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Editorial: Frontier research in equatorial aeronomy and space physics

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Editorial on the Research Topic
Frontier research in equatorial aeronomy and space physics

Pioneering aeronomy and space physics research has long been underway near the geomagnetic equator where, for example, a magnetic observatory has been in operation in Huancayo, Peru, since 1919 when it was founded by the Carnegie Institution (Ishitsuka, 2015). In the 1930s, the Huancayo Observatory also hosted cosmic ray detectors and an ionosonde prototype which can be seen today as having been the first pulsed radars in operation anywhere. The ionosonde propelled ionospheric research and discovered so-called "equatorial spread *F*" (ESF), a disruptive form of space weather that obscures ionograms among its many effects (Booker and Wells, 1938). ESF continues to consume much of the attention of the aeronomy community. Due in part to the notoriety of the Huancayo Observatory, the Jicamarca Radio Observatory was established near Lima in the 1960s at about the same time as the Arecibo Radio Observatory in Puerto Rico. Well before it was even completed, Jicamarca was producing some of the earliest incoherent scatter radar observations of the ionosphere (Woodman et al., 2019). Early results from Jicamarca identified some discrepancies in the theory of incoherent scatter emerging at that time and paved the way to their resolution (Bowles et al., 1962; Farley, 1964; Dougherty, 1964). Jicamarca also detected intense coherent scatter from field-aligned plasma density irregularities (FAIs) in the *F* region that would be associated with ESF (Farley et al., 1970). Moreover, it observed FAIs in the *E* region coming from the electrojet, a strong, permanent current system that had been studied systematically much earlier at Huancayo (Bowles et al., 1960). Pioneering observational and theoretical studies established a variety of plasma instabilities as the causes of *E*- and *F*-region FAIs shortly thereafter (Farley, 1963; Balsley and Farley, 1971; Woodman and La Hoz, 1976). These discoveries ushered an age of computational simulations and explorations of the instabilities in question. Notably, the instabilities do not rely on solar or geomagnetic activity for their existence, distinguishing the equatorial zone from middle and high latitudes.

In subsequent years, additional plasma instabilities would be discovered to inhabit the equatorial ionosphere where the horizontal geomagnetic field lines support a range of instability mechanisms that cannot operate elsewhere. These include unstable, long-lived, non-specular meteor trail echoes (Chapin and Kudeki, 1994), the so-called "150-km echoes" found in the daytime valley region (Balsley, 1964), seemingly unrelated irregularities that sometimes occur in the nighttime valley region (Chau and Hysell, 2004), and topside irregularities characterized by a lower-hybrid resonance observed in the inner magnetosphere during solar minimum (Derghazarian et al., 2021). That some of these phenomena have been discovered only recently hints at the possibility of still more instability mechanisms awaiting discovery.

The purpose of this Research Topic was to capture contemporary discovery research pertaining to observation, theory, and modeling of processes in the equatorial ionosphere. Unsurprisingly, most of the submissions deal with plasma instabilities and irregularities. More surprisingly, some of them prompt a reexamination of the theory used in aeronomy research, the experimental methods, and some of the assumptions underlying causality and variability, particularly as it pertains to space weather.

The equatorial plasma depletions or bubbles (EPBs) at the root of ESF were reconsidered by a number of authors in this Research Topic. Wu et al. demonstrated a novel method for geolocating plasma irregularities responsible for radio scintillations globally using satellite measurements. Kirchman et al. argued that practical forecasts of the phenomenon based mainly on background electric field measurements are possible and practical, but the underlying electric fields themselves are highly variable even during quiet times and remain difficult to predict. However, Yokoyama showed that the *E*-region conductivity also plays a crucial role in EPB occurrence. Additionally, Bossart et al. found an association between EPB occurrence and the positive/northward meridional wind phase of the quasi-two-day wave in the mesosphere. Finally, Huba reviewed the complicated role of meridional winds on EPB occurrence including destabilization associated with the midnight temperature maximum. Together, the papers constitute a study of overlooked influences on equatorial ionospheric stability that cannot be neglected.

Subjects of the Research Topic were not confined to EPBs, however. Yamazaki et al. examined the afternoon equatorial electrojet from the point of view of CSES satellite data, showing that the current is governed mainly by the DE3 and DE2 tidal modes while also scaling in intensity with the local electron density.

To the extent quiet-time ionospheric variability arises from variability in the mesospheric and lower thermospheric winds, methods of forecasting the latter takes on central importance in equatorial aeronomy and space weather. Mauricio et al. describe a hybrid model combining time-series analysis with machine learning, showing that it outperforms other models based on conventional, established forecast methods. Machine learning was also applied by Villalba et al., here to the emerging problem of ionogram forecasting.

However, storm-time effects cannot be neglected when considering variability in the equatorial ionosphere. Fejer et al. reviewed experimental and theoretical work relating storm-time drivers to climatological equatorial electrodynamic responses, highlighting the complex and spatially structured pathways involved and outlining the most important questions that remain. Valladares et al. examined large-scale traveling ionospheric and atmospheric disturbances (LSTIDs, LSTADs) from the points of view of space- and ground-based ionospheric measurements, following the flow of energy from polar to equatorial regions carried by these perturbations.

Finally, fundamental theoretical questions regarding how the ionosphere is modeled were examined in this Research Topic. Dimant derived a new set of five-moment fluid equations for electrons and ions starting from kinetic theory, taking into account conditions appropriate for the partially-magnetized *E* region. Their model equations form a basis for more accurate fluid simulations of the *E* region going forward. Koontaweepunya et al. furthermore considered how the strong electric fields in the electrojets can cause the ions to depart from Maxwellian distributions both theoretically and from the point of view of particle-in-cell simulations. They found that the non-Maxwellian distributions led to more isotropic heating than would otherwise be predicted.

The equatorial ionosphere continues to be a wellspring of discovery science with both fundamental and practical findings regularly coming to prominence as the field enters its second century. The future of the research discipline remains bright, with several new instrumentation deployments, experimental campaigns, and model developments in planning or underway. These include sweeping upgrades nearing completion at the Jicamarca Radio Observatory, the modern phased-array Incoherent Scatter Radar in Sanya with tristatic capabilities, the deployment of two LWA-class radio array telescopes (J-ARGUS) that will work together with and also independently of Jicamarca, the deployment of SIMONe-class multistatic meteor radar systems in South America, a NASA sounding rocket campaign (Cielo) tentatively planned for Punta Lobos, Peru in 2028, contributions to equatorial aeronomy by the DYNAMIC and GDC missions, and improvements to coupled GCMs to tackle the problems highlighted by this Research Topic. Research avenues where theory, model and simulation, and experimental work in concert are especially promising.

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