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Morning Geomagnetic Bays at Polar Latitudes and Their Magnetospheric Sources

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Abstract—A study is performed of morning polar bay-like magnetic disturbances observed at latitudes above 70° MLAT with no simultaneous geomagnetic activity at lower latitudes. It is shown that such disturbances can be caused by the spatial expansion of both nighttime substorms and daytime polar magnetic bays to the morning side, along with the generation of convective magnetic bays. The simultaneous development of nighttime substorms and convective polar bays is typical. It is shown that individual events of morning polar magnetic bays observed during the development of nighttime substorms can be accompanied by mid-latitude positive morning magnetic bays.

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INTRODUCTION

In the 1970s, bay-like magnetic disturbances observed during evening and nighttime hours at latitudes above 70° MLAT (referred to below as polar latitudes) were called substorms along a contracted oval [1–4], since they are usually recorded under weakly disturbed geomagnetic conditions when the auroral oval is contracted to the pole. The authors of [5–8] proposed referring to such high-latitude disturbances accompanied by a set of geophysical phenomena typical of a substorm as polar substorms. Polar substorms are observed at low solar wind velocity after the passage of a high-velocity recurrent flow or during a slow solar wind flow, and during the late recovery phase of a magnetic storm [8, 9].

At the same time, our analysis of high-latitude observations on the Scandinavian IMAGE magnetometer network shows that negative magnetic bays at polar latitudes can be observed not only in the evening and night but in the morning as well. While evening polar substorms have been studied in many works, e.g., [1–8], morning polar bays have so far been ignored.

The aim of this work was to study spatial features and possible magnetospheric sources of morning polar negative bay-like magnetic disturbances (below, polar magnetic bays) observed on the Scandinavian IMAGE magnetometer network at geomagnetic latitudes above 70° MLAT (Fig. 1a).

MAGNETIC BAYS IN THE MORNING SECTOR OF POLAR LATITUDES

Figure 1a shows the geographical location of stations of the IMAGE network (http://space.fmi.fi/image/). The polar magnetic bays discussed in this work were observed at the Svålbard archipelago under absence of the geomagnetic disturbances at continental stations. The Bear Island station (BJN, 71.4° MLAT) is an intermediate station between the archipelago and the continent. To the south of the island, lies the sea on whose shore the Nordkapp continental station (NOR, 68.2° MLAT) is located. If magnetic bays are observed at BJN but not at NOR, the midpoint between points BJN and NOR (i.e., near 70° MLAT) can be considered the conventional low-latitude boundary of the appearance of magnetic bays.

The magnetogram presented in Fig. 1 shows an example of a typical morning polar magnetic bay recorded on the IMAGE network in the form of a negative disturbance with a smooth start and an equally smooth end, with no sharp pulsed intensifications. The absence of geomagnetic disturbances in lower auroral latitudes indicates the considered bay is not a result of the polar expansion of an auroral substorm. Like nighttime polar substorms, it was recorded along a contracted oval. Both nighttime polar substorms and morning polar bays are normally observed at the low solar wind speed ($V < 450$ km/s).

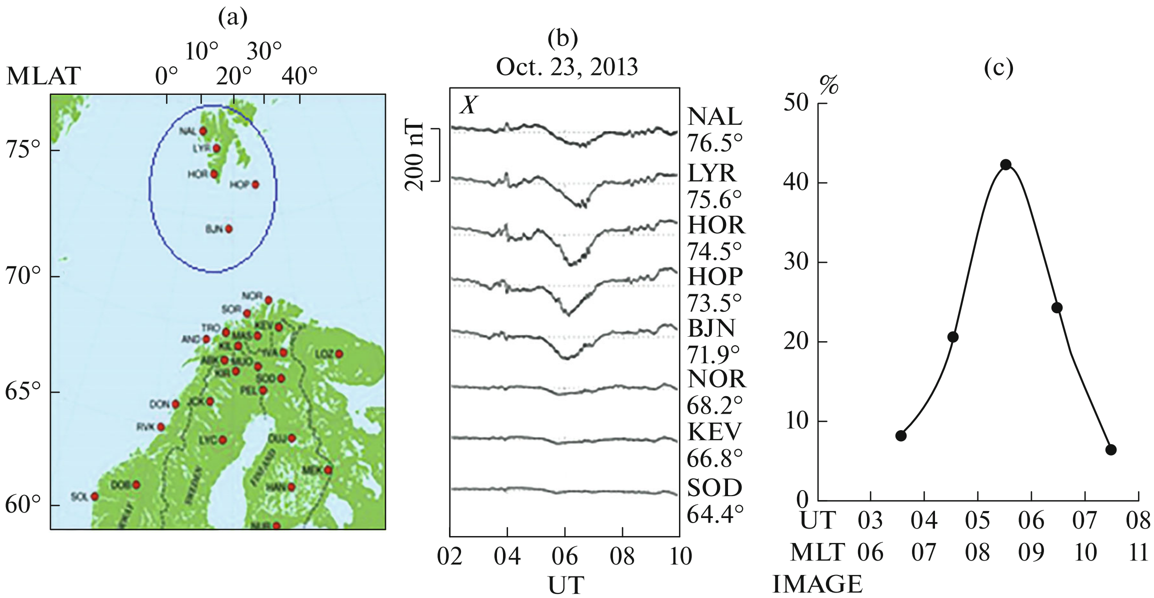

Fig. 1. (a) Map of stations of the Scandinavian IMAGE network showing the areas in which morning polar bays were observed. (b) Example of a morning polar bay magnetogram; on the right, codes and geomagnetic latitudes of the stations. (c) Diurnal variations in the formation of morning polar bays.

The maximum amplitude of a morning polar bay is usually on the order of 200–300 nT, and they last no more than 2 h. Figure 1c shows the diurnal variation in the appearance of morning polar bays during 112 events in 2006–2017. We can see a clear maximum at 08–09 MLT (i.e., in the morning).

The planetary distribution of geomagnetic activity during morning polar bays was studied using magnetic recording data from 66 communication satellites of the AMPERE (Active Magnetosphere and Planetary Electrodynamics Response Experiment) project operating simultaneously at heights of 780 km [10]. Our work employed public AMPERE project data presented on the website http://ampere.jhuapl.edu/products in the form of 10-min summarized geomagnetic disturbances distribution maps constructed according to results from spherical harmonic analyses of magnetic measurements and field-aligned current distributions calculated from these data. Currents flowing into the ionosphere are shown in blue on the maps. Those flowing out are shown in red.

During the period of recording by AMPERE satellites in 2010–2017, 48 cases of morning polar magnetic bays were identified at high-latitude stations of the IMAGE profile (BJN–NAL).

Analysis of the planetary geomagnetic activity distribution during the studied morning polar magnetic bays shows they can originate from such disturbances in the high-latitude magnetosphere as daytime polar bays, nighttime substorms, and convective bays. Let us consider these in more detail.

Daytime Polar Bay-Like Disturbances

The authors of [11–13] found that under northward the interplanetary magnetic field (IMF)—i.e., during quiet conditions, when the auroral oval is contracted and shifted to the pole—magnetic bay-like high-intensity disturbances can be observed in the daytime sector of the polar latitudes. Their temporal variations and signs are usually controlled by the *By* component of the IMF, as was shown in, e.g., [13–15]. They were referred to as *DPY*-variations in [4].

Analysis of AMPERE data shows that the ionospheric electrojet responsible for midday polar magnetic bays and enhanced field-aligned currents can be observed in a fairly wide daytime longitude range from the morning to the afternoon sector of polar latitudes. It can be recorded on the Earth's surface as a negative magnetic bay in the morning sector of polar latitudes. An example of such an event is shown in Fig. 2a. The left panel presents magnetograms of high-latitude stations of the IMAGE profile in which the development of the morning magnetic bay at 04–06 UT at Svålbard at latitudes above ~70° MLAT is seen. The right panel shows maps of the planetary distribution of electrojets and field-aligned currents constructed using data from a spherical analysis of magnetic measurements on AMPERE satellites during that bay. We can see from the plots that this morning bay was a result of the azimuthal development (expansion) of the daytime polar electrojet to the morning sector. Unfortunately, there were no ground-based measurements in the daytime sector of polar latitudes during this event. It is clear

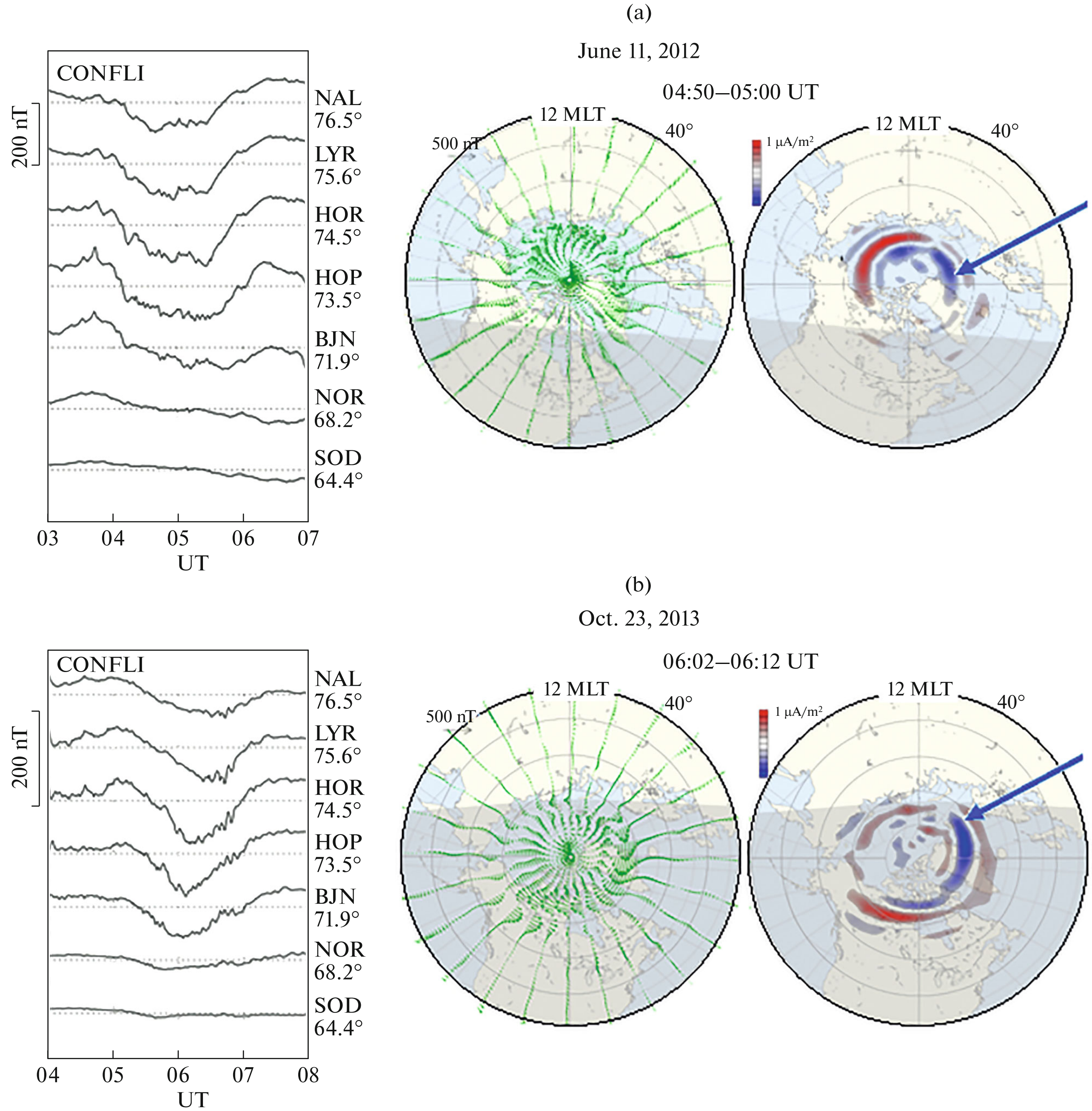

Fig. 2. (a) Example of a morning polar bay (left panel) and the global distribution of magnetic disturbances and field-aligned currents (right-hand panels; the upward currents are shown in red; the downward currents, in blue) according to data of the AMPERE project. (b) The same for a morning polar bay that is an azimuthal expansion of a nighttime auroral substorm.

from AMPERE maps that this event developed over open space of the Arctic Ocean.

Among the considered 48 events of morning polar magnetic bays, such situations were observed in six events, all of which were recorded in summer. Five were observed at a stable negative *By* component of the IMF. In one event, the *By* component turned from around –3 to +6 nT during the considered interval.

Nighttime Substorms

It is well known that magnetospheric substorms developing in the nighttime sector can also be observed in a wide interval of longitudes from the evening to the morning sector. The morning polar magnetic bays recorded in the IMAGE profile could therefore result from the azimuthal expansion of nighttime disturbances to the morning side. To demonstrate this, we must consider the distribution of geomagnetic activity on a global scale, as was done in the previous section.

A result from such an analysis with using global maps of the AMPERE project is shown in Fig. 2b for the morning polar magnetic bay recorded on October 23, 2013, by the IMAGE network (the magnetograms in the left part of Fig. 2b).

As seen on the AMPERE maps (Fig. 2b, right), the westward electrojet and enhanced field-aligned currents were observed at that time from the evening sector to the late morning sector. A classical substorm in which the high-latitude westward electrojet was accompanied by a lower-latitude eastward jet was observed at that time in the after midnight sector of the Earth (~00–01 MLT). This is typical of the current wedge of a substorm. The westward electrojet was also observed in the late morning sector during the considered event. We can see an interesting feature: the currents flowing out in the premidnight sector of the substorm development (shown in the maps in red) were more intense than those flowing in (shown in blue). The reverse was observed in the morning sector where the morning polar bay was recorded: the downward currents were more intense than those upward.

According to data from ground-based SuperMAG magnetometers, a substorm occurred at ~05:30 UT over Canada and Greenland. The most intense disturbances were over Greenland (i.e., in the after midnight sector). The central meridian of the current wedge was between the STJ (MLAT = 52.6°; MLON = 31.6°) and VAL (MLAT = 49.1°; MLON = 70.4°) stations; the western edge, near the STJ station; and the eastern edge of the current wedge, near the ODE (MLAT = 42.1°; MLON = 104.5°) station (the SuperMAG magnetograms are not shown). Thus, we see that the current wedge expanded from St. Johns station to Odessa, i.e., to the meridian at which IMAGE stations are located. Morning polar bays recorded at high-latitude IMAGE stations in this event were therefore an extension of the nighttime substorm to the morning sector.

There were five such events in the considered period when the enhanced electrojet and field-aligned currents were recorded at the IMAGE station according to AMPERE data in the nighttime and morning sectors, but were not in the afternoon and early evening sectors during the development of the morning polar bay.

Convective Magnetic Bays

It is known that plasma convection in the form of a twin-vortex structure [16] with vortex centers in the morning and evening sectors and enhanced with an increase in the southward IMF is almost permanently observed in the high-latitude ionosphere. Long (several hour) periods of the stable state of the southward IMF favor a continuous input of energy to the magnetosphere's tail and the establishment of the regime of the so-called steady magnetospheric convection (SMC) discussed in, e.g., [17–19]. Individual intensifications of it were called a convective bay in [20].

There are considerable differences between a classical magnetospheric substorm and a convective bay [20–23]. In contrast to a convective bay with a gradual beginning, a classical substorm is characterized by a sudden onset with an auroral breakup accompanied by the formation of a substorm current wedge [23, 24] that is the *DP*1 single-vortex ionospheric current system [24] observed in the near-midnight sector. A convective bay is a development of the twin-vortex current system *DP*2 with vortex centers in the morning (westward electrojet) and evening (eastward electrojet) sectors, as shown in the scheme presented in Fig. 3a [22].

The morning polar magnetic bays observed at Svålbard had a gradual beginning with a considerable poleward shift; i.e., they were similar to convective bays in morphological characteristics. The planetary distribution of high-latitude geomagnetic activity according to AMPERE data was used to determine whether the recorded bay-like morning polar disturbances were convective bays. Analysis of these data showed that most of the considered 48 events were a complicated picture of the superpositioning of individual intensifications in different time sectors simultaneously. There were only five pure cases in which disturbances were observed simultaneously only in the morning and afternoon sectors typical of enhanced convection as in the scheme in Fig. 3a, and were missing in the nighttime sector. The map of the planetary distribution of the high-latitude magnetic disturbances during one such event on June 17, 2013, is presented on the right in Fig. 3a. The corresponding IMAGE magnetogram is presented in Fig. 4a.

This distribution corresponds fully to the scheme of the planetary electrojet distribution during a convective bay (on the left in Fig. 3a), when a westward electrojet (a negative magnetic bay) develops in the morning sector and an eastward electrojet (a positive magnetic bay) develops in the afternoon sector. Figure 3a also shows that negative values of the *Bz* component of the IMF (i.e., the southward IMF) were observed that day several hours before the morning substorm, which is typical of a convective bay [19, 20, 22].

Superpositioning of Different Sources

Analysis of observations showed that the most (32 events of 48) of the morning polar negative magnetic bays were superpositionings of disturbances caused by interaction between nighttime substorms and convective phenomena, the separation of which is a very complicated (and not always solvable) problem, especially under disturbed conditions. Figure 3b presents an example of one such complicated case (December 7, 2015) where geomagnetic disturbances were recorded on AMPERE maps in the morning,

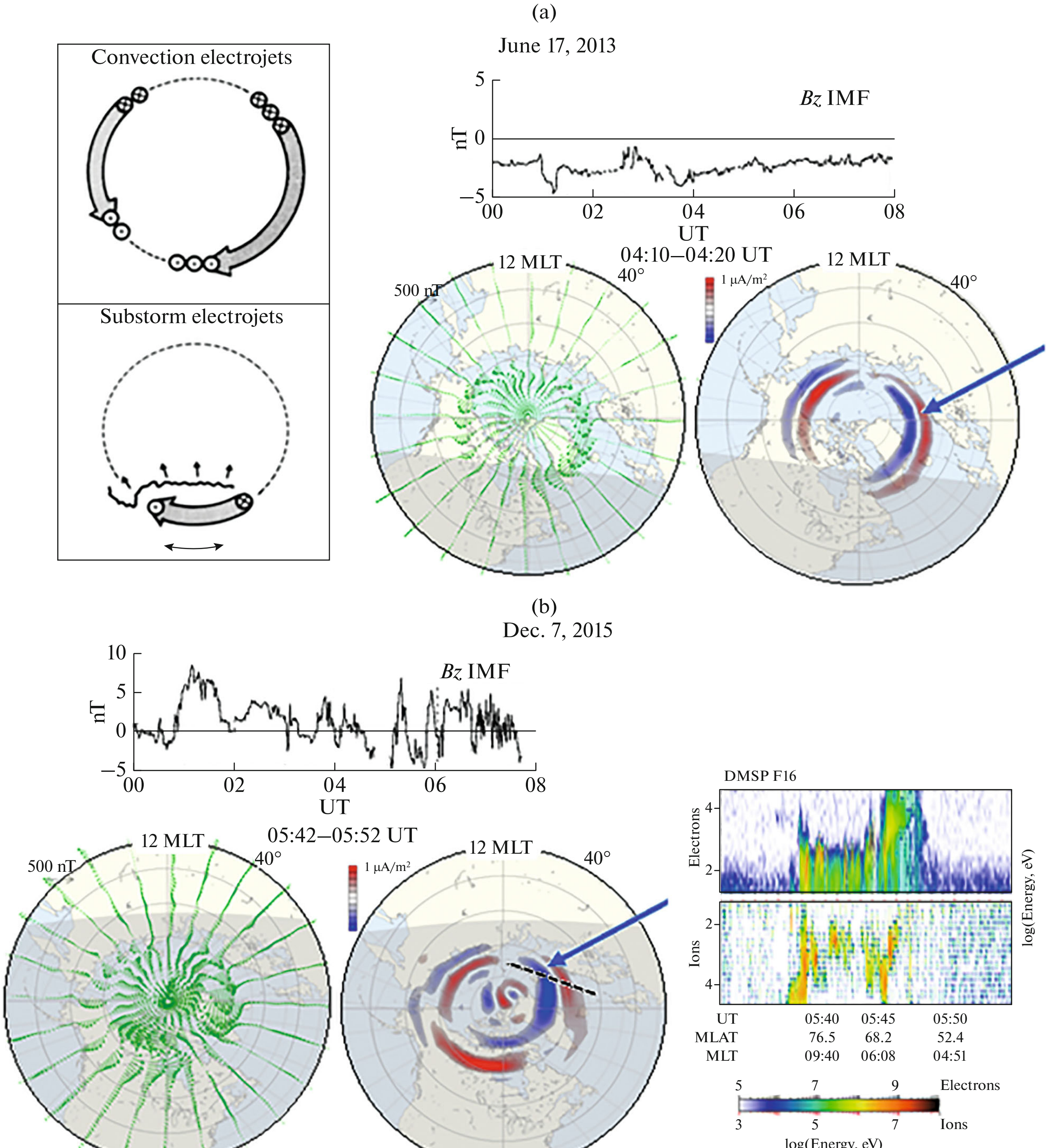

Fig. 3. (a) The upper left panel shows the electrojet distribution for a convective bay and a classical substorm in [22], an example of the global distribution of magnetic disturbances and field-aligned currents according to AMPERE data, and variations in the IMF *Bz* during the convective magnetic bay. (b) The same for the complicated event of the morning polar bay on Dec. 7, 2015, and measurements of precipitating electrons and ions on the DMSP F16 low-apogee satellite.

evening, and afternoon sectors simultaneously. In the AMPERE map in Fig. 3b, we can see the westward electrojet in the premidnight sector was accompanied by an intense eastward electrojet at lower latitudes, which is typical of the current wedge of a substorm.

This event was observed during the passage of a high-speed solar wind flux (the solar wind speed was ~600–650 km/s). A jump of the dynamic pressure was also recorded. The resulting complicated event can be presented as a superpositioning of magnetic distur-

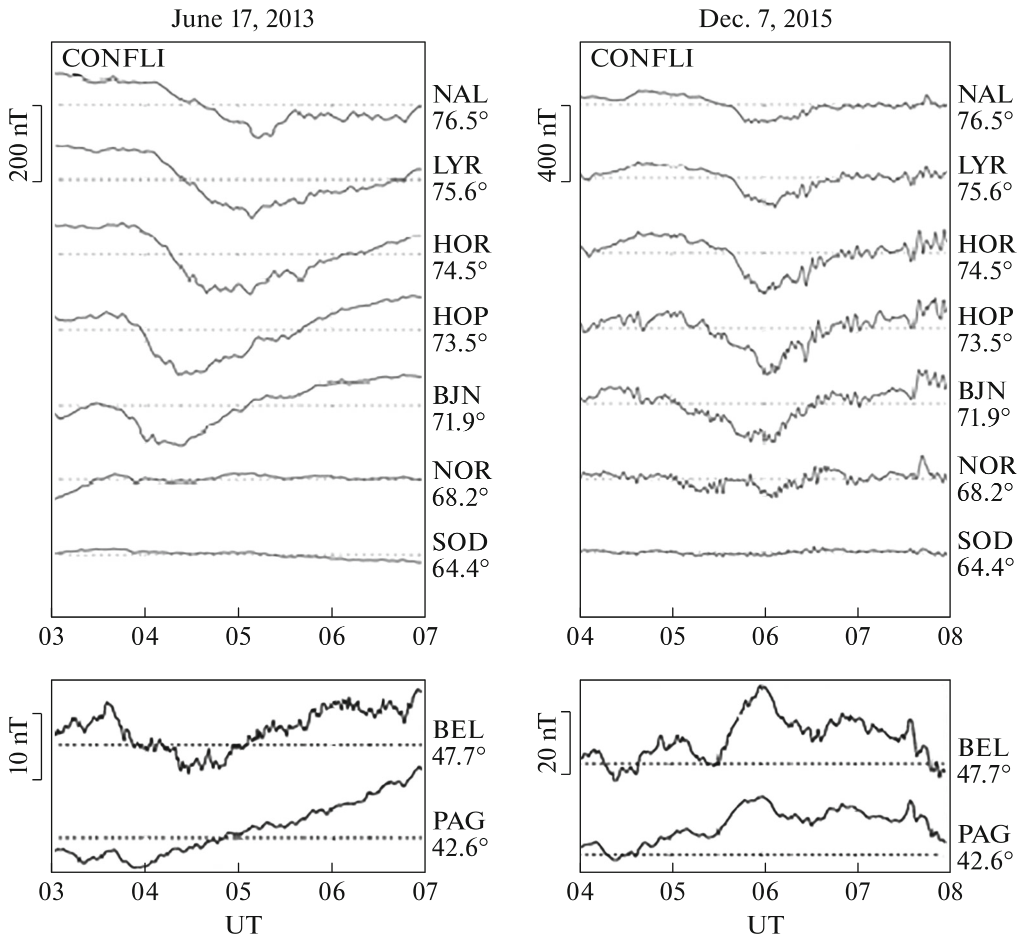

Fig. 4. Magnetograms of morning polar bays considered in Fig. 3 (June 17, 2013, and Dec. 7, 2015) and their midlatitude effects.

bances caused by the interaction between the nighttime substorm and convective phenomena.

This example was also chosen because the DMSP F16 low-apogee (~830 km) satellite [25] measuring the fluxes of precipitating electrons and protons at that time crossed ionospheric heights over Svålbard in the start of a morning polar bay. The descending part of the flight is shown schematically in Fig. 3b. The satellite first crossed the region of downward field-aligned currents (shown in blue) and then the region of upward currents (shown in red). The spectrograms of precipitating particles obtained by the F16 satellite (http://sd-www.jhuapl.edu/Aurora/spectrogram) are shown in Fig. 3b. We can see there was considerable enhancement of precipitating electrons at 05:45 UT, when the satellite crossed the region with the center of ~70° MLAT corresponding to the location of upward field-aligned currents (the middle panel in Fig. 3b).

It is known (e.g., [26]) that the formation of a three-dimensional substorm current wedge whose central part corresponds to the meridian of the start of the explosive phase of the substorm in the nighttime sector is accompanied by the formation of nighttime midlatitude positive magnetic bays. Our objects of study were the morning polar magnetic bays which maximum was observed at 08–09 MLT. This longitudinal sector is not projected to the magnetosphere tail where the substorm current wedge formed, so it is not surprising that a comparison of the formation of morning polar bays on the IMAGE network with simultaneous geomagnetic observations at the midlatitude Belsk (BEL, 47.7° MLAT) and Panagyurishte (PAG, 42.6° MLAT) stations in the longitudinal sector of the IMAGE network revealed no morning positive midlatitude bays in the overwhelming majority of cases. Neither were morning convective bays accompanied by midlatitude effects. An example of such an event is presented in Fig. 3a, and the absence of its midlatitude effect is shown in Fig. 4a.

In individual events, however, when substorm disturbances (an enhanced westward electrojet accompanied by the development of an eastward electrojet at lower latitudes, which is typical of the substorm current wedge) were observed in the nighttime sector during morning polar bays on the IMAGE network according to AMPERE satellite recording data, morning polar bays were accompanied by the formation of positive magnetic bays in Belsk (usually with amplitudes of 10–15 nT) and in Panagyurishte (about 6–10 nT).

One such event (December 7, 2015) is shown in Figs. 3b and 4b. It is difficult to uniquely determine the current wedge by ground data for this event because there are few stations in the required sector. According to SuperMAG data, however, a substorm did develop close to midnight in the nighttime sector over Canada. According to data from ground-based magnetometers, the central meridian of this substorm was close to the meridian of the Ottawa station (OTT, MLAT = 54.98°; MLON = 2.5°). The western edge of the current wedge was at the meridian of the T16 Carson City station (MLAT = 44.77°; MLON = –55.5°), and the eastern edge cannot be determined precisely because there were no stations in the required sector (the magnetograms of the SuperMAG stations are not shown). AMPERE data (Fig. 3b) also show an intense eastward current was observed at that time in the nighttime sector of the Earth to the South from the westward electrojet, which is a typical picture of the development of a current wedge of the substorm developing in the nighttime sector. It expanded throughout North America, from the west to the east. We can see that morning bays (08–09 MLT) were not related to this substorm but formed an individual phenomenon. In Fig. 4b, we can also see a morning positive magnetic bay was observed during the morning polar magnetic bay on the IMAGE network at the middle latitudes of the same longitude sector, and it is difficult to believe it was related to the near-midnight substorm current wedge.

The formation of a morning positive magnetic bay at middle latitudes during the development of a morning polar (negative) bay in the same longitude sector is not infrequent. It was observed in 18 events in 2010–2017 (i.e., in almost half the complicated cases of morning polar bays recorded at Svålbard). We hope that future detailed investigations of these events will allow us to understand their nature.

CONCLUSIONS

Analysis of ground-based high-latitude observations on the IMAGE magnetometer network and a comparison of results obtained with the AMPERE satellite recording of the spatial distribution of the planetary geomagnetic activity shows the morning polar magnetic bays observed at Svålbard could originate from the spatial current inflow to the morning side of the nighttime or daytime polar electrojets, and from generation of convective magnetic bays. The most frequent situation is the simultaneous development of classic nighttime substorms and convective polar bays.

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CONFLICT OF INTEREST

The authors declare that they have no conflicts of interest.

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