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Multi-scale processes of the Kelvin-Helmholtz instability at Earth's magnetopause

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The Kelvin-Helmholtz Instability (KHI) is a large scale convective instability which occurs anywhere the velocity shear between two fluids is large, such as Earth's magnetopause where the fast flowing magnetosheath abuts the relatively stagnant outer magnetosphere. The KHI was initially believed to contribute only to energy and momentum transfer from the solar wind to the magnetosphere, but was eventually shown to support mass transport and plasma heating. Recent advancements in *in-situ* observational capabilities and high scale computer modeling have once again shifted our understanding of the KHI from a large scale process, to an active environment which connects the global and kinetic scales through a variety of multi-scale processes and phenomena. In this mini-review, we provide an update on the latest findings in Kelvin-Helmholtz (KH) related processes at kinetic scales and the effects of the global environment on KH development.

KEYWORDS

Kelvin-Helmholtz instability, plasma transport, reconnection, multi-scale processes, diffusive transport, turbulence

1 Introduction

The solar wind must supply energy to the magnetosphere at a rate of $\geq 10^{10}$ W to account for the energy dissipated in the auroral oval and the formation of the ring current (Osmane et al., 2015). The processes contributing to this energy transfer were first classified in terms of magnetic reconnection (Dungey, 1961), responsible for mass transfer, and viscous interaction (Axford and Hines, 1961), responsible for momentum transfer. Spacecraft observations have since verified the existence of magnetic reconnection and its impact on geomagnetic activity (Paschmann et al., 1979; Oieroset et al., 2005; Angelopoulos et al., 1994; Burch et al., 2016b). The primary process responsible for viscous interaction is the velocity shear driven Kelvin-Helmholtz instability (KHI), which is ubiquitous at Earth's magnetopause (Kavosi and Raeder, 2015; Rice et al., 2022).

In the last few decades, it has been shown that the KHI is not only responsible for viscous momentum transfer (Miura, 1987), but supports myriad secondary processes down to kinetic scales including reconnection, ion and electron scale plasma waves, and plasma turbulence. These secondary processes can further enhance mixing and heating and in some cases, interact with or drive each other. Recent observations and simulations have also shown that the fluid scale KHI impacts and is impacted by global scale patterns within the magnetosphere and heliosphere. In this mini-review, we provide an overview of the most recent findings which inform our current understanding of the KHI as a phenomena connecting physics across multiple scale sizes.

2 The KHI and kinetic scale processes

Though initially believed to be responsible only for momentum and energy transfer to the magnetosphere (Miura, 1987), it is now known that the KHI is also able to drive plasma transport and heating via kinetic scale processes such as reconnection, diffusive transport, and kinetic scale wave modes. Recent technological advances in *in-situ* measurements (Burch et al., 2016a; Angelopoulos, 2008; Escoubet et al., 2001) and the accessibility of petascale kinetic simulations (Bowers et al., 2009), have enabled numerous studies resolving the nature of kinetic scale processes associated with the KHI. In this section we review a few of these phenomena.

2.1 KHI induced reconnection dynamics

As magnetic reconnection requires a thin current sheet, on the order of the ion inertial length, the inertia of the Kelvin-Helmholtz (KH) driven vortex motion can provide a powerful external driver for reconnection to occur. An example of one such current sheet driven by KH vortex motion is shown in Figure 1. KHI driven reconnection signatures have been detected by multiple spacecraft missions at both low and high-latitudes (Nykyri et al., 2003b; 2006b; Eriksson et al., 2016; Li et al., 2016; Burkholder et al., 2020b; Li et al., 2013).

The importance of KHI to reconnection was first recognized by Otto and Fairfield (2000), who compared boundary layer signatures observed by the Geotail spacecraft (Fairfield et al., 2000) during strongly northward interplanetary magnetic field (IMF) with two dimensional (2D) magnetohydrodynamic (MHD) simulations. Those simulations showed that KHI was able to grow to non-linear stages and twist the magnetic fields into an anti-parallel configuration when the IMF and geomagnetic fields were initially parallel along the shear flow direction and the Alfvén speed along the wave vector, k, was less than the shear flow speed. This resulted in intense current layers and magnetic reconnection within the high-density filament of the KH vortex. Both 2D MHD (Nykyri and Otto, 2001) and 2D Hall-MHD (Nykyri and Otto, 2004) plasma approximations show this mechanism can provide mass transport velocities of 1–2 km/s during strongly northward IMF, corresponding to a diffusion coefficient of 10^{9} ^{2}/s. At this rate, KH activity could populate the plasma sheet with cold, dense magnetosheath material in about two hours.

In three dimensions (3D), magnetic reconnection also occurs above and below the shear flow plane leading to a higher transport rate, 10^{10} m^{2}/s, during strongly northward IMF (Ma et al., 2017). A comparison of Hall-MHD and test particle simulations with hybrid simulations demonstrated that the particle mixing rates are similar in both cases, but "plasma is transported through a few big magnetic islands […] in the fluid simulation, while magnetic islands in the hybrid simulation are small and patchy" (Ma et al., 2019).

When magnetic fields are initially anti-parallel across the shear flow plane, magnetic reconnection can occur in both the high and low filaments of the vortex, which results in the mixing and capture of low density magnetospheric material into the magnetosheath (Nykyri et al., 2006b; Eriksson et al., 2016). In the case of a symmetric plasma density across the shear flow layer, the direction of plasma transport is determined by the strength of the current density in either spine (Nykyri and Otto, 2004).

The 3D dynamics of magnetic reconnection driven by the KHI during southward IMF have been associated with Alfvénic plasma jets propagating perpendicular to the initial shear flow plane and the escape of magnetospheric electrons into the magnetosheath (Li et al., 2023). Simulations of this geometry have shown that the KHI can increase the reconnection rate even when the Hall term is switched off (Ma et al., 2014a; b).

Reconnection in KH vortices often leads to the mixing of plasmas with different energies and densities which can lead to anisotropic velocity distribution functions (Nykyri et al., 2006b; Moore et al., 2016) and the generation of ion and electron scale plasma waves which can in turn lead to ion and electron heating (Moore et al., 2016; 2017; Nykyri et al., 2021b). The KHI can also effectively drive plasma turbulence to further enhance plasma heating (Stawarz et al., 2016; Delamere et al., 2021). Thus, the efficiency of plasma transport due to reconnection within KHI should not be considered in isolation with regard to other kinetic scale processes, as will be discussed in the following sections.

2.2 Diffusive transport within the KHI

The large-scale KHI has been found to drive secondary instabilities like the Rayleigh-Taylor instability (Nakamura et al., 2022a) and/or secondary KHI (Matsumoto and Hoshino, 2004; Nakamura et al., 2004; Faganello et al., 2008) which interfere with the large-scale evolution of KH vortices and influence the transport of plasma. Inside fully developed vortices, turbulence (Matsumoto and Hoshino, 2004; Stawarz et al., 2016) and magnetic reconnection (see Sec.2.1) lead to diffusive particle transport. At the spine region of the vortices, magnetic reconnection can strongly influence the diffusive transport within the KHI.

Further, the multi-scale nature of the KHI has been discussed in previous studies focusing on turbulent intermittency and anisotropy related to the KHI (Stawarz et al., 2016), nonlinear wave-particle interactions (Sorriso-Valvo et al., 2019) and the distortions of the ion distribution functions due to kinetic effects (Settino et al., 2020; 2021). More recently, Blasl et al. (2022) and Nakamura et al. (2022a,b) reported the development of the Lower Hybrid Drift Instability (LHDI) and a related thickening of the spine region of KH vortices by diffusive plasma transport during southward IMF from both kinetic simulations and MMS data. Further, Blasl et al. (2023) identified small-scale current sheets and ongoing electron-only reconnection related to this diffusive process, shown in Figure 1. These results highlight the importance of a multi-scale and multi-process approach for future studies of the KHI.

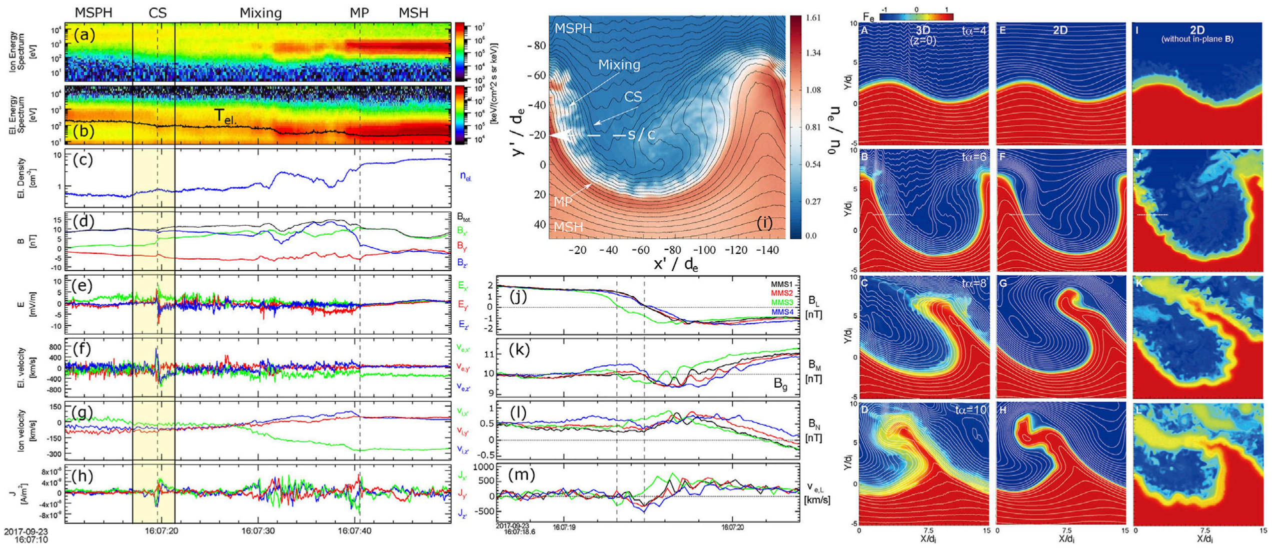

FIGURE 1
Kinetic scale effects of the KHI. Left, MMS1 observations of the spine region of a KH vortex with a kinetic scale current sheet (yellow shade) observed on 23 September 2017: ion **(A)** and electron energy spectrogram with overplotted electron temperature **(B)**; electron density **(C)**, magnetic field (including |B|) **(D)**, electric field **(E)**, electron **(F)** and ion **(G)** velocities, and current density **(H)**. Center bottom, MMS1-4 observations of the current sheet interval, magnetic field components **(J–L)** and L-component of electron velocity **(M)**. Center top, 3D simulation of electron density within the KHI vortex shown in MMS observations with LHDI evident in mixing region. At right, time evolution of the kinetic scale mixing parameter for 3D **(A–D)**, 2D **(E–H)**, and 2D without initial in-plane fields **(I–L)** simulations of the KHI event shown at left. Left and center panels **(A–M)** from Blasl et al. (2023). Right panels **(A–L)** from Nakamura et al. (2022b).

2.3 Wave heating driven by the KHI

The plasma mixing, magnetic field twisting, and strong gradients of density, velocity, and pressure inherent to the KHI can support the growth of wave modes which in turn leads to plasma heating. Several wave modes associated with the KHI are known to drive plasma heating across scale sizes at the magnetopause boundary. At the ion scale the most intensely studied are Kinetic Alfvén waves (KAWs), electromagnetic ion cyclotron (EMIC) waves, and magnetosonic waves.

For example, velocity gradients both parallel and perpendicular to the background magnetic field are known to drive electrostatic and electromagnetic ion cyclotron waves (Nykyri et al., 2003a; 2006a; Peñano and Ganguli, 2002; Kim et al., 2004). Zhang et al. (2017) demonstrated that EMIC waves may also be generated in regions where hot anisotropic plasma overlaps with a separate cold and dense population as is the case in well developed KH vortices where hot magnetospheric plasma is mixed or captured into the magnetosheath.

The strong magnetic field gradients present in the KHI also give rise to Alfvén resonance regions, where the surface wave speed matches the local Alfvén speed. At these regions, surface Alfvén waves mode convert to KAWs (Chaston et al., 2007; Johnson and Cheng, 2001). KAWs energize and demagnetize ions, allowing cross field transport of sheath ions into the magnetosphere where they contribute to boundary layer formation Chaston et al. (2007); Johnson and Cheng (2001). A portion of the KAW electric field is parallel to the background magnetic field, allowing for field aligned electron heating (Hasegawa, 1976; Nykyri et al., 2021b).

Kinetic magnetosonic waves, the kinetic counterpart of fast mode MHD waves, can arise from shell distributions in the ion population, such as those produced by reconnection within KH vortices. Fast mode waves carry energy perpendicularly across field lines and can be triggered by a combination of fast sheath flows and pressure perturbations, which appear at the center of KH vortices. Fast mode and kinetic magnetosonic waves have been shown, both in theory and observation, to effectively heat ions (Lembege et al., 1983; Terasawa and Nambu, 1989; Moore et al., 2016; 2017).

In recent years, advances in *in-situ* instrumentation have allowed significant progress investigating the effects of KH associated waves above the ion cyclotron frequency. Observations of ion acoustic waves and turbulence within KH vortices were reported shortly after MMS's launch (Wilder et al., 2016; Stawarz et al., 2016). Lower hybrid waves have also been observed and kinetic simulations indicate they are effectively able to heat the cold sheath plasma as it mixes with the magnetospheric population (Blasl et al., 2022; Blasl et al., 2023).

3 KHI and global scale influence

The KHI is subject to influence by changes in the larger heliospheric environment, such as IMF orientation and seasonal variations. Consider that even though the KHI can and does occur for all IMF orientations (Kavosi and Raeder, 2015; Rice et al., 2022), including southward IMF (Hwang et al., 2012; Blasl et al., 2022; Li et al., 2023), the IMF orientation can influence its occurrence rate and location. Henry et al. (2017) found that during Parker-Spiral IMF, the KHI occurs most frequently at the dawn sector due to smaller magnetic tension (Nykyri, 2013); while at the dusk sector it is detected mostly for strongly northward IMF (Taylor et al., 2012; Henry et al., 2017). The KHI is not restricted to the equatorial plane, and has been detected at high-latitudes close to the exterior cusp (Hwang et al., 2011; Ma et al., 2016; Nykyri et al., 2021a). The KHI can also, in turn, affect global scale processes, such as the development of the magnetospheric plasma sheet. In this section we provide an overview of the global scale processes affecting and affected by the KHI.

3.1 Comparison of plasma transport at the cusps and flanks

During extended periods of northward IMF, solar wind entry into the magnetosphere leads to the formation of a cold, dense plasma sheet (CDPS) (Wing et al., 2014). The CDPS exhibits a characteristic dawn-dusk asymmetry in density and temperature (Wing et al., 2005). In general, the dawnside plasma sheet is denser than the duskside and exhibits a broad thermal distribution while the duskside plasma sheet comprises disjoint hot and cold populations (Nishino et al., 2007). The two primary entry paths of the solar wind into the magnetosphere during northward IMF are the KHI at the low-latitude magnetospheric flanks and double cusp reconnection at high-latitudes.

Only recently has it become feasible for global modeling to directly study the relative importance of cusp and flank entry to the formation of the CDPS and the development of dawn-dusk asymmetry. Sorathia et al. (2019) used a combination of high-resolution global MHD and test particle simulations during a synthetic interval of northward IMF to track the entry of solar wind plasma into the magnetosphere and its acceleration on its way to the central plasma sheet. They found comparable contributions from flank-entering (KHI) and cusp-entering (high-latitude reconnection) plasma, but very different effects on the entering plasma. Flank-entering plasma was largely cold and dawn-dusk symmetric, while cusp-entering plasma was predominantly deflected dawnward and accelerated through its interaction with the dusk-dawn directed high-latitude electric field (Burke et al., 1979). The net impact is that the dawnside plasma contains the cold flank-entering plasma and a wide range of accelerated cusp-entering plasma, consistent with the broad thermal distribution observed, as shown in Figure 2. The duskside plasma consists of cold flank-entering plasma and a high-energy subset of the dawnside cusp-entering plasma that is able to drift to the duskside. In this way, it is found that the observed dawn-dusk thermodynamic asymmetries are a consequence of the combined cusp- and flank-entering populations.

3.2 Dipole tilt effects

New results highlight KHI as an important factor in enhanced geomagnetic activity around the equinox. Kavosi et al. (2023) used data from THEMIS (Angelopoulos, 2008) and MMS (Burch et al., 2016a) over a full solar cycle to investigate the impact of Earth's dipole orientation on the formation and occurrence of KHI and found that the KHI exhibits seasonal variation. The KHI is more commonly produced during the equinoxes when Earth's dipole is not tilted toward or away from the Sun, which favors the formation of the KHI at the magnetopause. During solstices, when Earth's dipole is tilted at extremes toward or away from the Sun, Earth's magnetic field suppresses KH wave activity (Kavosi et al., 2023).

At Earth's magnetopause the KHI is primarily driven by a velocity shear aligned with the wave vector, k. Any magnetic field component aligned with k acts to stabilize the KHI. This stabilization is facilitated by magnetic tensions in the magnetosheath and magnetosphere, which are associated with the IMF and geomagnetic dipole field, respectively. The orientation of Earth's magnetic dipole axis varies both seasonally and diurnally due to the combined effects of Earth's orbit around the Sun (as seen in Figure 2) and the rotation of the magnetic dipole about Earth's rotation axis. These variations introduce seasonal and diurnal fluctuations in the growth of the KHI by altering the intensity of the magnetic tension forces.

The tilt of Earth's dipole axis towards or away from the sun modulates the magnetic tension due to the orientation of the magnetospheric field relative to the shear flow in the GSM-X-Y plane. At equinoxes, the dipole axis is aligned with the GSM-Z axis, perpendicular to the velocity, and the magnetospheric magnetic tension diminishes to 0. Consequently, the dipole field lines exert no stabilizing influence on the KHI and the probability of KHI occurrence increases. At solstices, when the dipole is at its maximum angle relative to the GSM-Z axis, the magnetospheric magnetic tension is also maximized and exerts more stabilizing force on the KHI, which decreases the probability of KHI occurrence. These effects have been confirmed in observations by Kavosi et al. (2023), as shown in Figure 2.

The dominance of the shear flow in the X direction suggests that the magnetosphere's magnetic tension, influenced by the dipole's tilt towards or away from the Sun, plays a significant role in stabilizing KHI. Consequently, the equinoctial effect exerts a significant influence on the seasonal and daily variations of KHI, as corroborated by KHI occurrence rate analysis in Kavosi et al. (2023).

4 Discussion and conclusion

As recounted here, recent advancements in observational and computational capabilities have expanded our understanding of the KHI as an active environment which influences and is influenced by processes across scales sizes. At kinetic scales, reconnection, diffusive transport, and wave activity contribute to enhanced plasma transport and heating. These small scale processes can also interrupt the development of KH vortices from linear to non-linear and rolled up stages. At global scales, the location and occurrence of KHI is modulated by IMF orientation and seasonal dipole tilt effects. The KHI contributes to the formation of the CDPS during northward IMF and its pronounced dawn-dusk asymmetry. Overall, the results summarized here paint a picture of the magnetopause not as a static boundary that is merely traversed by solar wind plasma, but as an active participant in the transfer of mass between the magnetosphere and solar wind, a process in which the KHI plays a significant role.

Questions still remain about the nature and development of the KHI. What are the origins of energetic particles within

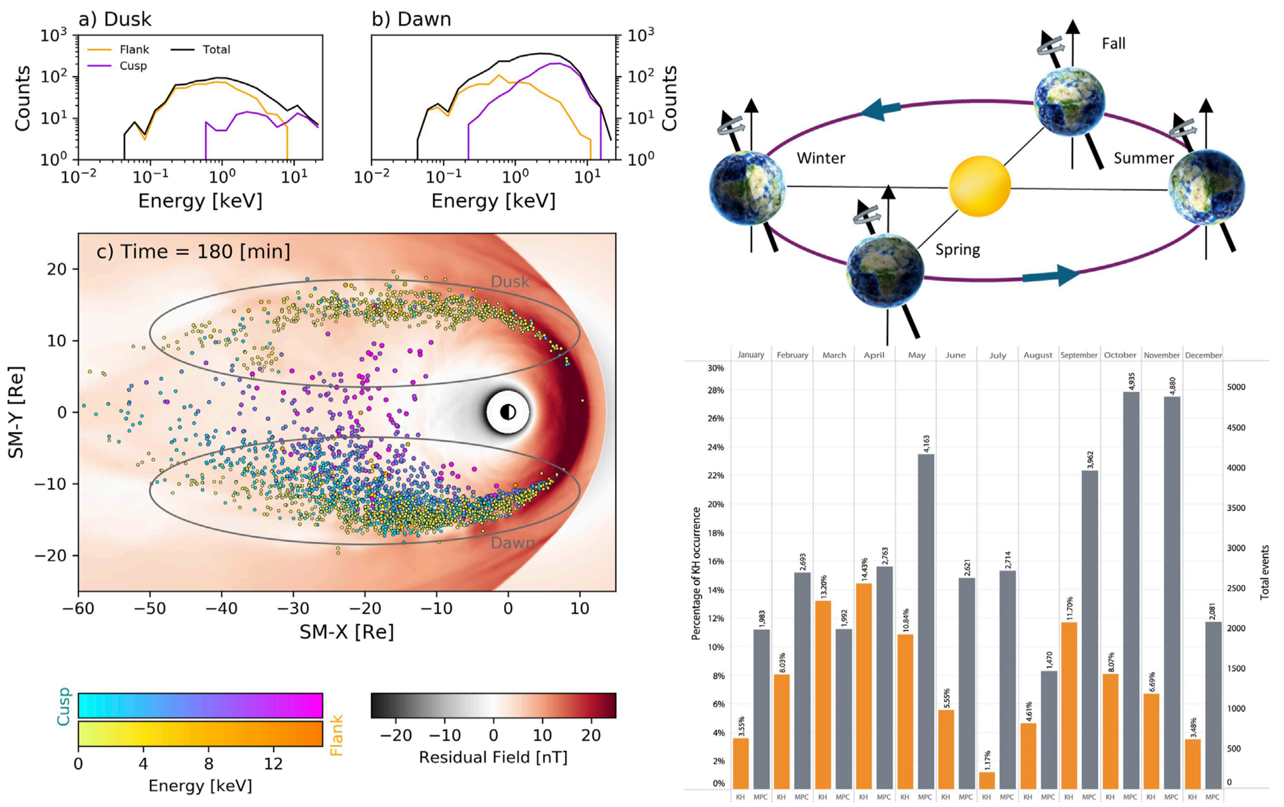

FIGURE 2
KHI on a Global Scale. At left, from Sorathia et al. (2019), global simulations indicate KHI driven flank entry and reconnection driven cusp entry of solar wind plasma contribute to dawn-dusk asymmetries in the magnetopshere. Energy distributions of test particles that reside in the dusk **(A)** and dawn **(B)** flank; and equatorial projections of test particles initialized in the solar wind colored by their energy, using separate color maps based their entry either through the cusp or flank **(C)**. At top right, adapted from Kavosi et al. (2023), the relative orientation of Earth's rotation axis (black arrow) to the ecliptic plane is subject to seasonal variation. A survey of *in situ* observations, bottom right, from Kavosi et al. (2023), shows KHI occurrence rate (orange bars) is maximized(minimized) at equinoxes(solstices).

the KHI? How might geomagetic storm conditions affect the development of the KHI? What effects might heavy ion species have on the behavior of the KHI? What influence does the KHI exert throughout the heliosphere, such as at the edges of coronal mass ejections, co-rotating interaction regions, or other planetary magnetospheres? Evidence of KH activity has been observed at Mercury (Paral and Rankin, 2013), Mars (Ruhunusiri et al., 2016; Poh et al., 2021; Wang et al., 2022), Saturn (Ma et al., 2015; Dialynas, 2018; Burkholder et al., 2020a), and Jupiter (Ranquist et al., 2019; Montgomery et al., 2023), but it is not yet known how the scale size of the planetary magnetosphere affects the multi-scale nature of the KHI.

The above questions and our new understanding of the KHI as a multi-scale process should inform the direction of future research. New studies on the diffusive transport within the KH vortices should consider the multi-scale and multi-effect nature of the KHI rather than focusing on single effects and scales. Efforts should be made to relate the KHI to global parameters, such as the solar wind conditions and season, in order to obtain a global picture of the instability, its influences, and the implications for global solar wind transport. Simulation studies should consider the role of more realistic solar wind IMF orientations or the role of kinetic physics (e.g., Ma et al., 2019) in KHI development and its effects. Space weather forecasters may incorporate dipole tilt effects on KHI into their models, resulting in more accurate and reliable forecasting.

Author contributions

RR: Conceptualization, Writing–original draft, Writing–review and editing. KB: Writing–original draft, Writing–review and editing. KN: Conceptualization, Writing–original draft, Writing–review and editing. SK: Conceptualization, Writing–original draft, Writing–review and editing. KS: Writing–original draft, Writing–review and editing. Y-LL: Writing–review and editing.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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