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# Plasma-neutral interactions in the lower thermosphere-ionosphere: The need for *in situ* measurements to address focused questions

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The lower thermosphere-ionosphere (LTI) is a key transition region between Earth's atmosphere and space. Interactions between ions and neutrals maximize within the LTI and in particular at altitudes from 100 to 200 km, which is the least visited region of the near-Earth environment. The lack of

*in situ* co-temporal and co-spatial measurements of all relevant parameters and their elusiveness to most remote-sensing methods means that the complex interactions between its neutral and charged constituents remain poorly characterized to this date. This lack of measurements, together with the ambiguity in the quantification of key processes in the 100–200 km altitude range affect current modeling efforts to expand atmospheric models upward to include the LTI and limit current space weather prediction capabilities. We present focused questions in the LTI that are related to the complex interactions between its neutral and charged constituents. These questions concern core physical processes that govern the energetics, dynamics, and chemistry of the LTI and need to be addressed as fundamental and long-standing questions in this critically unexplored boundary region. We also outline the range of *in situ* measurements that are needed to unambiguously quantify key LTI processes within this region, and present elements of an *in situ* concept based on past proposed mission concepts.

#### KEYWORDS

lower thermosphere ionosphere, plasma neutral interactions, *in situ* measurements, decadal survey, atmosphere space transition region, altitudes below 200 km, LTI, ion neutral coupling

## 1 Introduction

### 1.1 Overarching Goal

The Lower Thermosphere and Ionosphere (LTI) has accurately been described as the transition layer between atmosphere and space. Within this layer, the neutral gases of the upper layers of the atmosphere coexist and interact with the ionized gases of the lower edge of the plasma-dominated space. In particular, interactions between ions and neutrals maximize at altitudes between 100 and 200 km: it is within this altitude range that electrical conductivities, electrical currents, ion-neutral collisions and the resulting frictional heating maximize (Richmond (2017); Strangeway (2012)); it is also within this region that the auroral peak emission height is found and auroral structures maximize (Partamies et al., 2022). At the same time, energetic particle precipitation passing through this region has profound effects on chemistry at altitudes below and significantly influences conductivity within this region.

Whereas the underlying principles of the physical processes related to ion-neutral interactions is well known theoretically, their quantification is still largely unknown. The reason is that processes related to ion-neutral interactions involve and require the knowledge of a large number of parameters, which include ion, electron and neutral temperatures ( $T_i$ ,  $T_e$  and  $T_n$ ), ion, neutral and electron densities ( $N_i$ ,  $N_n$ ,  $N_e$ ), ion and neutral composition ( $n_{ix}$  and  $n_{nx}$ ), ion drifts  $v_i$ , neutral winds ( $u_n$ ), electric field ( $\vec{E}$ ), and magnetic field ( $\vec{B}$ ). These measurements need to be co-temporal and co-spatial, and to be made at the right temporal and spatial scales.

However, these measurements have never been simultaneously available, as the altitude range from 100 to 200 km remains to this date the least visited region in the near-Earth environment (Sarris (2019); Palmroth et al. (2021)). With the exception of the Atmosphere Explorer satellites (1973–1981), which sampled periodically this region along elliptical orbits achieving a lowermost altitude of 128 km by use of propulsion, and also with the exception of short-lived sounding rocket flights, these altitudes have remained scarcely sampled *in situ*, primarily due to the enhanced atmospheric drag in this region. Whereas a wealth of information is currently provided by remote sensing measurements, either from space or from the ground, obtaining all the above parameters simultaneously can only be done with *in situ* measurements by a spacecraft equipped with a comprehensive instrument suite. This lack of co-located measurements of all involved parameters leads to great discrepancies between estimations of, for example, conductivities, electrical currents and frictional heating, which are critical parameters for the accurate description of the upper atmosphere.

In pursuit of the overall community goal to understand how geospace works within the larger heliophysical system, it is important to understand how the LTI acts as the dynamical interface between the atmosphere and space. The two-way interactions between the atmosphere and the LTI as well as those between the magnetosphere and the LTI that constitute this interface are strongly controlled by the variable conditions within LTI and its internal physical processes. Central to this multifaceted interface are the features of the LTI system associated with direct interactions between the plasma and neutral gas. Thus the

overarching goal and main theme of the mission discussed here is to: Understand the role of charged-neutral collisions in the LTI in its larger role as a physical mediator between the atmosphere and space.

## 1.2 Science questions of an in situ mission to the lower thermosphere-ionosphere

The approach to making progress on this goal first divides the task into three broad areas: Energetics, Dynamics, and Chemistry. Key uncertainties in these areas are then used to develop focused science questions which, if answered, will provide significant progress toward this goal. Focused science questions under each area that will need to be answered in the coming decade include the following:

### Q1. Energetics.

How and to what extent is energy deposited as frictional or Joule heating in the LTI? How does this heating affect, and is affected by, the thermal structure, local transport, and composition within LTI altitudes? How does the magnitude, extent and evolution of this heating affect neutral density and satellite drag?

### Q2. Dynamics.

What is the momentum budget in the LTI and the relative contributions of magnetospheric, solar and atmospheric forcing? What are the consequences of these forcings on fluid dynamics and electrodynamics at high, middle and low latitudes? How do collisions between charged and neutral gases in the LTI affect the density, composition, winds and drifts in the region?

### Q3. Chemistry.

What are the effects of Energetic Particle Precipitation (EPP) on the ionization and composition of the LTI? To what extent does EPP impact the mesosphere and stratosphere?

Addressing the above questions will fundamentally advance our understanding of the atmosphere-space transition region and of the neutral-plasma interactions that shape it; at the same time, addressing the above science questions will also assist in addressing topics related to critical societal and operational needs, as discussed below.

## 1.3 Societal relevance

Together with the need to fundamentally advance our understanding of the physics of the atmosphere-space transition region, as documented, e.g., by [Palmroth et al. \(2021\)](#) and [Karlsson et al. \(2020\)](#), the urgency to significantly improve the climatological specification and empirical models of the LTI by incorporating new LTI datasets has been described by, e.g., [Emmert et al. \(2021\)](#); furthermore, the importance of enhancing the predictive capability of the LTI for operational

needs and applications by better knowledge of the LTI has been highlighted by [Crisp et al. \(2020\)](#). A key reason is that the LTI is the epicentre of multiple activities of modern, technology-based civilization, and addressing the above science questions is linked to addressing a number of societal and operational space weather needs. In particular, knowledge of the neutral density and its variability are critical to predicting orbit trajectories of low Earth orbiting satellites: in view of the recent transition of space usage from GEO (which dominated public usage of space until recently) to LEO (where New Space mega-constellations are operating), accurate predictions of atmospheric drag in relation to geomagnetic activity is an essential parameter in spacecraft operations. The recent loss of 40 Starlink satellites near 210 km during a moderate geomagnetic storm ([Hapgood et al. \(2022\)](#)), which occurred due to enhanced Joule heating in the LTI, shows that such predictions are still lacking. Furthermore, the induced currents in power grids associated with high latitude ionospheric currents driven by storms is another space weather application where detailed knowledge of the current systems and of conductivity will advance our understanding of how sudden current surges affect power infrastructure when large scale magnetic storms are present. Finally, localised electron density increases in the LTI and above, associated with particle precipitation or other sources of density irregularities, are known to affect radio wave propagation. This leads to uncertainties in navigation in the form of scintillation of Global Navigation Satellite System (GNSS) signals, as well as distortion of telecommunication signals ([Xiong et al. \(2016\)](#)). The development of mitigation techniques for radio propagation perturbations require new insight on LTI processes that lead to the increase in ionisation, in particular during active geomagnetic conditions.

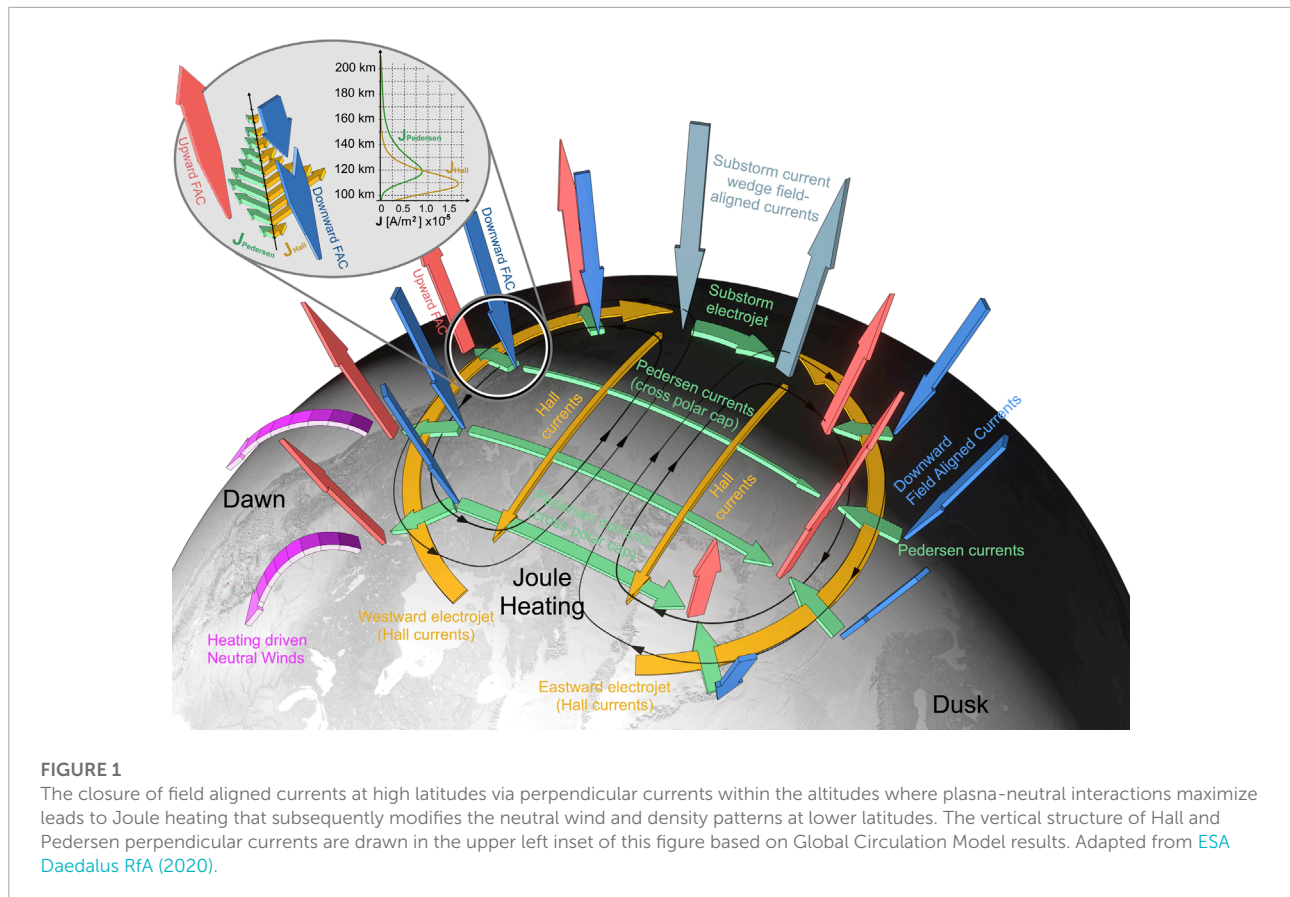
In the following, focused science questions in the LTI are further described under each of the three broad areas in terms of energetics, dynamics, and chemistry/energetic particle precipitation effects. The need for *in situ* measurements to address these questions and elements of a notional “way forward” to address these questions are further elaborated in the Discussions section.

This paper evolved from a white paper ([Sarris et al., 2022b](#)) that was submitted in response to the call for white papers for the Decadal Survey for Solar and Space Physics 2024–2033, which aims to present a prioritized strategy of basic and applied research to advance scientific understanding in the field of Heliophysics.

## 2 Energetics

### 2.1 Background and motivation

The largest uncertainty in the energetics of the LTI is the impact of frictional heating, or, equivalently, Joule heating



(Strangeway, 2012). Frictional or Joule heating occurs within the LTI when the ionospheric plasma is forced by electromagnetic fields to convect relative to the neutral gas. This coupling is strongly related to solar activity: During geomagnetically active times, the closure of field aligned currents at high latitudes occurs within the ionospheric E and F regions where plasma-neutral collisional interactions are important. The resulting Joule heating subsequently modifies the neutral wind and density patterns globally (see [Figure 1](#)). While the heating rates maximize in the E region, the effects are significant also above in the F region where the relatively lower density atmosphere clearly reacts to these processes in geomagnetically active periods. This has the effect that spacecraft within this region will experience enhanced atmospheric drag, which can lead to sudden loss of orbital altitude, decrease in orbital lifetime and potentially reentry (e.g., [Fang et al. \(2022\)](#)). Without detailed knowledge of Joule heating rate, its distribution in altitude, latitude and local time and its effects on the thermosphere, predicting drag effects and spacecraft orbits is extremely difficult. During even moderate geomagnetic storms, our present knowledge indicates, albeit with large uncertainties, that Joule heating is the largest heating source, larger than the heat created by absorption of EUV solar radiation, which otherwise is the

major driver for upper atmospheric dynamics. At moderate to strong activity, the effects of electromagnetic coupling with space are not confined to high latitudes but will propagate to the equator.

The ways in which neutral winds, ion drifts and electric fields interact in this heating process, which maximizes in the LTI, are largely unknown, primarily due to the lack of co-located measurements of all key parameters involved. Current estimations are based on primarily ground-based measurements, which, however, only provide a subset of the required measurements that are needed to resolve Joule heating in the LTI (for example, they lack neutral wind measurements), with limited spatial resolution, with lower accuracy compared to *in situ* measurements and above geographically fixed locations. Key factors affecting Joule heating include the ionospheric Pedersen conductivity,  $\sigma_p$ , neutral winds,  $u_n$ , electric fields,  $E$ , and ion drifts,  $v_i$ . In particular,  $\sigma_p$  is dependent on knowledge of precipitating electrons, whereas neutral winds are affected by Lorentz forcing, both of which are poorly characterized in the LTI. Accurate estimates of  $\sigma_p$  and neutral wind variations in the LTI are also needed for improved space weather forecasts ([Mannucci et al., 2016](#)), and for Joule heating statistics ([Cai et al., 2016](#)).



**TABLE 1** List of primary products or geophysical observables needed to address the science questions listed herein and commonly used instruments for their derivation.

Geophysical Observables of an LTI in situ mission			
	Symbol	Geophysical observable	Commonly used instruments
Ionosphere	$\tilde{v}_i$	Ion drift velocity	Thermal ion imager, ion Drift meter
	$T_i$	Ion temperature	Retarding potential analyzer
	$T_e$	Electron temperature	Langmuir Probe
	$N_i$	Ion number density	Mutual Impedance Probe
	$N_e$	Electron number density	
	$n_{ix}$	Ion composition	Ion mass spectrometer
Thermosphere	$\tilde{u}_n$	Neutral wind velocity	Ram and cross-track wind sensors
	$\rho$	Neutral mass density	Accelerometer
	$T_n$	Neutral temperature	Neutral mass spectrometer
	$n_{nx}$	Neutral composition	
Fields	$\vec{B}$	Magnetic field	Magnetometer
	$\vec{E}$	Electric field	Electric field instrument

Comparisons of different models and estimation methodologies show great discrepancies in the amount of energy that is deposited *via* Joule heating in the LTI (e.g., Palmroth et al., 2021). A main reason for these discrepancies is that models can not currently resolve small scales, which are believed to contribute significantly to the total Joule heating, even though the distribution of this heating at various scales is not known. It is known, however, that auroral arcs, which are important conduits for energy input, are structured at scales on the order of 1 km and lower (Maggs and Davis (1968); Borovsky and Suszcynsky (1993)). Electric field structures can be significant on these and possibly even smaller scales, and the effect of these small-scale structures does not average to zero since Joule heating is proportional to  $E^2$ . This energy is hence significantly under-estimated in physics-based general circulation models (GCMs), which lack the ability to resolve intense localised electric fields in the vicinity of auroral arcs (see, e.g., Deng and Ridley (2007); Aikio and Selkälä (2009)). In lack of an accurate characterization of Joule heating at small scales, GCMs commonly need to introduce a scaling or multiplication factor that arbitrarily adjusts Joule heating (e.g., Emery et al. (1999)) so as to reproduce realistic temperatures in GCMs that can be compared reasonably well against those of empirical models and observations. This insufficient Joule heating in GCMs or uncertainty of its altitude distribution (e.g., Huang et al. (2012)) has been attributed primarily to the contribution of small-scale variability or structuring of the electric field (e.g.; Codrescu et al. (1995)), the relative importance of which can only be obtained *in situ*: For example, previous studies based on DE-2 data (e.g., Matsuo et al. (2003);

Matsuo and Richmond (2008)) have shown that this variability in the electric field can be comparable in magnitude or can even exceed the average.

## 2.2 New data needed

Measurements of all parameters involved in the Joule heating equation need to be obtained simultaneously, at relevant scales where Joule heating is significant, down to 1 km or below. This includes measurements of neutral winds, ion drifts, electric field, magnetic field, ion and neutral composition, densities and temperatures, and energetic particle precipitation are needed. These are summarized in Table 1, separated in terms of ionosphere (or plasma) parameters, thermosphere (or neutral) parameters, and fields. In the right column of Table 1, instruments that are commonly used to obtain these parameters *in situ* are also listed. These measurements should be made by collecting statistically representative distributions that cover the pertinent range of auroral latitudes, local times and targeted altitudes, which lie in the 100–200 km region, and, ideally, down to the altitudes where plasma-neutral interactions and hence Joule heating maximize, which is estimated to be at ~120 km. At the same time, the altitude profile of Joule heating and its contributing parameters should be resolved, statistically and with a combination of satellite and ground-based assets. These measurements can be used to anchor ground-based observations and test current assumptions and parameterizations of Joule heating as well as of Pedersen conductivity in models.

## 3 Dynamics

### 3.1 Background and motivation

Forcing from the magnetosphere, from the atmosphere, and direct solar influences have profound impact on the LTI and how it evolves. These influences on the LTI are affected by the exchange of momentum between charged and neutral components, resulting in the transport of momentum vertically and horizontally. Dynamics in the LTI refer to the motion of plasma and neutral gases in relation to the forces that drive and affect them, and to the overall momentum budget in the LTI. The presence of an ionised component and the geomagnetic field within the LTI greatly affect the forces that drive the motion of both neutral and ion species. Electromagnetic coupling introduces a direct Lorentz force to the set of forces governing the dynamics of the LTI. Deviations between ion and electron ( $\vec{E} \times \vec{B}$ ) drifts are strongly altitude dependent within the 100–200 km range due to large vertical gradients in neutral density and collision rates, and results in altitude-dependent horizontal electric currents. An example of the idealized ion and electron ( $\vec{E} \times \vec{B}$ ) drifts in the frame of the neutral gas is shown in [Figure 2](#); the resulting ion drifts, electron drifts and neutral winds are shown in the right-hand side of [Figure 2](#), as captured by the National Center for Atmospheric Research (NCAR) Thermosphere-Ionosphere-Electrodynamics General Circulation Model (TIEGCM) ([Qian et al., 2014](#)), for three sample altitudes. With simultaneous, co-located measurements of ion drifts, neutral winds and electric magnetic fields in the LTI, direct measurements of the ion drift can readily be compared with the neutral winds and with the ( $\vec{E} \times \vec{B}$ ) drift at lower altitudes where ion-neutral collisions change both the amplitude and direction of the ion drift, which is critical to determine how this relative plasma motion drives currents and effects the generation of neutral winds.

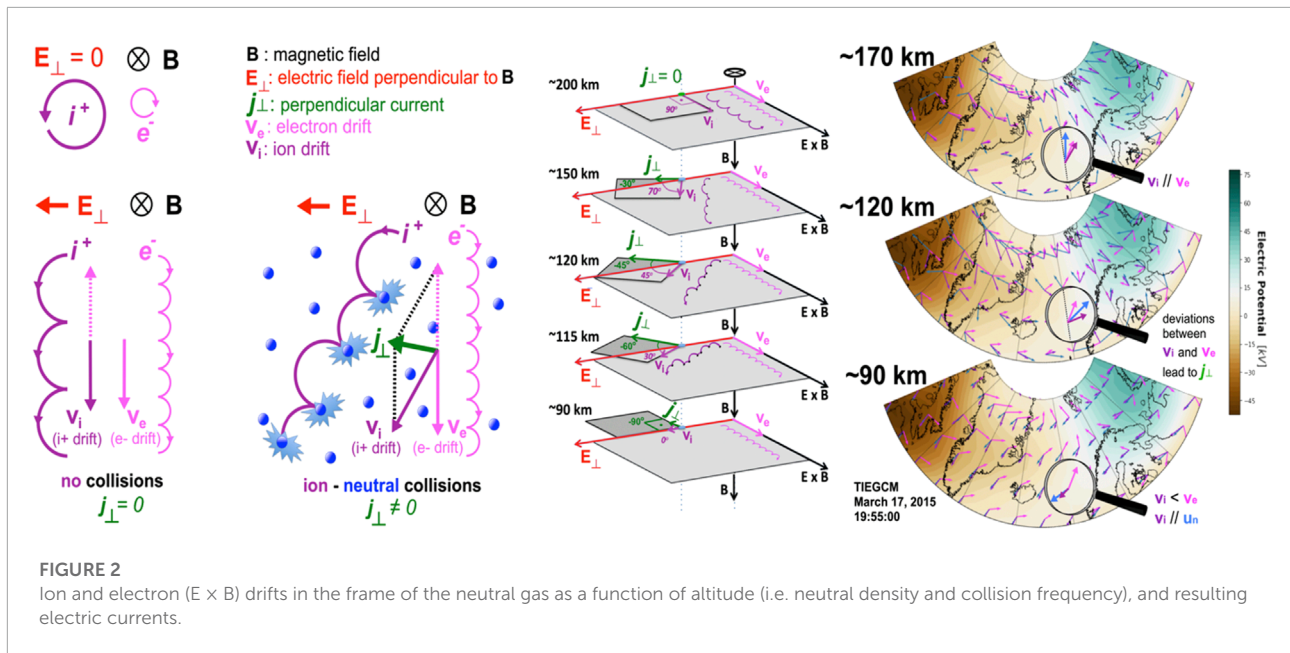
Currents flowing through the LTI are associated with plasma motions and co-located neutral gas motions *via* ion-neutral collisions. Furthermore, the LTI is the critical region where neutral dynamics, including tidal, planetary and gravity waves, drive the ionospheric dynamo and its variability in the E and bottom-F regions ([Liu, 2016](#)). Although these processes are understood theoretically, their quantification and characterization are largely absent due to a lack of measurements in the regions where magnetospheric forcing and collisions between charged and neutral gases maximize, which is mainly within the 100–200 km altitude range. In particular, comprehensive measurements of neutral winds are critical in advancing current knowledge of LTI dynamics and, presently, such measurements are sparsely distributed in time and space ([Heelis and Maute \(2020\)](#); [Emmert et al. \(2021\)](#)). It is noted in particular that no current or prior set of observations combines simultaneous and co-spatial measurements of horizontal and

vertical neutral winds together with electric currents. In addition, estimates of collision rates are currently based on cross-sections from ground laboratory experiments, which, however, cannot reproduce the complex LTI environmental plasma, neutral and electromagnetic conditions ([Yamauchi et al., 2022](#)). At small scales, strong flow shears and steep gradients can drive a variety of instabilities and turbulence in both plasma and neutral gas, the understanding of which is an outstanding challenge in space physics community. Instabilities and turbulence, in turn, result in irregularities of various scales, which have practical implications for the propagation of waves. In particular, variations and gradients in the plasma density can strongly affect the propagation of trans-ionospheric radio waves on which our modern communication and navigation systems rely.

### 3.2 New data needed

Sampling with high cadence the physical properties of the charged and neutral gas alongside electromagnetic fields within the 100–200 km altitude region, where collisions between charged and neutral particles maximize, would close the gaps in our understanding of the dynamics and its electrodynamic coupling on relevant scales. Co-temporal and co-spatial measurements of neutral winds, ion drifts, electric field, magnetic field, ion and neutral composition, densities and temperatures in the 100–200 km altitude range are needed, as summarized in [Table 1](#).

It is noted that a single-satellite *in situ* mission can provide local measurements of the above properties, however resolving LTI electrodynamic, such as addressing the ionospheric dynamo problem, investigating the altitude distribution or 3D structure of currents, *etc.*, is more challenging since it involves non-local processes. In particular, since the field lines are essentially equipotentials, flux tube integrated quantities are needed to fully explain the dynamics. In one approach, local measurements as provided by an *in situ* mission need to be combined with models to address this problem. Statistical ensembles of local measurements that extend up into the F-region can also be used to address the ionospheric dynamo problem. In another (optimal) approach, using twin-satellite measurements that are displaced in altitude enables obtaining altitudinal gradients and height- or flux-tube-integrated profiles of, e.g., electron density, Pedersen conductivity and Joule heating directly, rather than statistically. In a recent study, [Vogt et al. \(2022\)](#) investigated the optimal separation in altitude between two satellites for obtaining altitude profiles, *via* implementing extrapolation horizons, also involving models; this approach demonstrates the pathway towards vastly improving current estimates of height-integrated quantities.



## 4 Chemistry

### 4.1 Background and motivation

A significant amount of the chemistry of the LTI and also the middle atmosphere below is controlled by energetic particle precipitation (EPP). This chemistry in turn strongly affects the balance of heating and cooling in and near the LTI, influencing not only the energetics discussed above, but the production and transport of these potent species, that changes the character of the LTI's plasma-neutral interactions.

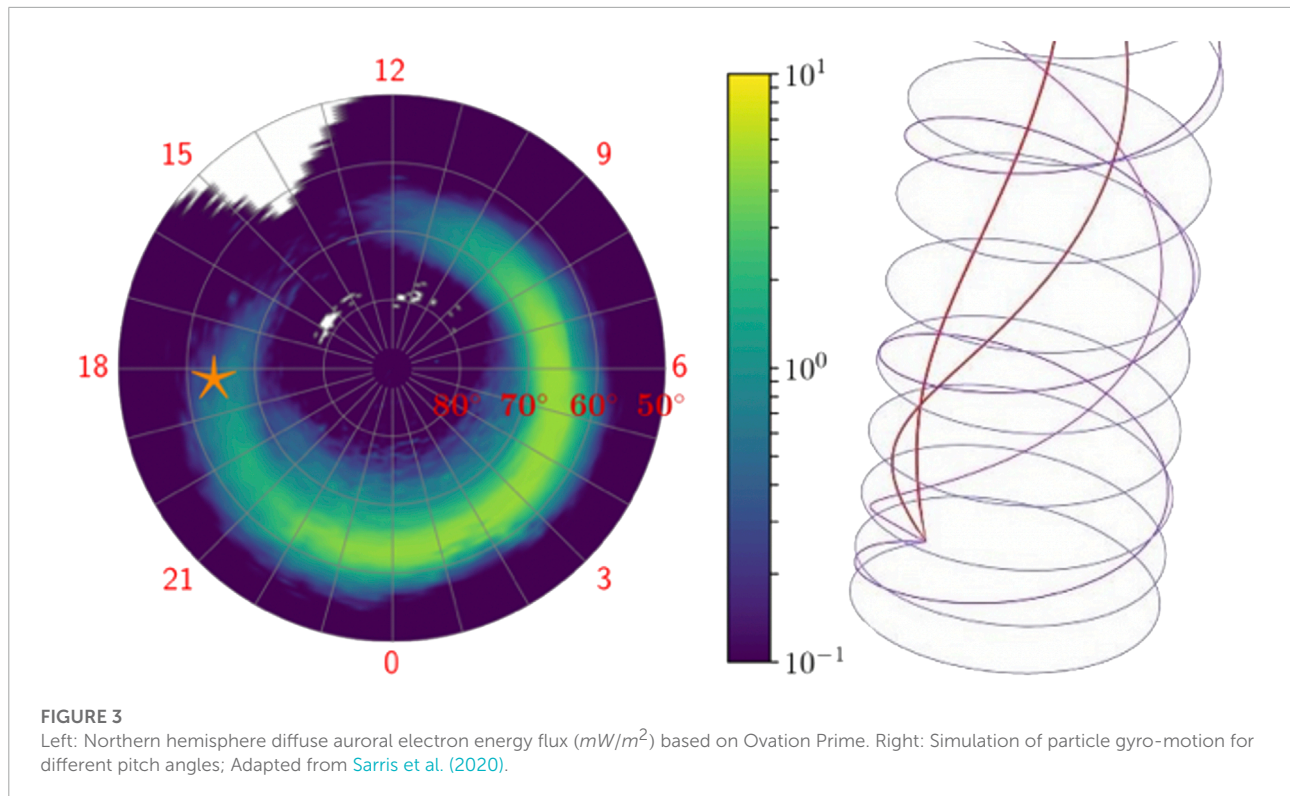
EPP consists of energetic (keV-MeV) electrons and ions that follow the Earth's magnetic field towards the atmosphere (Figure 3). EPP leads to the excitation and ionization of neutrals, dissociation of molecular species, and electron temperature enhancements, all of which affect conductivity. EPP fluxes between 100 and 200 km and their contributions to key physical processes at these altitudes and below are largely unknown.

The altitude of maximum energy deposition by EPP is determined by the energies of the precipitating particles. Knowledge of the energy spectrum as a function of solar and geomagnetic conditions, magnetic latitude and local time is therefore key to understanding the role of EPP within the LTI and below. Investigation of coupled-climate model runs and atmospheric reanalysis datasets have further shown that, as higher energy ( $>30\text{keV}$ ) electron precipitation passes through the LTI, it generates  $\text{NO}_x$  and  $\text{HO}_x$  at lower altitudes, leading to the catalytic destruction of ozone in the mesosphere and below (Turunen et al., 2009). Through the complex coupling of

chemical composition changes affecting atmospheric heating and cooling rates, the mean circulation, and wave propagation and breaking, EPP also affects temperatures and dynamics of the atmosphere from the source region down to the stratosphere and possibly even down to the surface (Sinnhuber et al., 2012). However, simulated altitude distributions of polar  $\text{NO}_x$  have substantial differences to those observed. One potential reason is incomplete representation of the EPP forcing and uncertainties in the formation rate of different  $\text{NO}_x$  species, indicating that EPP measurements within the LTI are a missing link between heliophysics and lower atmosphere/Earth science.

Energetic Particle Precipitation (EPP) impacts are currently implemented in chemistry-climate models reaching from the surface up to the mesosphere or lower thermosphere, however, there are still many open questions not only in the quantification but also in the theoretical description of the impacts of EPP. The most important issue concerns the uncertainties associated with the production rate of the different  $\text{NO}_x$  species by EPP, and the complex coupling between chemical changes, atmospheric heating and cooling rates, and atmospheric dynamics. Improved EPP measurements will lead to the improvement of the EPP specification in models.

It is noted in particular that the recent solar forcing recommendation for the Coupled Model Intercomparison Project Phase 6 (CMIP6) includes EPP for the first time (Matthes et al., 2017), indicating a wider recognition of the potential importance of EPP for the middle and lower atmosphere. However, currently, CMIP6 forcing comes from a proxy model that is based on MEPED/POES satellite



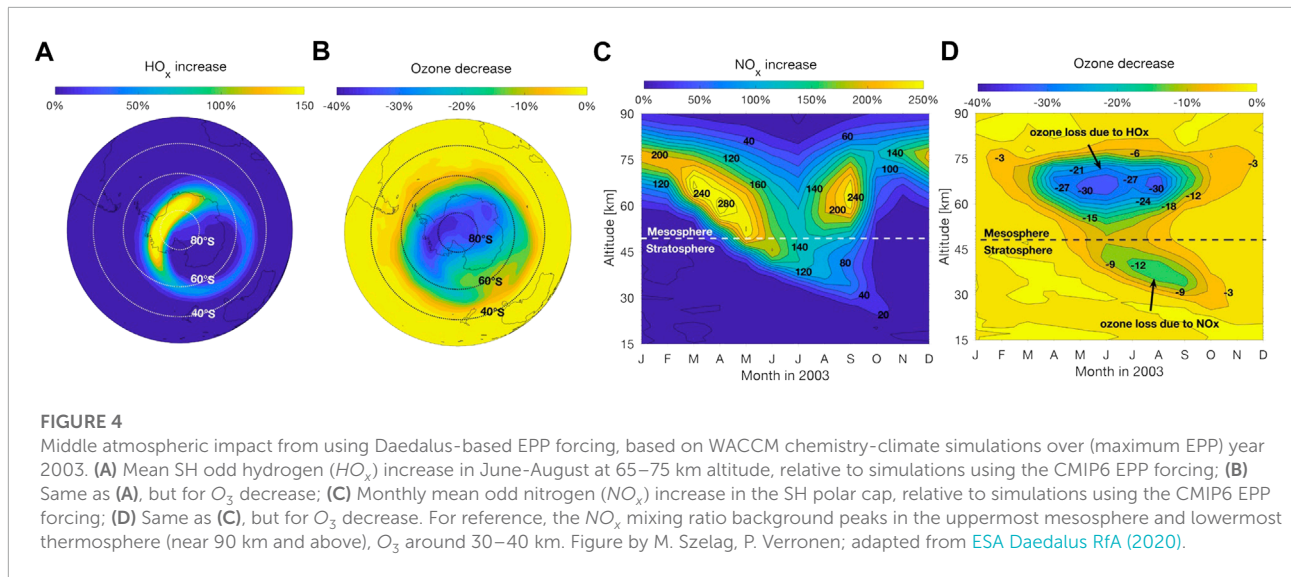
observations (Van de Kamp et al. (2016), which only provide three energy channels between 30 and 1,000 keV, and only measure a part of the precipitation entering the atmosphere (Rodger et al. (2010)). Due to the inadequate energy resolution and measurement geometry, it is believed that current measurements do not capture the precipitation fully, and a recent re-analysis of MEPED/POES data by Nesse Tyssøy et al. (2016) has shown that fluxes could be under-estimated or overestimated by a significant factor, depending on pitch angle and reaching close to an order of magnitude for lower flux levels. As a demonstration of the potential impacts of an improved EPP specification, in support of the Daedalus mission science case definition (ESA Daedalus RfA, 2020), a variation of EPP forcing was used in a climate mode run compared to the current CMIP6 recommendation, and impacts on  $HO_x$ ,  $NO_x$  and  $O_3$  were simulated. The variation in EPP was based on the range of potential under-estimations or over-estimations of the current specification. The differences in middle atmosphere impacts between the two forcing datasets, *via* changes in atmospheric ionisation rates, have then been simulated with 1-year chemistry-climate model experiments with specified dynamics (WACCM-D, Verronen et al. (2016)). Averaged changes, shown in Figure 4 (adapted from Figure 51 of ESA Daedalus RfA (2020)), suggest that any substantially different fluxes that an *in situ* mission might detect would translate into substantial

differences in simulated middle atmosphere chemistry. In this figure we can see that ozone depletion due to additional  $HO_x$  maximises in the mesosphere in the southern auroral oval; stratospheric depletion is due to  $NO_x$  and maximises during austral winter/spring. Crude extrapolations of the ozone changes onto stratospheric temperatures, dynamics and regional surface climate impacts, by scaling results from e.g. Rozanov et al. (2005), Rozanov et al. (2012), could imply significant polar regional surface temperature signals. These need to be known when assessing long-term warming trends due to global climate change, to account for solar-driven natural variability and regional biases in simulations.

## 4.2 New data needed

EPP observations with a better geometry and improved pitch angle and energy resolution are essential when addressing the question of EPP-climate connection. Satellite-based observations of electron fluxes with high temporal, energy and pitch angle resolution within the 100–200 km altitude range are needed, together with coincident electric and magnetic field data, so as to determine their correlation with EPP for its accurate parameterization in models.





## 5 Discussion

The science questions that are presented herein in terms of energetics, dynamics and effects of precipitating particles are intricately linked, and addressing all relevant processes requires a methodological approach that utilizes comprehensive instrumentation to measure all parameters involved. For example, Joule heating maximizes per unit volume at low altitudes from 100 to 200 km where the Pedersen conductivity is highest; heating in this region also occurs due to energy deposited by impacting particle precipitation, which, similarly to Joule heating, is enhanced during active times. Particle precipitation is also directly linked to enhanced Pedersen conductivity. Field aligned currents close in this region through fundamental processes that occur in high latitudes: these processes concern perpendicular (horizontal) currents, which are of critical importance for dissipation and heating in the upper atmosphere, and feedback mechanisms, which help to regulate magnetosphere-ionosphere coupling. Furthermore, in this region originate large-scale neutral wind circulation changes, but also smaller-scale intense neutral wind “jet streams,” which have been associated with auroral formations. These “jet streams” peak at 150 km ([Brinkman et al., 1995](#)), and close to the region where the ion-drag force per unit mass peaks. Quantifying such large-scale and small-scale neutral winds, and determining their circulation patterns and relevant intensities, are critical in determining the dynamics and the overall momentum budget in the LTI. At the same time, the neutral winds are known to significantly contribute to and influence the resulting Joule heating rates, demonstrating a linkage between energetics and dynamics in the LTI. In addition, the relative motion of ions (which are slowed down by neutrals), electrons (which undergo an ExB drift in this region), and neutrals (whose dependencies

and intensities are among the largest unknowns in the LTI) are all inter-connected in complex neutral-plasma interactions and neutral as well as plasma circulation patterns. Resolving the interplay of the above processes requires simultaneous measurements of all relevant parameters.

In the following, we first summarize key reasons that highlight the need for *in situ* measurements to address the above science questions. We then provide an overview of the status of *in situ* measurements in the LTI. We proceed with presenting the notional concept for a space mission targeting to sample the LTI below 200 km with *in situ* measurements. Specific advantages of multi-point measurements and synergistic activities with ground-based instruments are also presented. This section is concluded by a summary of the notional way forward.

### 5.1 On the need for *in situ* lower thermosphere-ionosphere measurements

Whereas ground-based remote sensing facilities have been providing continuous measurements of key LTI parameters as a function of altitude and local time, and are currently a main source of information on ion-neutral interactions across the LTI (see, e.g., [Wahlund et al. \(1992\)](#); [Rishbeth and Van Eyken \(1993\)](#); and, as examples of recent studies, e.g. the work by [Tesema et al. \(2022\)](#); [Günzkofer et al. \(2022\)](#)), there are limitations of remote sensing methods in addressing the science questions outlined herein. These limitations are related to the temporal and spatial resolution that ground-based instruments can provide as well as to the need for co-temporal, co-spatial measurements of all parameters involved. In contrast, *in situ*



measurements offer a number of specific advantages and unique capabilities, as outlined in the following.

In terms of spatial and temporal scales, *in situ* measurements offer vastly better resolution, enabling to resolve the contribution of small-scale variability to the total Joule heating, which is a major unknown in the LTI. For example, electric fields down to 1 km or smaller are known to be significant at times, with variability at these scales often exceeding the average. High-cadence *in situ* measurements also enable detecting field-aligned currents at small scales (10 km and less) through measurements of magnetic perturbations,  $\delta B$ . Further to the spatial resolution, *in situ* measurements offer the ability to resolve  $E$  and  $\delta B$  fields on time scales of 10 s and faster, which are in the realm of energy transfer *via* Alfvén waves (e.g., Lotko and Zhang (2018)).

In terms of the completeness of the datasets, to accurately and unambiguously determine Joule heating in the LTI, according to Strangeway (2012) (eq. 38), simultaneous and co-located measurements of the electron number density,  $N_e$ , ion and electron velocities perpendicular to the geomagnetic field,  $\vec{v}_{i,\perp}$  and  $\vec{u}_{e,\perp}$ , the electric and magnetic field,  $\vec{E}$  and  $\vec{B}$ , and the bulk velocity of the neutrals,  $\vec{u}_n$  are needed, from which the electric field in the reference frame of the neutrals,  $\vec{E}^* = \vec{E} + \vec{u}_n \times \vec{B}$  can be obtained. Furthermore, for an ion population that consists of  $i$  species with  $N_i$  number densities, where  $i = O_2^+, NO^+, O^+, \dots$ , ion composition and the ion-neutral collision frequency,  $\nu_{in}$  are needed in order to calculate the relevant equivalent expressions for frictional heating, according to Strangeway (2012) (eq. 28); the equivalence between the two expressions for Joule and frictional heating is described in Sarris et al. (2022a). With respect to the ion neutral collision frequencies,  $\nu_{in}$ , it is noted in particular that in the LTI system the interactions of ions and neutrals influence the velocities, temperatures and densities of both species, thus playing a vital role in momentum and energy exchange between the thermosphere and the ionosphere. These interactions are characterised through  $\nu_{in}$ , and subsequently (fundamentally) through the ion-neutral cross sections,  $\sigma_{in}$ , which are fundamental parameters in the coupling between the neutral atmosphere and the ionosphere. However, collision cross-sections, as documented in, e.g., Schunk and Nagy (2009); Richmond (2017), have been determined primarily through laboratory experiments, which are not necessarily representative of the real LTI environment, and are believed to have systematic biases. The estimation of  $\sigma_{in}$  according to Banks and Kockarts (1973) requires also measurements of neutral composition,  $N_n$ , and ion, electron and neutral temperatures,  $T_i$ ,  $T_e$  and  $T_n$  respectively, on top of the parameters listed above. Co-located knowledge of temperatures  $T_i$ ,  $T_e$  and  $T_n$  is also important for the estimation of energy transfer rates between species: when different temperatures between ions and neutrals are observed, then the heat transfer between the two species can be estimated according to Killeen et al. (1984).

The distribution and magnitude of neutral winds is another missing piece in accurately estimating the energy budget and determining the dynamics in the LTI: for example, Joule heating has a neutral wind contribution which can be either positive or negative (e.g., Lu et al. (1995)), and which can be significant, even though this contribution is often ignored, due to lack of co-located measurements. As some rare co-located *in situ* rocket and trail-gas measurements indicate (e.g., Sangalli et al. (2009)), the effects of the neutral winds can be significant but can only be evaluated by co-temporal, co-spatial measurements of all the relevant parameters, which cannot be provided by ground-based remote sensing measurements. The ability to make neutral density and composition measurements co-located with plasma particle and field measurements in the LTI is also key, as these are necessary for direct estimation of conductivities; it is noted that conductivities are critically important for ongoing efforts to couple ionosphere and magnetosphere models (Ridley et al., 2004), and are currently estimated only from the ground through the combined use of measurements and models, which have significant uncertainties. Furthermore, an *in situ* platform allows to examine neutral density structuring and compositional changes and, importantly, to determine the causes of these variations, which cannot be determined remotely. Another example highlighting the importance of comprehensive *in situ* observations is the direct comparison of Joule heating with Poynting flux energy input at the same location, while examining how the heating effects the ambient neutral density, winds, and composition locally. Finally, the ability to resolve ion composition, including species  $N^+$ ,  $O^+$ ,  $N_2^+$ ,  $O_2^+$ , and  $NO^+$  is another important missing parameter that can only be provided by *in situ* ion mass spectrometry, as these are important tracers of chemical and dynamical processes that are highly relevant in the LTI region and significant to understanding the coupling between lower and upper atmosphere.

In summary, the required parameters include the vector ion motions and  $(\vec{E} \times \vec{B})$  drifts, vector winds, neutral and ion number density, composition, and temperatures, and energetic particles with resolved pitch angles, which are summarized in Table 1. Commonly used *in situ* instruments to obtain these measurements are also listed in the right-hand side column of Table 1. These data must be gathered simultaneously and on the same platform in the region of interest to understand, quantify and disentangle the contributing processes involved in the energetics, the dynamics and momentum budget in the LTI, as well as in the effects of energetic particle precipitation on the local chemistry and dynamics.

Such direct measurements in the LTI can only be performed by an *in situ* mission of a fully instrumented spacecraft, which flies at optimal orbital configurations that permit detailed, in-depth analyses of the physical processes both *via* event studies as well as *via* statistical studies of the behavior of the LTI region as a function of local time, latitude, season, and

magnetic activity. The ability of an *in situ* mission to statistically represent global processes and the global state of the LTI as a function of geomagnetic latitude, local time and activity levels by measurements performed over the mission's lifetime has been demonstrated in [ESA Daedalus RfA \(2020\)](#) for the case of the Daedalus mission concept by performing mission performance demonstration simulations using Daedalus MASE (Mission Assessment through Simulation Exercise), an open-source package of scientific analysis tools aimed at research in the LTI ([Sarris et al., 2022a](#)).

## 5.2 Current status of *in situ* measurements below 200 km

The only systematic *in situ* spacecraft observations within the 100–200 km region to date were made by the Atmosphere Explorer AE-C, AE-D, and AE-E satellites (1973–1981), which measured density, ion drifts, neutral and ion composition and temperatures along elliptical orbits, achieving measurements down to a lowermost altitude of 128 km by use of propulsion. However, as shown in [Figure 5](#), the total observation time from the three missions combined is only ~60.3 h below 200 km, with a much smaller subset of this time allocated to high latitudes, the theater of key LTI processes. At the same time, AE spacecraft lacked neutral wind, electrodynamics and energetic particle measurements, and the interpretation of some critical measurements, such as mass spectrometer composition data, proved difficult at low altitudes. The Dynamics Explorer DE-2 satellite (1981–1983) included also measurements of energetic particles, electric field and neutral winds; however DE-2 did not include propulsion and the lowermost altitudes sampled were above 250 km. In the absence of other systematic co-temporal and co-spatial measurements, sounding rockets have proved to be an invaluable mean to obtain *in situ* measurements in the LTI, however, by nature, they are limited by providing only a snapshot of an altitude profile and most often carry limited instrumentation.

## 5.3 Notional concept for a space mission to sample the lower thermosphere-ionosphere below 200 km

Since the time of the Atmosphere Explorers, there have been a number of matured mission concepts highlighting the need to sample plasma-neutral interactions at altitudes below 200 km with a fully instrumented satellite. These include: (a) the Thermosphere-Ionosphere-Mesosphere Energetics and Dynamics (TIMED) mission concept as originally proposed, and in particular the descoped *in situ* components of the twin-spacecraft mission, labeled TIMED-H and TIMED-L

([NASA TIMED SDT, 1991](#)); (b) the Geospace Electrodynamics Connections (GEC) mission concept ([Sojka et al. \(2001\)](#); [Grebowsky and Gervin \(2001\)](#)) (not to be confused with the Geospace Dynamics Constellation (GDC) mission concept ([NASA GDC STDT, 2019](#)), currently being selected for Phase A studies, which targets altitudes at 350 km or higher); (c) the Atmosphere-Space Transition Region Explorer (ASTRE) mission concept ([Pfaff, 2022](#)); (d) the Daedalus mission concept ([Sarris et al. \(2020\)](#); [ESA Daedalus RfA \(2020\)](#)). These mission concepts promise to offer an order-of-magnitude or more measurements than are currently available: as shown in [Figure 5](#), whereas the total observation time at altitudes below 200 km is only 60.3 h from all past *in situ* measurements combined, the targeted total observation time from a 3-year *in situ* mission dedicated to studying LTI processes is ~2000 h at altitudes < 200 km. These estimates are based on the Daedalus mission concept, and coverage times are calculated using the Daedalus MASE mission simulator ([Sarris et al., 2022a](#)). MAVEN, an active Mars mission, successfully performs measurements in the Martian thermosphere-ionosphere ([Jakosky et al., 2015](#)); such measurements are still lacking at the Earth's upper atmosphere. In the following, we outline the striking commonalities between these mission concepts that point to the notional concept of an *in situ* mission targeting to study plasma-neutral interactions in the LTI at altitudes below 200 km. Since circular orbits below 200 km are short-lived by nature due to atmospheric drag, a common component of all the above mission concepts is that the *in situ* sampling scheme is performed along elliptical orbits. Apogee altitudes of 1,500 km were baselined for TIMED-L and ASTRE, and 2000 km or above for TIMED-H, GEC and Daedalus. Nominal perigee altitudes ranged from 150 km (TIMED-H, TIMED-L, Daedalus) to 185 km (GEC) and 285 km (ASTRE). MAVEN also sampled the Martian upper atmosphere from elliptical orbits. By laws of orbital dynamics, elliptical orbits lead to perigee and local time precession, allowing sampling of perigee altitudes at both high and low latitudes and of extended local times; thus, even if the above science questions (and in particular Q1 and Q3) are primarily focused at high latitudes, both high, mid and low latitude objectives can be addressed by the above *in situ* mission concepts.

For sampling altitudes below the nominal perigee, all the above mission concepts make use of propulsion to episodically lower perigee, a maneuver that has been called a “deep-dip” or “deep-dive.” The lowermost altitudes targeted by the above concepts are all below 200 km: TIMED-H, TIMED-L and Daedalus target measurements down to 120 km, GEC targets 130 km “and possibly lower,” and ASTRE aims to perform measurements “below 200 km.” With respect to the lowermost altitudes to be sampled, it is noted that, whereas the entire LTI range from 100 to 200 km is of interest to LTI ion-neutral interaction processes, the lowermost altitudes targeted by the missions listed above are as low as 120 km. This is based on

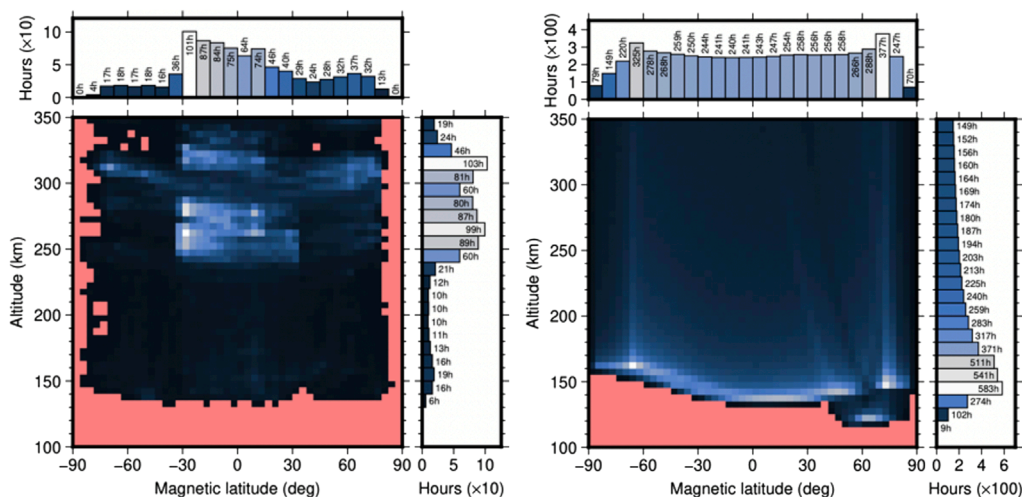


FIGURE 5

Left: Total observation time from AE-C, AE-D and AE-E combined, as a function of altitude and magnetic latitude. Total observation time at altitudes below 200 km is 60.3 h (Unified Abstract data). Right: Targeted total observation time from a 3-year *in situ* mission dedicated to studying LTI processes: ~2000 h at altitudes < 200 km. Deep-dips (perigee descents) according to this concept are performed down to 120 km when perigee is over high latitudes. [Figure by E. Doornbos; adapted from Sarris et al. (2020)].

trade-offs between science return, such as capturing the peak of Joule heating and Pedersen conductivity, which is assumed to be at 120 km (see, e.g., Figure 16 of ESA Daedalus RfA (2020)), versus risks and mission performance related to the enhanced densities at the lowermost altitudes to be sampled. A proposed approach is further discussed below in Section 5.6.

Another striking similarity across the above mission concepts, highlighting the optimal path towards conclusively resolving processes related to plasma-neutral interactions in the 100–200 km transition region, is the need for comprehensive measurements of all parameters involved; thus, the instrument suites of all missions include *in situ* measurements of neutral winds, ion drifts, electric-magnetic fields, ion-neutral composition, densities and temperatures, and EPP.

## 5.4 Multi-point measurements in the lower thermosphere-ionosphere

Several of the above mission concepts have highlighted the substantial additional benefits of multi-point measurements: beyond significantly enhancing coverage, a second spacecraft can bring about estimation of gradients, shears and altitude profiles, or space-time effect disambiguation. For example, it has been demonstrated how simultaneous measurements at two altitudes by identically instrumented satellites enable determining altitudinal gradients or profiles of electron density, Pedersen conductivity and Joule heating directly, rather than

statistically (Vogt et al., 2022). A concept has been proposed where nano-satellites in the form of CubeSats are deployed from a mothership (Sarris et al., 2020); these can be used as reference points or “buoys” for the estimation of local gradients of key properties while the mothership dips down to lower altitudes. Other concepts such as GEC emphasize the need for multi-point measurements in a “pearls-on-a-string” and “petal” configuration, addressing, respectively, spatial/temporal scales and exploring spatial extent of processes (Sojka et al., 2001). It is noted that the mission concepts involving multi-spacecraft observations emphasize the possibility of modifying the orbital configurations at different phases of the mission, to address different aspects of spatial and temporal characteristics of LTI processes.

## 5.5 Synergies between *in situ* and ground based measurements in the lower thermosphere-ionosphere

An *in situ* mission, such as described above, can uniquely be paired with ground-based measurements, such as from Incoherent Scatter Radars and SuperDARN. Networks of such ground-measurements can provide the large to regional picture of the LTI as well as context measurements for an *in situ* mission concept. In addition, investigations by a mission with *in situ* probes that are carried out in conjunction with radars and other ground based instruments offer a unique telescope-microscope view across multiple scales, enhancing the return

of an *in situ* mission. At higher altitudes, this approach has been demonstrated in a number of investigations, including the work by Aikio et al. (2018), who used Swarm satellite and EISCAT radar observations of electrodynamical parameters to reveal details of a plasma flow channel, and Ogawa et al. (2008), who used Reimei satellite and EISCAT radar observations to study the relationship between ion upflows and suprathermal ions. *In situ* missions have also been used in conjunction with ground-based stations that are used as heaters; in this case, satellite overflights are used to provide *in situ* measurements of the response of the magnetosphere and ionosphere to the heating (e.g., Robinson et al. (2000); Pokhotelov et al. (2004)). We note in particular the capabilities enabled by the upcoming EISCAT\_3D facility with volumetric measurement capabilities of electron density and ion velocity vector that is currently under development, which offers unique opportunities for highly complementary and synergistic measurement campaigns with an *in situ* mission such as outlined herein; details of EISCAT\_3D and on its important role in supporting current and future spacecraft missions has been outlined in McCrea et al. (2015).

In addition to the above synergistic opportunities, *in situ* measurements within the fields of view of remote sensing measurements offer the unique opportunity to test different assumptions and methodologies used in the retrievals of ionospheric parameters. For example, Kavanagh et al. (2022) used data from three decades of operations of the EISCAT radar to study the difference between the tristatic method and the scanning monostatic method. They found that large variability exists in the relation between the two techniques, resulting in different levels of Joule heating, particularly during active times. An *in situ* mission with appropriate instrumentation would provide a unique opportunity to test such assumptions and retrieval techniques.

## 5.6 Notional “way forward” including technology development needs

Based on heritage from the early AEs of the 1970's and from the NASA and ESA studies listed above, an *in situ* mission to sample the lower thermosphere-ionosphere to perigee passes of at least 120 km is entirely feasible. Since the 1970's, early generations of instruments covering all required parameters have been flown successfully within the LTI region (80–200 km) on sounding rockets (with nominal velocities of  $\sim 1$  km/s), however, comprehensive measurements of the region will require coverage from orbit. For some measurements, this demands a new generation of measurement techniques capable of coping with non-geophysical perturbations, such as shock-induced variations and sputtered ions from the spacecraft surfaces at the lowermost altitudes. Fortunately, well-established techniques

exist to model and address such satellite-generated disturbances and can be studied to mitigate these concerns. Given that satellite drag and re-entry considerations become a concern below 120 km, and due to the tremendous scientific return promised from such an unprecedented low perigee mission, we strongly urge that a satellite be flown as soon as possible with instruments to measure all of the relevant parameters to altitudes as low as 120 km; measurements below 120 km can be carried out on an exploratory basis during an extended mission phase based on findings from initial low perigee excursions to 120 km. The mission promises to open a new world of understanding of how the lower thermosphere and ionosphere works as a system, addressing all of the major outstanding questions outlined above.

## 6 Summary and conclusion

The focused questions presented here argue strongly for an *in situ* mission to sample the lower thermosphere—ionosphere in the coming decade, to address critical, yet unquantified processes related to plasma-neutral interactions in the transition region from the neutral atmosphere to plasma-dominated space. A satellite equipped with instruments to provide co-located measurements of ion drifts, neutral winds, electric and magnetic fields, ion and neutral density, composition and temperature, and energetic particle precipitation is anticipated to yield a wealth of crucially lacking information, which will support a broad range of advances in atmospheric and space sciences. The above measurements in the heart of the under-sampled atmosphere-space transition region are key toward future advances in modeling the lower/middle/upper atmosphere - ionosphere - magnetosphere as a multi-coupled system. These measurements will enable the accurate quantification of Joule heating, the specification of which is currently a major challenge in global circulation models. Accurate estimates of ionospheric conductivity will lead to improvements in magnetospheric models, as conductivity specification determines, among others, the closure of currents, the evolution of magnetospheric and ionospheric dynamics, the convection state, and the timing and strength of auroral substorms. Measurements within this region will lead to improvements of whole atmosphere models that include the LTI. Data assimilation using these new datasets will help improve numerical models. Better understanding and parameterizations will improve predictions of drag effects and spacecraft re-entry. *In situ* measurements of perpendicular electrical currents and magnetospheric forcing will provide insights on their relationship and will improve our understanding of the cause of Geomagnetically Induced Currents, a significant Space Weather threat. Measurements within this region will also assist in additional topics, not described above, such as in improving satellite-level gas-surface



interaction modelling algorithms and assumptions, enhancing existing models of Earth's global lithospheric magnetic fields at medium to small scales (e.g., Olsen, 2022), and investigating the interaction of particles with electromagnetic waves (e.g., Tourgaidis and Sarris, 2022).

An *in situ* mission based on a single spacecraft can achieve all of the above objectives. However, beyond significantly enhancing coverage, simultaneous measurements by a second spacecraft at a different altitude would enable the estimation of gradients, shear and altitude profiles; measurements by a second spacecraft in a “pearls-on-a-string” configuration would enable differentiating between temporal and spatial effects; and measurements by a second spacecraft on a “petal” configuration would enable exploring the latitudinal extent of processes.

This mission can be paired with longer-term ground-based remote-sensing measurements, such as with SuperDARN and EISCAT\_3D, to provide context measurements and a telescope-microscope view across multiple scales; this mission can also be paired with upcoming missions such as GDC (NASA GDC STDT, 2019) that will sample the 300–400 km altitude range, significantly above the altitude ranges of interest targeted herein, and DYNAMIC (NASA, 2022), that will provide a more global perspective of the neutrals in the lower thermosphere.

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## Author contributions

TS coordinated the writing of the manuscript and wrote the first draft. All authors contributed to the drafting of the manuscript and the ideas presented herein. All authors contributed to manuscript revision and approved the submitted version.

## 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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