Neutral wind dynamo and ionospheric electrodynamics at low and mid-latitudes

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Abstract

Neutral winds in the thermosphere push the plasma through Earth’s magnetic field and generate ionospheric currents, and electric fields are set up to make the total current system divergence-free. This wind dynamo imposes electrodynamic forcing on the ionosphere and is the key to understanding a variety of ionospheric climatology and variability (including space and terrestrial weather) processes and phenomena, which constitute significant heliophysics science topics in the ionosphere-thermosphere-magnetosphere coupling area. Among these prominent phenomena are the equatorial ionization anomaly (EIA) and the equatorial electro jet (EEJ) effects; the pre-reversal enhancement (PRE) of zonal ionospheric electric field and vertical ion drift near dusk and its influence on equatorial irregularities; storm-generated disturbance wind dynamo electric fields (DDEF); and gravity wave generated perturbation wind electric fields (GWEF). Winds are subject to strong spatiotemporal variations due to a complex spectrum of lower atmospheric wave forcing, and therefore the wind dynamo is the essential cause of ionospheric electrodynamics, driving ionospheric variability on various spatial-temporal scales at low- and mid-latitudes. In order to advance the heliosphere science in the new decade for characterizing and forecasting ionospheric variability, substantial observational and modeling efforts are needed with a focus on the wind dynamo and its drivers.
Introduction

Plasma electrodynamics is some of the most significant features of the ionosphere at low and middle latitudes (Heelis, 2004). Electric fields are generated via strong ion-neutral coupling which varies with altitude in the upper atmosphere and are influenced by solar wind and magnetosphere coupling, resulting in electric field penetration. They play a unique role in driving $E \times B$ plasma drift. This process is effective in the F region and becomes more complex at lower altitudes due to collisional influences by neutrals. This paper recognizes and highlights the fundamental importance of the wind dynamo for understanding key ionospheric variations at low- and mid-latitudes.

Ionospheric currents and electric fields are generated when neutral winds drive the ionospheric plasma of the upper atmosphere across the geomagnetic field. By definition, the ionospheric current, $J = N_e (V_i - V_e)$, is determined by ion and electron velocities, $V_i$ and $V_e$ respectively. $J$ can be expressed in the form of Ohm’s law (e.g., Maute, 2021; Richmond, 2016):

$$J = \sigma_\parallel E_\parallel b + \sigma_P (E_{\perp} + U \times B) + \sigma_H b \times (E_{\perp} + U \times B)$$

where $J$ is the current density; $E_\parallel$ and $E_{\perp}$ are the components of the electric field parallel and perpendicular to the geomagnetic field $B$; $U$ is the neutral wind velocity; $b$ is a unit vector in the direction of $B$; $\sigma_\parallel$ is the conductivity parallel to $B$; $\sigma_P$ is the Pedersen conductivity; and $\sigma_H$ is the Hall conductivity with the latter two perpendicular to $B$. The conductivities are strongly anisotropy with $\sigma_\parallel$ several orders of magnitudes larger than $\sigma_{\perp}$ allowing to assume that field lines are equipotential on scales of $\geq$ minutes and 100s km. In this electrostatic electrodynamo system the field-aligned current $J_\parallel$ is determined by the divergence of perpendicular currents. It is clear that the neutral wind effect on $J$ depends strongly on the altitude dependent $\sigma_P$ and $\sigma_H$ which maximizes at the daytime E region (here defined roughly 100-150km). Interesting and challenging about the ionospheric electrodynamo is that it is a non-local problem where the wind dynamo in one location affects the electric field at another location. In addition, the ionospheric electrodynamics is oriented along field lines and the wind dynamo forcing $U \times B$ along the whole field line has to be weighted by the conductivities (see Equation (1)), however, this is generally dominated by contributions in the region between 90-200 km (assuming zero conductance below), and therefore the wind-generated electric field is regulated by the conductivities in this dynamo region. It is believed that the E region dynamo contributes the majority of the total current during the day while at night the relative contribution of the F region dynamo is approximately 50% (Rishbeth, 1981).

Sq currents and Equatorial Electrojet (EEJ) (Yamazaki et al., 2016): The neutral wind dynamo is responsible for several large-scale electrodynamical processes. The E region dynamo produces the quiet-time dayside current system (Sq currents) as a regular ionospheric electrodynamical feature at low- and mid-latitudes. Specifically, at equatorial latitudes where the magnetic field is horizontal, the relative magnitude of $\sigma_P$ to $\sigma_H$ controls the Cowling conductivity ($\sigma_P + \sigma_H^2 / \sigma_P$) and is one of the main reasons for strongly enhanced equatorial electrojet (EEJ). Both Sq and EEJ are driven by conductivity-weighted winds and therefore the wind climatology and weather in the lower thermosphere have
profound influences on the Sq and EEJ variability on temporal scales from hours to days and on spatial scales of few to several degrees in latitude and longitude (Manoj et al., 2006). The lower thermospheric winds are strongly influenced by highly complex upward propagating atmospheric waves at a variety of oscillation modes; electric field components $E_{\perp}$ cause plasma motion in the F-region which provides ion drag and affects variations of the neutral wind $U$. The electrodynamic processes involving ion-neutral coupling in the aforementioned dynamo region cause some of the well-known ionospheric variation features, to name a few, equatorial ionization anomaly, wave-4 ionospheric longitudinal patterns at low latitudes, two-day oscillations in the winter ionosphere, anomalous equatorial ionospheric diurnal variations during sudden stratospheric warming periods (e.g., Goncharenko et al., 2010; Siddiqui et al., 2021).

**Pre-reversal enhancement (PRE) vertical ion drift** (Fejer et al., 1991; Maute, and Richmond, 2017; Richmond, and Fang, 2015): The neutral wind dynamo, particularly the F region dynamo, is responsible for electrodynamical changes near the solar terminator at low latitudes. At dusk, zonal and vertical gradients of the winds cause vertical gradients of zonal ion drifts (through the wind dynamo action) that require a vertical convergent flow and thereby a large upward ion drift (PRE) at the low F region altitude is set up in the evening. Neutral winds in the low latitude region where plasma density (conductivity) is large and altitude and local time variations of the winds relative to plasma density are particularly important. PRE is highly variable, subject to large day-to-day variability as well as seasonal and longer-term variations. It is particularly sensitive to the nighttime conductivity. PRE ion drifts push equatorial plasma upward and provide sustained EIA crests at night; in other scenarios, PRE and its associated large gradient in plasma density is a necessary condition for the development of equatorial plasma bubbles (EPBs). Similar to the wind dynamo-driven PRE, the dawn sector can exhibit strong vertical drifts whose generation mechanism is less understood (Chen et al., 2020).

**Storm-time disturbance wind dynamo electric field (DDEF)** (Blanc et al., 1980; Fuller-Rowell et al., 2002; Maruyama, 2020): Intense storm-time Joule and particle heating in the auroral region generate strong equatorward winds, which are opposite to the regular solar EUV-produced poleward winds at midlatitudes generating Sq currents. These storm-time meridional wind surges cause westward winds due to Coriolis force. The westward winds above 120 km altitude generate the equatorward Pedersen current and corresponding poleward electric field, which results from accumulating charge toward the equator, and westward $E \times B$ drift. The poleward electric field further produces an eastward Hall current, resulting in a westward electric field on dayside and an eastward electric field on nightside due to positive charge buildup toward the sunset terminator. This eastward current at midlatitudes closes at low latitudes via a westward current, forming over the middle and low latitudes a current vortex similar in shape to the Sq current system which prevails on quiet days, but of the opposite direction. As a result, the storm-time low and mid-latitude current system is a weakened and distorted version of quiet-time Sq and EEJ.

**Gravity wave-induced dynamo electric field GWEF**: Gravity waves
in the thermospheric altitudes are known to cause traveling ionospheric disturbances (TIDs) predominately because wind oscillations can drive plasma motion along the magnetic field line. This GW-TID connection facilitates the meridional dispersion of geospace storm-time energy in the entire upper atmosphere via atmospheric disturbances (TADs) and large-scale TIDs. GWs with significant zonal propagation components in the ionosphere, however, are expected to set up perturbation electric fields because of the dynamo action of the perturbation winds (particularly in the zonal direction). The polarization electric field oscillations associated with MSTID events have been observed recently at mid-latitudes during the passage of zonally propagating GWs following the sunrise terminator (Zhang, Erickson, Gasque, et al., 2021).

Challenges
It is clear the ionospheric electrodynamics with the wind dynamo processes and their effects are at the core of understanding a variety of ionospheric phenomena. While essential frameworks of fundamental physical processes have been established, our understanding remains preliminary and faces many challenges.

Advances in our understanding can be archived with appropriate observations as demonstrated by the ICON mission. When ICON crosses the magnetic equator it makes simultaneous measurements of neutral winds and plasma velocities along common magnetic field lines. For the special conditions at low latitude around noon-time assuming that the zonal current is not changing Immel et al. (2021) calculated dynamo-induced vertical plasma drifts from ICON’s neutral winds, and compared these with measured plasma velocities. Predicted drifts show significant (∼0.5 correlation coefficient) correlations with actual plasma drifts at spacecraft altitude along the same magnetic field lines. However, the study also pointed out that 75% of the drift variability cannot be attributed to the neutral wind along the field line, which are probably due to non-local wind dynamo action as well as the influence from magnetosphere-ionosphere coupling which is even present during quiescent times.

A key challenging is to understand the wind dynamo and its effect on ionospheric variability: what degree the wind-dynamo-driven ionospheric electrodynamics is responsible for low and midlatitude ionospheric variations, including short-term and day-to-day variability, and seasonal and solar cycle trends?

Neutral winds are extremely variable, especially in the E region. We do not understand these winds sufficiently well due to a massive lack of direct observations with good coverage as well as the complication associated with multiple atmospheric wave modes and their super-positions generating varying local and regional effects. Due to limited driver information, we cannot attribute ionospheric variability to neutral wind variability on time scales of days. However, modeling studies have indicated that neutral wind variability is important. Does wind variability account for the majority of ionospheric variability?

Observation and modeling challenges: Some of those ionospheric electrodynamical phenomena (such as PRE and EEJ) have been under decade-long debate for their plausible physics. Although all suggestions were related to the
dynamo, the details of different theories vary. First-principal models have advanced to provide improved modeling for the whole atmosphere and help clarify the physics, however, sparse observations (not necessarily error-free) often deviate from simulations. Direct observational evidence linking winds and electric fields has recently become available (Immel et al., 2021) but only instantaneously during specific observing geometry when the satellite is at the magnetic equator at noon. Otherwise, connecting observationally the two quantities is currently only possible on approximately monthly time scales, which in addition limits using numerical modeling to examine the coupling mechanisms due to neutral wind driver uncertainty. Dynamics in transitional domains are generally difficult to model, including dusk/dawn times, GWs to mesoscale waves, the E to F region, and mid- to high latitude electric fields. In general observational coverage and modeling capability are clearly persistent challenges for the community.

**Short-term ionospheric variability:** New findings related to terrestrial weather and surface events have suggested the wind dynamo could be severely modified leading to substantially ionospheric disturbances and even irregularities. For example, the solar eclipse shadow is expected to perturb the wind dynamo and EEJ in the equatorial region and therefore impact the F-region ionospheric response to the eclipse (Maurice et al., 2011). The E region conductivity enhancements during solar flares modify the E-region wind dynamo and therefore the F region ionospheric variations (Zhang, Liu, et al., 2017). The 2022 Tonga volcanic eruption has reportedly caused changes in EEJ during the day (Harding et al., 2022; Le et al., 2022) and PRE near dusk (Aa et al., 2022) at disturbances several thousand kilometers away from the epicenter. The questions are what is the regional and global extent of these disturbance wind fields in different layers of the atmosphere (for both eclipse and volcanic eruption cases), and what exactly happens to the wind dynamo when other simultaneous processes (e.g., geomagnetic storms and substorms or solar flares) occur?

Ionospheric electrodynamics at midlatitude is also closely related to certain plasma instability through the wind dynamo. The sporadic-E (Es) instability at night results from the zonal wind shear which generates polarization electric fields and corresponding upward and downward ion drifts over those NW-SE elongated Es patches (e.g. Cosgrove et al., 2002). These electric fields can be mapped to the F region along magnetic field lines and amplify the growth of Perkins instability (Perkins, 1973), leading to MSTIDs and ionospheric irregularities. This important link from the E region winds and the dynamo to Es instability and large electric fields and eventually MSTIDs and irregularities developed at nighttime midlatitudes is supported by limited sets of observations, however, direct measurements of electric fields inside the Es and in the F region with coincident E region winds are not widely available to explain dramatic variability in the occurrence of Es, MSTID, and irregularity. No observations have been available to examine other competing processes, such as the impact of GWs in the E region height on Es instabilities (Makela et al., 2011).

**Do we really understand storm-time electric field and current systems at mid- and low latitudes?** The disturbance wind dynamo DDEF concept has been suggested to explain some ionospheric plasma drift measure-
ments at the magnetic equator. These storm-time measurements result from a mix of competing processes including the disturbance dynamo as well as the penetrating electric field originating from the magnetosphere. The penetration could be either prompt and short-lived or long-lasting, and the disturbance dynamo could be prompt reaching low latitudes within 10s minutes. These make it quite challenging to distinguish in observations the disturbance dynamo from the penetration effect. Simultaneous wind and electric field measurements at multiple points meridionally along mid, low, and equatorial latitudes remain extremely rare to confirm the proposed DDEF effects and latitudinal evolution. The storm-time neutral composition changes modify the conductivities during the storm recovery and this process is often overlapped with the disturbance dynamo development. Also, DDEF currents are not completely anti-Sq but dusk and dawn times are very dynamic and difficult to be simulated. Even less understood in the proposed disturbance dynamo framework is the mid- and low-latitude current changes and current closes (a more general problem is currents in the interaction region between mid- and high-latitude electric field boundaries.) No sufficient observations are readily able to characterize the large-scale current system and related low and midlatitude coupling and to verify the disturbance dynamo theory. Finally, it should be pointed out that subauroral winds can become extremely dynamic during intense subauroral polarization stream (SAPS) events, with characteristic enhanced westward winds which sometimes are accompanied by enhanced poleward winds (Zhang, Erickson, Foster, et al., 2015). These dramatic regional disturbances could potentially alter the disturbance wind dynamo when the disturbance winds propagate from the auroral source region into low latitudes, however, the exact impact remains yet to be established in both observations and modeling.

**Gravity wave-related electrodynamics:** This topic first occurred in the ~1960s at the start of correlating TIDs to GWs but has been lack of significant progress for decades. Recently renewed interests are triggered by the advance of nighttime MSTIDs at midlatitudes which exhibit highly electrified nature and conjugate effects. The GW role in TID dynamics is well established, but poorly known for the TID electrodynamics. Observational challenges remain major obstacles. To understand the exact physics, advanced modeling capability is essential where simulating gravity waves under the non-hydrostatic assumption and simulating 3-D electrodynamics under non-electrostatic appear important. Appropriate spatial resolution is also needed to address the 200-300 km characteristic wavelengths.

**Observables**
The wind dynamo theory includes several key parameters that can be observed and inferred from measurements:

- **Wind vector profiles** at low and equatorial latitudes from the lower thermosphere (during both daytime & nighttime) through the upper thermosphere (especially at night.) It is typical that we build the wind field specification using fitting techniques with various tide modes to deal with sparse observation
problems. A minimum requirement for these techniques is the data availability spanning different local times (daytime and nighttime hours). Winds at midlatitudes relevant to Sq are also very important. At midlatitudes where it peaks, the SW2 mode has a significant influence on the low latitude drift. Measurements in both northern and southern hemispheres are essential to distinguish between symmetric and antisymmetric modes.

During geomagnetic storms, great temporal coverage (beyond the nighttime only for the Fabry–Pérot interferometer case) and fine temporal resolution are required to evaluate the time evolution of the winds. Measurements along meridional chains on both dayside and nightside are critically important to establish the disturbance wind progression and latitudinal extent. These are some of the most needed information in order to distinguish the influences of the wind dynamo and the penetration electric field. It should be noted also that as neutral winds at subauroral latitudes driven by intense SAPS could impact the disturbance wind dynamo propagation through the region, a regional network with fine latitudinal and appropriate temporal resolutions is required to evaluate the upstream status of disturbance dynamo at midlatitudes.

- **Electric field vector:** anywhere and anytime where winds and ionospheric plasma state parameters are available. Electric field data can be mapped along the magnetic field to the locations with wind data. It is one of the direct measurements of the wind-dynamo effect and key to understanding ionospheric variations. Storm-time electric fields at subauroral latitudes may serve as a driver for subauroral disturbance winds which have a potential impact on the downstream wind dynamo.

- **Electric currents:** anywhere and anytime where electric field data are available. Equivalent currents, which generate the same magnetic field perturbations at the ground as the true 3D ionospheric current system, are often derived using ground-based magnetometers. The equivalent current however does not contain any information about the altitude variation of the current. Having co-located observations of neutral wind and electric field the local ionospheric current can be derived to better understand current closure e.g., during geomagnetic activities or large wind changes.

- **Conductivity:** anywhere and anytime where the electric field and electric current data are available. It is often inferred based on ionospheric ion density and neutral composition and temperature. Most ionospheric sensors measure electron density and therefore an ion composition model has to be in place; profiles of electron density spanning E and F regions are critical. Neutral parameters are often from empirical models, however, actual measurements (especially during storms) could benefit significantly the conductivity calculations.

- **Neutral composition and temperature profiles:** See the conductivity discussion. We emphasize their importance on the F region at different storm phases.

- **Ionospheric plasma density profiles:** these are some of the target ionospheric characteristics that need to be understood, but they are also embedded in some of the key parameters such as conductivity. Measuring and modeling electron density accurately at nighttime, especially below F1 region, are challenging issues but these data are important for understanding the conductivities.
and therefore ionospheric electrodynamical phenomena such as PRE (a wind dynamo effect) and SAPS (a storm-time electric field with impact on subauroral winds and potentially downstream wind dynamo).

- **Ionospheric drift vector:** In the F region, a drift component perpendicular to $\mathbf{B}$ is interchangeable with an electric field through $\mathbf{E} \times \mathbf{B}$. The ion drift parallel to $\mathbf{B}$ contains information on meridional winds and plasma diffusion.

- **Total electron content:** 2-D horizontal ionospheric information with persistent spatiotemporal coverage is essential for the characterization of ionospheric variability. Additional information from GNSS TEC data on TIDs is important for the study of GW dynamo effects.

- **Upper atmospheric airflow maps:** these maps visualize emissions at various wavelengths by the nighttime upper atmospheric processes. They are often used to study atmospheric waves (e.g. red and green lines in All-sky Imagers) and plasma density distributions (GOLD at 135.6 nm).

**Final remarks on observational strategy**

Geospace Dynamics Constellation (GDC) with multiple satellite constellations are able to provide great spatial and temporal coverage for the study of several ionospheric electrodynamics topics related to wind dynamo effects. In situ measurements of the winds and plasma drifts (or electric fields) are key parameters. Importantly, GDC measurements at high latitudes can specify the drivers of geospace storm-time disturbance winds at the specific location and time and help identify appropriately the disturbance wind dynamo effects.

Current missions including GOLD, ICON, and Swarm remain important because they provide winds, plasma drifts, ion density, and currents information which enable the study of wind dynamo and ionospheric variability but are not able e.g. to derive tidal forcing in time scales of less than 30 days or comprehensive data set of simultaneous measurements of neutral and plasma characteristics. Dynamical Neutral Atmosphere-Ionosphere Coupling (DYNAMIC) is a future mission envisioned to “substantially advance understanding of the variability in space weather driven by lower-atmosphere weather on Earth”. Those wind measurements in the lower atmosphere are crucial to enhance our understanding of the ionospheric variability via the wind dynamic effect.

In situ measurements usually lack the critical altitudinal resolution, especially below 200 km which is the region where the wind dynamo is most effective. Ground-based observations play an indispensable role to advance the understanding of the creation of the wind dynamo and its effect. These include incoherent scatter radars (ISRs) that measure the ionosphere in a broad height range for multiple plasma state parameters (including densities, temperatures, as well as ion drift/electric field), always-on ionosondes that measure accurately the ionospheric electron density below the F2 peak, and GNSS TEC data that characterize the ionosphere in 2-D over the globe. The distributed array of small instruments (DASI) can be effective tools to study important regional features such as the wind field in extremely dynamic auroral and subauroral regions as well as equatorial regions.
References


