



Originally published as:

Liu, H., Yamamoto, M., Lühr, H. (2009): Wave-4 pattern of the equatorial mass density anomaly: A thermospheric signature of tropical deep convection. - *Geophysical Research Letters*, 36, L18104

DOI: [10.1029/2009GL039865](https://doi.org/10.1029/2009GL039865)

1 Wave-4 Pattern of the Equatorial Mass Density Anomaly - A
2 thermospheric signature of tropical deep convection

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7 The equatorial mass density anomaly (EMA) is an anomalous latitudinal
8 distribution of the atmospheric mass density, with its equinox configuration
9 consisting of a density trough near the Earth's dip equator flanked by density
10 crests around $\pm 25^\circ$ dip latitude. As a novel feature, this study it reveals a
11 pronounced 4-peak longitudinal pattern of the EMA, which is in reminis-
12 cence of the wave-4 like structure in the neutral wind and the equatorial ion-
13 ization anomaly (EIA). It is found that the wave-4 modulation in the EMA
14 trough region is in phase with that in the EMA crest region, in contrast to
15 the 180° phase reversal for the case of EIA. This difference strongly suggest
16 that although the latitudinal structure of the EMA is principally caused by
17 the EIA via ion drag, its wave-4 pattern likely arises from different sources.
18 The direct penetration of the non-migrating diurnal tides DE3 to the F-region
19 height or thermal budget modulation by the composition NO at lower ther-
20 mosphere are discussed as plausible candidates. Our results reveal a 4-hour
21 phase lag between the wave-4 patterns in neutral density and wind, and a 2%
22 peak-to-peak amplitude of the neutral density wave-4 pattern. These results
23 find good agreements with theoretical predictions based on direct penetra-
24 tion of the DE3 to F-regions heights, hence strongly support this mechanism.
25 Our observations thus add further evidence for the influence of tropical deep
26 convection on the thermospheric dynamics.

1. Introduction

27 The equatorial mass density anomaly (EMA) is an interesting and important feature of the
28 Earth's thermosphere in tropical regions, first observed by the CHAMP satellite [*Liu et al.*,
29 2005]. It is an anomalous latitudinal distribution of the atmospheric mass density, with its
30 equinox configuration consisting of a density trough near the Earth's dip equator flanked by
31 density crests around $\pm 25^\circ$ dip latitude. This structure is the neutral counterpart of the well-
32 known equatorial ionization anomaly (EIA) in the ionosphere, which has been recognized and
33 studied since the 1930s [*Appleton*, 1946; *Balan and Bailey*, 1995]. The EMA has been proposed
34 to form primarily under the influence of EIA via ion drag, with some contribution from chemical
35 heating fuelled by charge exchange between O^+ and O_2 or N_2 [*Liu et al.*, 2005]. It resembles
36 fairly well the EIA in many climatological aspects, e.g., the seasonal and solar cycle variations
37 [*Liu et al.*, 2007].

38 Recently the EIA has been revealed to exhibit a wave-4 longitudinal variation, which closely
39 resembles the land-ocean distribution [e.g. *Sagawa et al.*, 2005; *Immel et al.*, 2006; *Wan et al.*,
40 2008]. It is now generally accepted that this structure forms as an effect of the E-region dynamo
41 modulation by the eastward propagating non-migrating diurnal tide with wavenumber 3 (DE3)
42 [*Immel et al.*, 2006; *Hagan et al.*, 2007; *Jin et al.*, 2008]. When viewed at one fixed local time
43 from slowly precessing satellites, this feature manifests as a 4-peak structure. On the other
44 hand, thermospheric neutral wind at 400 km altitude has also been found to exhibit wave-4
45 longitudinal variation [*Häusler et al.*, 2007], whose formation was suggested to be due to DE3
46 tides. Given either the close relation between EMA and EIA via ion drag or the internal relation
47 between neural density and wind via pressure gradient, it does not seem far-fetched to speculate

48 that the neutral density and the EMA should also experience similar longitudinal modulations
49 as in other quantities. Thus, our purpose in this study is to identify such signatures and to
50 investigate its possible exciting agents.

2. Data

51 We utilize the thermospheric density and electron density data obtained simultaneously from
52 the CHAMP spacecraft, which is in a near-circular orbit with an inclination of 87.3° and an
53 initial height of ~ 450 km at launch in July 2000. It probes the in-situ thermospheric density
54 with a tri-axial accelerometer and the in-situ electron density with a Planar Langmuir probe.
55 Readers can refer to *Liu et al.* [2006] and *McNamara et al.* [2007] for details concerning the
56 derivation procedure and accuracy of the data.

57 In view that both EMA and EIA structures are more prominent around equinoxes at high solar
58 flux levels [*Liu et al.*, 2007], we choose data during March-April 2002 and Aug.-Sept 2002 for
59 the analysis that follows. Data under quiet conditions ($K_p \leq 3$) are used. Both electron and
60 neutral densities have been normalized to a common height of 400 km, using the NRLMSISE-
61 00 [*Picone et al.*, 2002] and IRI2000 model [*Bilitza*, 2003]. These data are then binned with 5°
62 latitude \times 10° longitude grids in geographical coordinates.

3. Results

63 Global distributions of the electron density and neutral density in geographic coordinates are
64 presented in Figure 1. These are average patterns between 14–18 LT, when the EMA structure
65 is prominent. Solid lines depict the dip equator.

66 The electron density in Figure 1a shows the familiar EIA structure, with a wave-4 longitudinal
67 modulation of crest density peaking near 0°E , 90°E , 180°W , and 80°W . This feature has been

Figure 1

68 observed from various satellites like IMAGE, Formosat3/COSMIC, and CHAMP [*Immel et al.*,
69 2006; *Lin et al.*, 2007; *Liu and Watanabe*, 2008].

70 Meanwhile, the neutral density (Figure 1b) exhibits a prominent EMA structure, with a trough
71 at the equator and density crests near $\pm 25^\circ$ dip latitudes. A pronounced 4-peak longitudinal
72 modulation similar to that in the EIA is clearly visible. It has three distinct density maxima
73 around 20°W , 70°E , 130°E , and a less obvious maximum around 130°W , with slight hemispheric
74 asymmetry. Note that these EMA peaks are somewhat shifted in location from those of the EIA.

75 To examine the longitudinal variation in more detail, densities in the trough and crest regions
76 are extracted. Trough densities are obtained by averaging densities within $\pm 5^\circ$ dip latitudes,
77 while crest densities are averages over both hemispheres within $[\pm 10^\circ \pm 20^\circ]$ dip latitudes for
78 the EIA and $[\pm 20^\circ \pm 30^\circ]$ dip latitudes for the EMA. Results are shown in Figures 2a and 2b.
79 Evidently, EIA trough and crest densities both display a prominent 4-peak structure, which are
80 anti-phase to each other. This is easily understood, given that EIA is driven by the equatorial
81 fountain process. The EMA also exhibits a pronounced 4-peak modulation in both trough and
82 crest regions. However, unlike in the case of EIA, these modulations are rather matching each
83 other quite well in phase. Note that using geographic latitudes for this analysis leads to the
84 disappearance of the wave-4 in the EIA, and a significant weakening of it in the EMA. This is
85 expected because both EIA and EMA are closely aligned with the dip equator as seen in Figure
86 1 and discussed in *Liu et al.* [2007]. Dip latitudes should be used to best extract the wave-4
87 feature in the crest and trough regions.

88 It is worth noting that the four peaks of EMA are somewhat displaced in longitude from those
89 of EIA. To quantify this displacement, a Fourier transformation is applied to the curves in Fig-

Figures 2

90 ures 2a and 2b. The synthesized wavenumber 4 component is shown in Figures 2c and 2d. The
91 peak-to-peak amplitude in the EIA crest/trough is about $2 \times 10^5 \text{ cm}^{-3}/1.5 \times 10^5 \text{ cm}^{-3}$, cor-
92 responding to approximately $10 \pm 0.05\%$ of the background electron density. The amplitude in
93 EMA has an amplitude about $0.15 \times 10^{-12} \text{ kg m}^{-3}$, corresponding to $2 \pm 0.2\%$ of the background
94 neutral density. We see that in the crest region, the EIA and EMA wave-4 variations are largely
95 displaced to each other. In the trough region, however, they are nearly in phase, and the EMA
96 peaks at about 10° east to the EIA.

4. Discussion

97 Results presented above provide a fairly clear picture of a marked 4-peak longitudinal modu-
98 lation of the EMA, in reminiscence of that in the EIA. Several interesting features are discussed
99 below.

100 First, wave-4 like modulations in EMA crest and trough region are in phase with each other,
101 while those in EIA are perfectly anti-phase to each other (Figures 2a, 2b). This anti-phase
102 relation in EIA trough and crest can be understood as a straightforward effect of the equatorial
103 fountain process which drives EIA. This process removes plasma from the EIA trough region
104 and transports it to the EIA crest region. Thus, the anti-phase relation provides strong evidence
105 for the suggested DE3 tidal modulation of the E-region dynamo [*Hagan et al., 2007; Jin et al.,*
106 *2008*]. In contrast, the EMA's crest and trough exhibit in-phase longitudinal modulation. This
107 difference between the EMA and EIA clearly disqualifies the EIA as a major cause for EMA's
108 wave-4 modulation via ion drag. It is because if ion drag were the cause, the longitudinal
109 structure of EMA should mirror that of the EIA, with the wave-4 pattern in the EMA crest and
110 trough being anti-phase to each other. Therefore, the in-phase relationship between the EMA

111 crest and trough strongly precludes any significant contribution from EIA's wave-4 structure to
112 the EMA's wave-4 longitudinal modulation.

113 With the in-situ exciting agent of ion drag being excluded, due consideration needs to be
114 paid to the direct upward propagation of the tidal component DE3. One possibility is the direct
115 penetration to F-region heights, which can potentially impinge a wave-4 structure on upper ther-
116 mospheric quantities [*Oberheide and Forbes, 2008b*]. Our results show that the wave-4 in the
117 EMA peaks around 30°W longitude and those separated 90° apart (Figures 2c, 2d). In the light
118 that wave-4 in the equatorial zonal wind at 16 LT peaks around 15°W [*Häusler and Lühr, 2009*],
119 we obtain a 15° longitude difference between the neutral density and wind, which translates to
120 a phase difference of 4 hours. This observed density-wind phase lag finds good agreement with
121 theoretical predictions by *Oberheide et al. [2009]* about the DE3-induced neutral density and
122 wind perturbations at 400 km. Furthermore, our analysis reveals a $2\pm 0.2\%$ peak-to-peak am-
123 plitude in the wave-4 variation of the neutral density, which is again very close to the predicted
124 value of 1.8-2% in *Oberheide et al. [2009]*. Therefore, these agreements between observations
125 and predictions give strong supporting evidence for a direct upward propagation of DE3 to F-
126 region heights. Another process via the DE3-induced wave-4 structure in NO composition in
127 the lower thermosphere [*Oberheide and Forbes, 2008a*] may contribute as well. Since NO acts
128 as the atmosphere's natural thermostat via its $5.3\ \mu\text{m}$ emission [*Mlynczak et al., 2007*], its wave-
129 4 variation might potentially affect the Earth's upper thermospheric energy budget. Note that
130 in comparison to the route via E-region dynamo process, which has induced a disturbance with
131 peak-to-peak amplitude of $\sim 10\%$ in the F-region electron density, direct penetration or via NO
132 has caused only $\sim 2\%$ disturbances in the neutral density.

133 To conclude, the EMA exhibits a pronounced wave-4 longitudinal pattern which results more
134 likely from the direct impacts of DE3 than from the EIA via ion drag. This wave-4 pattern
135 in the neutral density shows a 4-hour phase difference from the wave-4 pattern in the zonal
136 wind, which is consistent with theoretical predictions. We may envisage the following. The
137 DE3 penetrates upward and first reaches E-region heights, where it modulates the E-region
138 dynamo and consequently causes a wave-4 structure in the EIA when observed at constant local
139 time. The DE3 continues to penetrate upward and reaches F-region heights, where it impinges
140 a wave-4 signature in the neutral density and wind, but with a 4-hour phase difference. All
141 these observations add further evidence for the influence of deep convection in the tropical
142 troposphere on the thermospheric dynamics.

143 **Acknowledgments.** We thank Prof. T. Nakamura for interesting discussions and Dr. S.
144 Thampi for careful reading the manuscript. The work of H Liu is supported by the JSPS founda-
145 tion. The CHAMP mission is supported by the German Aerospace Center (DRL) in operation
146 and by the Federal Ministry of Education and Research (BMBF) in data processing.

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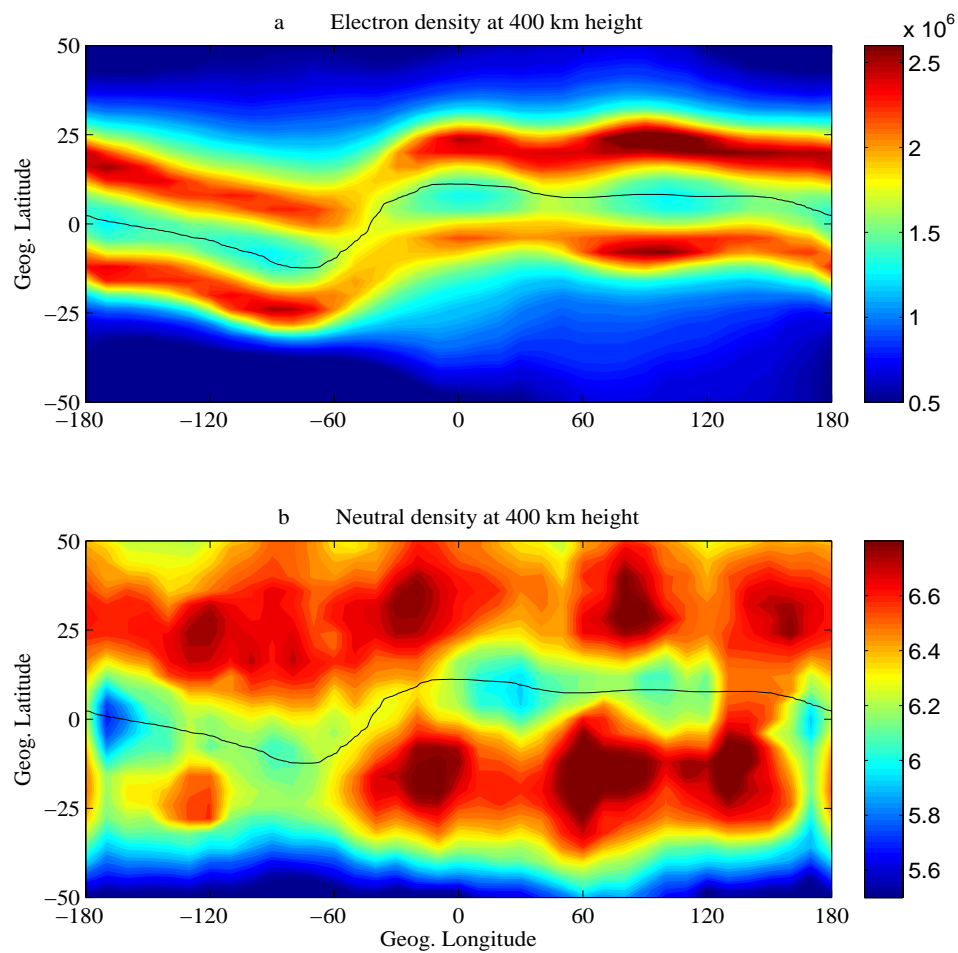


Figure 1. Distribution of the electron density (a. in unit of cm^{-3}) and neutral density (b. in unit of 10^{-12} kg) during 14–18 LT in the geographic coordinates near equinoxes in 2002.

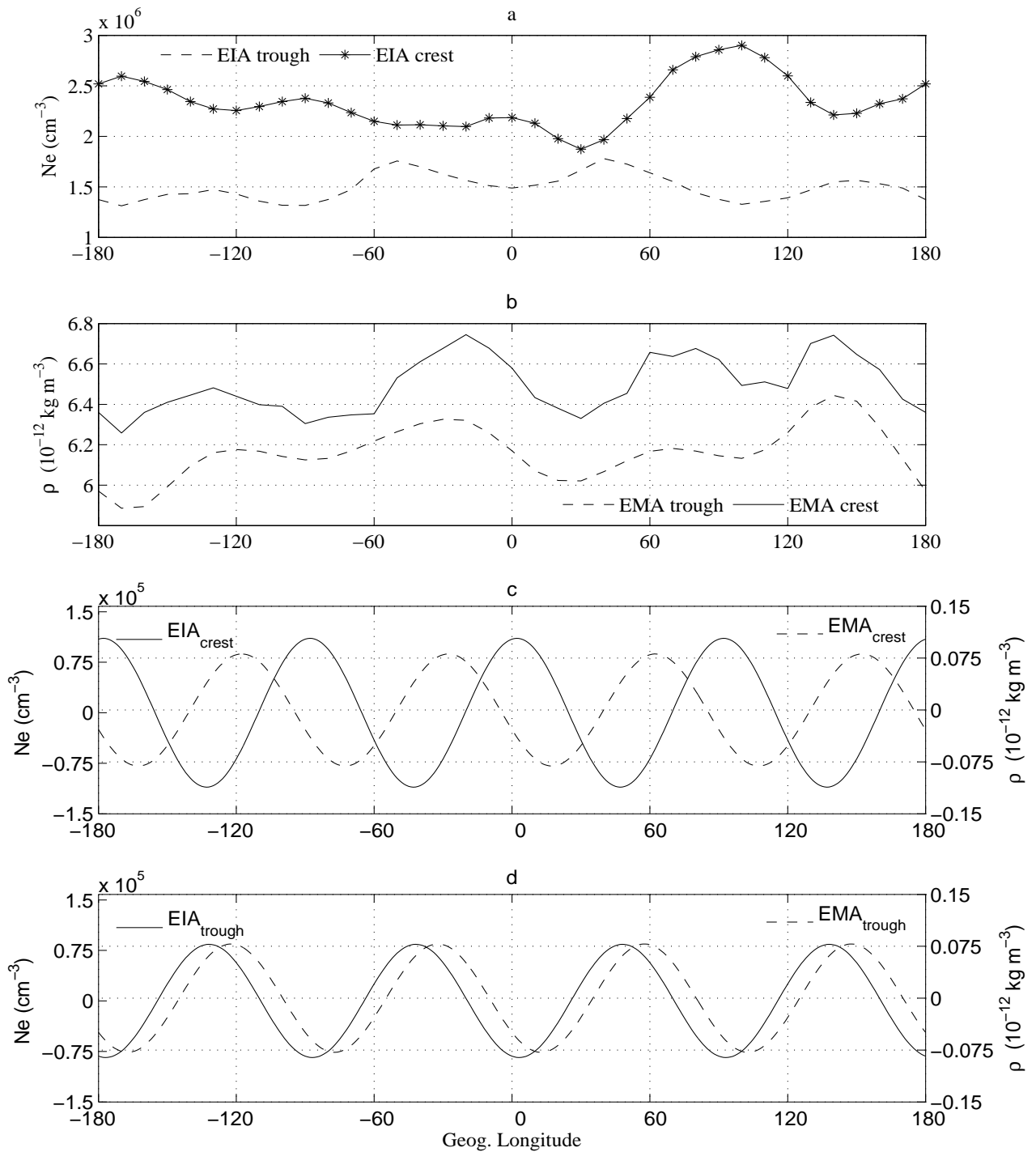


Figure 2. Longitudinal variation of the electron and neutral density in the trough and crest regions, along with their synthesized wavenumber 4 component.