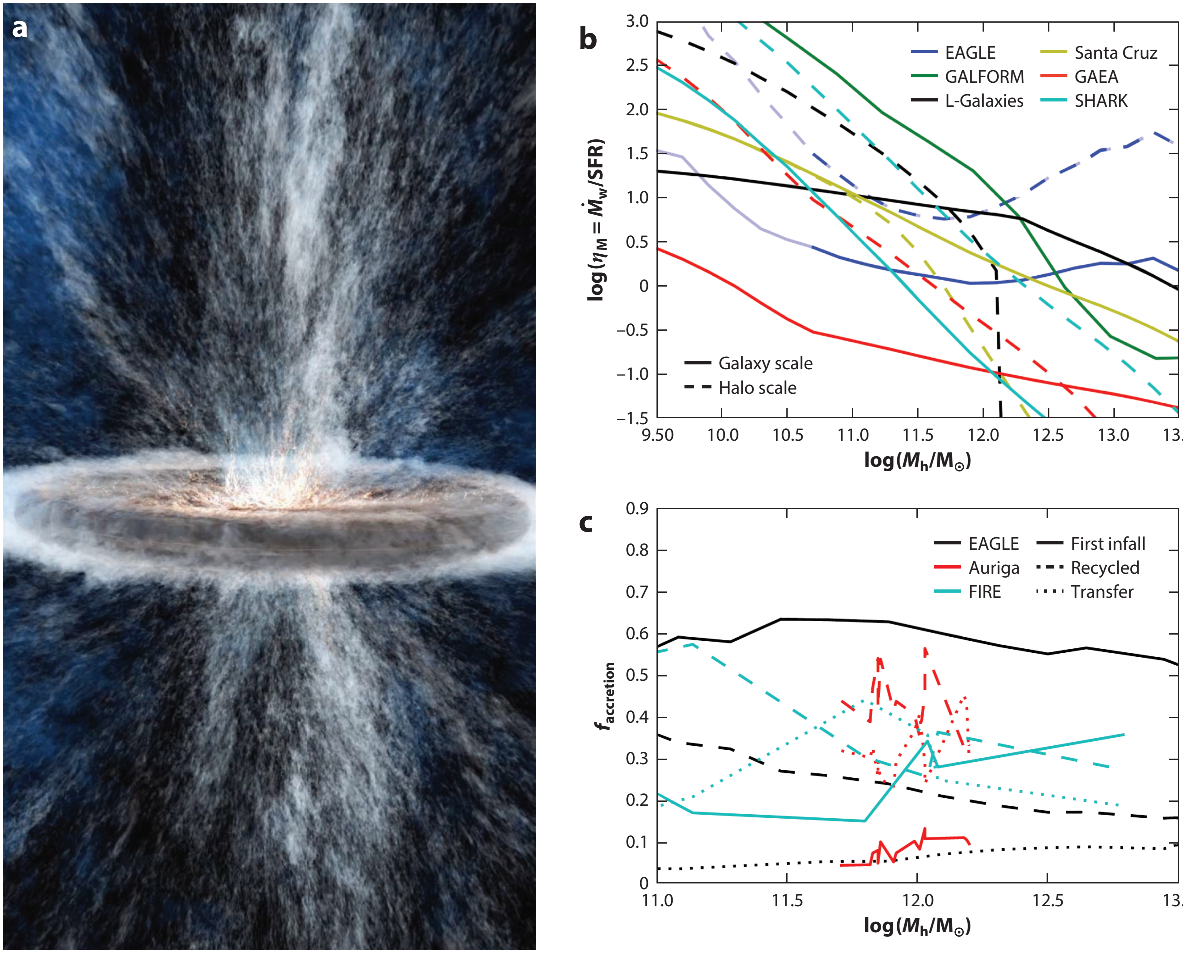

Figure 7

(*a*) Simulation of a galactic wind driven from a disk galaxy by supernovae. The density rendering highlights the multiphase nature of the outflow, with a low-density fluid heated by supernova explosions escaping the galaxy with a highly structured spectrum of cool clouds embedded in it. (*b*) Comparison of wind mass loading factors as a function of dark matter halo mass in different cosmological simulations and semianalytic models (labeled in the legend) at $z = 0$. The solid curves correspond to outflow rates from the galaxy, whereas the dashed curves correspond to outflow rates from the halo (at one virial radius). The outflow rate from the halo can be larger than that from the ISM because of gas entrainment in the CGM. (*c*) Fraction of the final stellar mass contributed by different accretion channels as a function of halo mass at $z = 0$, for different cosmological simulations. The accretion channels are defined similarly as in **Figure 2**, and correspond to gas that formed stars after directly accreting onto a galaxy from the IGM ("first infall"), gas that recycled in winds before turning into stars, and gas that transferred from one galaxy to another before forming stars. Panel *a* adapted with permission from Schneider et al. (2020); copyright 2020 AAS. Panel *b* adapted with permission from Mitchell et al. (2020b). Panel *c* adapted with permission from Mitchell et al. (2020a). Abbreviations: CGM, circumgalactic medium; IGM, intergalactic medium; ISM, interstellar medium; SFR, star-formation rate.

the prototypical example of the galactic wind driven by the M82 starburst galaxy (Strickland & Heckman 2009) and is also predicted by several models. In the models, the multiphase structure typically consists of a hot fluid heated by SN explosions with a spectrum of embedded cool clouds (e.g., Kim et al. 2020, Schneider et al. 2020, Fielding & Bryan 2022). However, winds accelerated by gentler processes such as radiation pressure or CRs could be cooler overall (e.g., Murray et al. 2005, Booth et al. 2013); the dominant driving mechanisms and wind properties could well vary with galaxy mass and redshift. Much of our discussion of the physics of multiphase gas in Section 3, including processes that govern cold cloud growth and survival, is relevant to galactic winds. We discuss a global thermal instability in winds in Section 3.1.3, and we discuss cloud–wind interactions extensively in Section 3.2.

2.3.1. Bulk scalings. Although the gas in galactic winds exhibits a range of velocities, densities, and temperatures (even in individual galaxies), there is some evidence that the mean (or median) wind velocity $v_{\rm w}$ scales linearly with the circular velocity of the galaxy ($v_{\rm c}$). This velocity scaling is predicted, for example, in `FIRE` simulations in which galactic winds emerge from the energy and momentum injected by multiple stellar feedback processes (including SNe, stellar winds, and radiation pressure) on the scale of individual star-forming regions (Muratov et al. 2015). In large-volume simulations in which the generation of galactic winds is not resolved but the wind properties are instead prescribed, it is also found that a wind injection velocity proportional to $v_{\rm c}$ can produce a reasonably good fit to the observed galaxy stellar mass function (e.g., Davé et al. 2011, Vogelsberger et al. 2014). Although we do not understand this scaling in detail, we can heuristically reason why it may emerge from the self-regulation of stellar feedback (e.g., Murray et al. 2005). Namely, $v_{\rm c}$ scales with the escape velocity in the potential, so much slower outflows would quickly fall back onto galaxies, strongly suppressing their net effect. However, much faster outflows would easily escape halos and halt galaxy formation.

The scaling with circular velocity can be used to derive how the mass outflow rate $\dot{M}_{\rm w}$ scales in different limits. When the wind is energy-driven, the product $\dot{M}_{\rm w} v_{\rm w}^2$ is fixed, so the mass outflow rate scales as $\dot{M}_{\rm w} \propto 1/v_{\rm w}^2 \propto 1/v_{\rm c}^2$. Similarly, when the wind is momentum-driven, the fixed product is $\dot{M}_{\rm w} v_{\rm w}$, so $\dot{M}_{\rm w} \propto 1/v_{\rm w} \propto 1/v_{\rm c}$. Because the feedback energy scales with the SFR, these scalings are often expressed in terms of the mass loading factor $\eta_{\rm M} \equiv \dot{M}_{\rm w}/{\rm SFR}$. An example of an energy-driven wind is a hot, SN-driven outflow in which radiative losses are negligible. An example of a momentum-driven wind would be one driven by radiation pressure, in which the momentum of photons is transferred to the gas but thermal energy plays a negligible role in the outflow expansion. **Figure 7*c*** compares mass loading factors measured from different cosmological simulations and semianalytic models as a function of halo mass.

We note that, because mass loading can occur in both the ISM and the CGM (see below), whereas the energy and/or momentum injection is concentrated in the galaxy, the energy and momentum loading factors $\eta_{\rm E} \equiv \dot{E}_{\rm w}/\dot{E}_{\rm feedback}$ and $\eta_{\rm p} \equiv \dot{p}_{\rm w}/\dot{p}_{\rm feedback}$ are often more robust predictions of the models. Here, the subscript "feedback" refers to the energy or momentum injected in the ISM by feedback processes, whereas the subscript "w" refers to the energy or momentum escaping in a wind. The energy loading factor $\eta_{\rm E}$ can be $\ll 1$, e.g., when the majority of the energy from SNe is radiated away in the ISM before wind break out (e.g., Fielding et al. 2017a).

2.3.2. Entrainment of CGM gas by galactic winds. The properties of outflows can change greatly as they expand into the CGM. As outflows expand, they are decelerated by gravity as well as by entrainment of CGM mass.[7] The entrainment of CGM gas modifies the mass outflow rate, as well as its chemical composition by mixing gas recently ejected from the galaxy with ambient CGM. CGM entrainment can be very important: For example, Muratov et al. (2017) and Mitchell et al. (2020b) showed that mass outflow rates at the virial radius can be dominated by entrained gas, in the `FIRE` and `EAGLE` simulations, respectively (for `EAGLE`, this is shown by halo scale mass loading factors that are larger than galaxy scale loading factors in **Figure 7*b***). In other simulations, such as

[7] In Section 3.2, we discuss the entrainment of cold clouds in hot winds. Here, the entrained CGM mass can be volume-filling hot gas as well as cold gas.

`IllustrisTNG`, the entrained CGM mass is less important relative to the gas directly ejected from the ISM (Nelson et al. 2019), again underscoring the model dependence of outflow results. Because the metallicity of the CGM is generally lower than that of the ISM, entrainment tends to dilute the outflow metallicity. These effects imply that it is critical to specify where outflow properties are measured (such as at what radius) when comparing model predictions to observations or different models to one another.

As they sweep up CGM, galactic winds can affect the properties of gas accretion in halos. For example, outflows may push out infalling gas and prevent some of it from accreting onto galaxies (e.g., Nelson et al. 2015, Tollet et al. 2019). Outflows may also affect the survival of cold streams, drive turbulence, or inject heat into halo gas. Thus, it should be borne in mind that galactic winds are likely to modify some aspects of our simplified discussion of gas accretion in halos (Section 2.1) in model-dependent ways.

2.3.3. Wind recycling. An important property of galactic winds is that some or most of their mass can recycle, i.e., reaccrete onto galaxies (see **Figure 2**). This implies that, in an instantaneous sense, some CGM gas that is observed to be infalling onto galaxies may have been previously part of a wind (e.g., Hafen et al. 2020). A phase change may occur as winds recycle, e.g., if a hot wind cools and cold clouds rain back onto the galaxy, but this does not necessarily occur if gas is ejected cold from the galaxy, as in some momentum-driven wind models. Recycling has also been shown to be very important in an integrated sense in shaping the galaxy stellar mass function, as was shown, for example, in the pioneering study of wind recycling by Oppenheimer et al. (2010). The fraction of wind mass that recycles depends on galaxy mass, redshift, and the feedback model (Mitchell et al. 2020a), but can be more than half and up to $\approx$1 in some simulations (e.g., Christensen et al. 2016, Anglés-Alcázar et al. 2017).

Useful concepts to characterize wind recycling include the distribution of recycling times and the distribution of the number of recyclings. Long recycling times mean that, after being ejected in a wind, a gas element spends a long time outside galaxies before being reaccreted. A given gas element can in general be recycled many times. In the `FIRE` simulations, the star-formation histories of dwarf galaxies are highly time-variable, and gas elements can be ejected then reaccreted up to $\sim$10 times by redshift zero. The multiple cycles of wind ejection and reaccretion in these dwarf galaxies may be an important factor driving the burstiness of star formation predicted by the simulations (Anglés-Alcázar et al. 2017). As we discuss below in Section 2.4, another form of wind recycling occurs when gas ejected by one galaxy reaccretes onto another galaxy.

2.4. Satellite Galaxies

In this review, we focus primarily on physical processes operating in the CGM of central galaxies, i.e., main galaxies at the center of dark matter halos. The CGM of satellite galaxies can be affected by additional effects and does not separate cleanly from the CGM of the central galaxy they orbit. In this section, we briefly list some of the ways in which satellite galaxies can affect the CGM of the central galaxy.

Most directly, gas that remains bound to satellite galaxies (e.g., satellite ISM) can give rise to strong absorption features in the spectra of background sources. If the satellite is faint, the satellite may not be detected in emission and the absorption features can be mistakenly attributed to the CGM of the central galaxy. Similarly, satellites could contribute to the spatially extended emission that sensitive experiments aim to detect from the CGM.

Gas originally belonging to satellites can also be lost and incorporated into the CGM of a central galaxy by several different processes. These include the following:

- Ram pressure stripping. When a body moves with velocity $v_{\rm rel}$ relative to a background gaseous medium of density ρ, the body experiences a ram pressure of magnitude $\sim\rho v_{\rm rel}^2$. This ram pressure strips gas from satellites, and this gas mixes with the CGM of the central galaxy, contributing both mass and metals. In dense environments, ram pressure plays an important role in quenching star formation in satellite galaxies. This effect has been studied extensively in the context of galaxy clusters (e.g., Tonnesen et al. 2007) and is theorized to produce "jellyfish" galaxies (e.g., Franchetto et al. 2021). If the relative velocity of the satellite (or, better still, the full orbital history of the satellite) is known, ram pressure can be exploited to infer the density of dilute halo gas, as has been done using observations and modeling the Large Magellanic Cloud (LMC) around the Milky Way (Salem et al. 2015).
- Tidal stripping. Tidal forces, which arise when gravitational forces are stronger on one side of a body than on the other, can also pull gas out of satellites. For a body of size ΔR, the tidal acceleration with which opposite parts of the body are pulled apart by the gravity of a point mass M at distance R is $\sim GM\Delta R/R^3$. We note that, because tidal forces scale as $1/R^3$, tides between low-mass satellite galaxies that are near one another can be more important than tidal forces between a satellite and the central galaxy. For example, Besla et al. (2012) modeled the Magellanic Stream (a band of HI gas trailing the Magellanic Clouds) as being caused by LMC tides stripping gas from the Small Magellanic Cloud (other models suggest an important role for ram pressure in addition to tides; e.g., Tepper-García et al. 2019, Lucchini et al. 2021). If the Milky Way were observed externally, the Magellanic Stream would appear as an important component of its CGM, so we must presume that some observed features of the CGM of other galaxies arise from similar tidal interactions.
- Satellite winds. Feedback in satellite galaxies can eject gas from the ISM of a satellite and into the CGM of the central galaxy. This effect is illustrated in the simulation shown in **Figure 2**, where it is labeled "intergalactic transfer" because some of the gas ejected by satellites can later accrete onto the central galaxy. This transfer process can contribute up to $\sim$1/3 of the baryons that end up as stars in Milky Way–mass galaxies in `FIRE` simulations (Anglés-Alcázar et al. 2017), although the importance of this mode of galaxy fueling differs in other simulations (**Figure 7*c***). Not all the gas ejected in satellite winds necessarily reaccretes onto galaxies. Winds from satellites can also affect the CGM by puffing up accreting filaments in which they are often embedded (see Section 2.1.4) and by creating overdensities that promote the precipitation of cool gas via thermal instability in the CGM (Esmerian et al. 2021). At a given time, the fraction of the total CGM mass contributed by winds from satellite galaxies can be substantial [e.g., up to $\sim$20% inside the virial radius of $L_\star$ galaxies in the `FIRE` simulations analyzed by Hafen et al. (2019)].

The different mechanisms listed above that remove gas from satellites are not mutually exclusive. The galaxy group containing M81 and M82 is a well-known example of a system in which intrahalo, filamentary HI clouds are associated with strong galaxy interactions and, thus, most likely involve tidal stripping (Chynoweth et al. 2008). In this system, M82 is also well known for its prominent galactic wind (e.g., Strickland & Heckman 2009), so this is an example in which both gas ejection in a wind and tidal interactions shape the observed CGM.

Even if gas mass losses by satellites are negligible, satellites can deposit into the diffuse CGM the gravitational potential energy they lose as they fall into, or orbit within, the halo. Ram pressure acts as an effective friction force and removes energy from the orbit, which can in principle go into heating the CGM (e.g., as wakes dissipate). Similarly, dynamical friction induces wakes that can dissipate in the CGM (El-Zant et al. 2004). These processes may contribute to the excitation of disturbances or turbulence in the CGM and operate on gas clumps that accrete in the halo

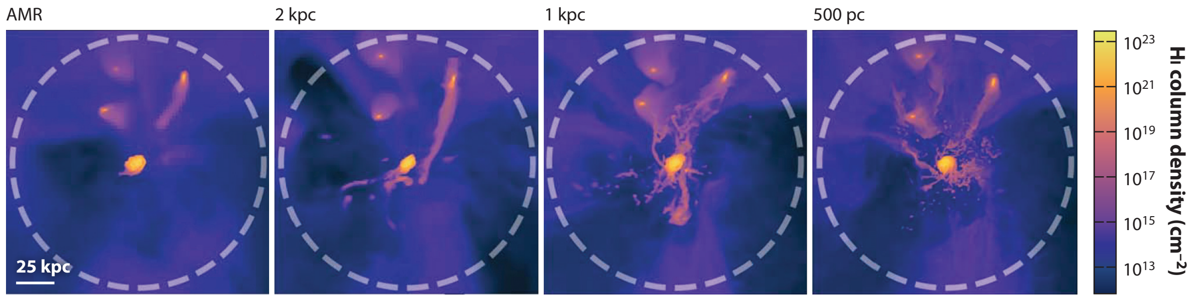

Figure 8

Cosmological simulations are unconverged in the CGM. Shown are column density projections of a simulated $L_\star$ galaxy with different levels of spatial resolution. Enhanced halo resolution leads to enhanced neutral hydrogen content, with no sign of convergence. Figure adapted with permission from Hummels et al. (2019); copyright 2019 AAS. Abbreviations: AMR, adaptive mesh refinement; CGM, circumgalactic medium.

even if these clumps do not correspond to satellite galaxies. Dekel & Birnboim (2008) analyzed clumpy gas accretion in massive halos and argued, based on simple estimates, that gravitational heating by cosmological accretion delivered to the hot gas in the inner halo could potentially maintain star-formation quenching in the long term. More recent high-resolution simulations that self-consistently include gravitational heating indicate that this process is not sufficient to quench galaxies (e.g., Su et al. 2019). However, more work is needed to understand whether and where these processes may have interesting effects on the CGM.

3. SMALL-SCALE PROCESSES: MULTIPHASE GAS

An outstanding problem in current large-scale simulations is that the amount of CGM cold gas is unconverged. It increases monotonically with resolution (Faucher-Giguère et al. 2016, Hummels et al. 2019, Peeples et al. 2019b, Suresh et al. 2019, van de Voort et al. 2019), indicating that key physical processes remain unresolved (see **Figure 8**). In this portion of the review, we survey-small scale processes in CGM gas. This frequently includes physics that is unresolved in galaxy- or cosmological-scale simulations and is often the realm of idealized simulations or analytic theory. The list of relevant physical processes is vast and similar to that in the ISM: magnetohydrodynamics (MHD), fluid instabilities, shocks, radiative cooling, anisotropic conduction and viscosity, turbulence, CRs, and gravity, to name a few. The more dilute nature of CGM plasma means that collisionality can be weak, and kinetic scale plasma processes can play a role. Entire textbooks could be devoted to some of these topics; we obviously cannot do them justice in a brief review.

To focus our discussion, we lean on the striking abundance of atomic ($T \sim 10^4$ K) and sometimes even molecular ($T \sim 10$–100 K) gas in the CGM (Tumlinson et al. 2017), even though virialized gas should be much hotter. Indeed, cold gas forms our main observational probe of the CGM: It is observed at high spectral resolution by quasar absorption line spectroscopy and also in spatially resolved emission maps by integral field spectrographs on large ground-based telescopes such as Keck and the Very Large Telescope. Direct observations of the hot gas component, in X-ray and Sunyaev-Zel'dovich measurements, are few and far between, except in hotter systems such as massive ellipticals, groups, and clusters; dispersion measure (DM) measurements of fast radio bursts (FRBs; Prochaska et al. 2019, Chawla et al. 2022) could eventually improve the situation. Given its observational prominence, and the likely importance of cold mode accretion in fueling star formation, we focus on physical processes relevant to cold gas in the CGM, and how it interacts with the hot phase. Parallels with the terrestrial water cycle are reflected in terminology (precipitation, condensation, evaporation). We consider the following: