



Case Study of a Large Mesospheric Front in Polar Mesospheric Clouds

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ABSTRACT

A large mesospheric front structure was observed on 16 July 2010 in Polar Mesospheric Clouds (PMCs) using common volume observations performed by the Aeronomy of Ice in the Mesosphere (AIM) Cloud Imaging and Particle Size (CIPS) instrument and the Odin Optical Spectrograph and Infrared Imager System (OSIRIS) at $\sim 75^\circ\text{N}$, 144°E . During the 4.5 hours long observation time, the front structure manifested in the PMC layer as an ice free elongated structure with sharp edges to the surrounding cloud field. A propagation direction from Southeast to Northwest and simultaneous clockwise rotation of $12^\circ/\text{hour}$ are observed and the horizontal extent of the structure is found to be about 1800 km long and 190 km wide. Common volume observations of the mesospheric environment in terms of temperatures and water vapor provided by the Odin Sub-Millimetre Radiometer (SMR) indicate an extensive elevated warm air mass during the occurrence of the front structure and colder temperatures at the sharp front edge. The presence of a wave structure with $\lambda_z \sim 6$ km at the altitude of 70–90 km coincides with a sharpening of the front edge. We compare the general characteristics of the current mesospheric front to earlier reports on mesospheric fronts based on ground-based and space-borne airglow and PMC observations.

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1. INTRODUCTION

Polar Mesospheric Clouds (PMCs) form in a region of the atmosphere that is constantly modulated by waves of different scales and often display a large variety of continuous wave patterns and complex structures. These structures carry valuable information about the dynamics of the mesosphere since the structures are believed to be caused by forcing from lower atmospheric regions (Dalin et al., 2016; Thurairajah et al., 2017) or generated in situ (Baumgarten and Fritts, 2014), and as such, have been used for more than a century to explore the mesospheric environment. PMC structures form as a result of wave induced density modulations, vertical displacement or sublimation due to local warming of the atmosphere. Airglow imaging is a standard technique for analysing gravity waves (GWs) and other dynamical structures in the mesosphere. In a similar way, observations of PMCs from the ground or from space can be used for analysing processes in the middle atmosphere. However, there is a fundamental difference between using airglow and using PMC as an observational tool. Airglow processes are governed by photochemical processes with time constants shorter than typical wave periods. Hence, airglow emissions largely provide an immediate and reversible response to wave activity. PMCs, on the other hand, are governed by microphysical processes with larger time constants, in particular connected to the sublimation or growth of cloud particles. This causes PMCs to respond in more complex and non-reversible ways to dynamic activity. Wave effects like vertical displacement or temperature variation will therefore imprint themselves onto the cloud, leading to features that are persistent over a range of different time scales and that can be advected with the cloud. In addition, PMC layers are often very thin in comparison to the OH airglow layer and hence the response to wave activity is more detailed. The use of PMC cloud structures to infer wave presence and to quantify waves and other complex structures is complicated due to vertical and horizontal mixing that dilute and distort the imprinted wave pattern. It is thus critical to understand how wave structures modulate the cloud and hence the appearance of the imprinted cloud structures seen from different remote sensing instruments. Also important to consider is the effect of horizontal transport by the background winds on the imprinted cloud structures.

While several studies have investigated small scale continuous wave features in PMCs using satellite observations (Chandran et al., 2010; Thurairajah et al., 2017; Rong et al., 2018), and ground based observations (Pautet et al., 2011; Kaifler et al., 2013; Baumgarten et al., 2012), only a few studies have analysed larger structures such as mesospheric fronts. Mesospheric fronts are large scale front structures caused by wave disturbances that form in the upper mesosphere or lower thermosphere

and are manifested as sharp brightness jumps in airglow, sometimes followed by a series of trailing waves (Brown et al., 2004). Mesospheric fronts can be sub-classed into wall waves (Bageston et al., 2011; Swenson and Espy, 1995) or bores (Smith et al., 2003; Taylor et al., 1995; Medeiros et al., 2016; Fritts et al., 2020) depending on their characteristics and the stability of the background atmosphere. Mesospheric front structures have also been attributed to nonlinear gravity wave interaction (Shiokawa et al., 2003) and ducted gravity waves (Isler et al., 1997). It is now well established that a bore needs stable atmospheric conditions in which the structure can propagate horizontally. Such conditions can be established by a thermal ducting region, a large wind shear or a combination of both (Brown et al., 2004). Simultaneous observations of temperature and wind conditions are therefore of absolute necessity to estimate the intrinsic wave parameters and also investigate the presence of a ducting region. However, even if simultaneous wind observations are not available, a front event can still be classified as a mesospheric front if other characteristics are fulfilled, as shown in Bageston et al. (2011). Wave fronts can also show non-linear appearance. Hozumi et al. (2018) for the first time reported on a spectacular undulating mesospheric wave front of a mesospheric bore observed in airglow using the Visible and near Infrared Spectral Imager (VISI) instrument. The horizontal extent of the bore perpendicular to the propagation direction was 2200 km and the wavelength of the undulation was 1000 km. Seyler (2005) and Laughman et al. (2009) investigated the generating mechanism of mesospheric bores using a model and showed how a wave front with a long horizontal wavelength can sharpen in a thermal duct and form a sharp wave front similar to a bore. Yue et al. (2010) reported on such an event using ground-based observations and additionally showed that GWs can generate bores that can propagate horizontally in a ducting region.

While numerous studies have reported on bore events in airglow, only a few studies have reported on observations of such structures in PMC. The first observation of a mesospheric front in PMC was reported by Dubietis et al. (2011) using ground-based photography. They identified the structure in the cloud field as a solitary wave of length ~200 km with sharp boundaries. Using the Cloud Imaging and Particle Size (CIPS) instrument on the Aeronomy of Ice in the Mesosphere (AIM) satellite Thurairajah et al. (2013) reported on 3 observations of isolated bands of bright clouds with horizontal extent of 500–1000 km over 78°N to 81°N in three consecutive orbits in the NH 2007 season. Based on the appearance to act as a boundary between different air masses, the authors referred to these structures as mesospheric fronts. They additionally estimated the front lifetime and propagation speed to at least 90 minutes and ~60 m/s. Due to the apparent resemblance to tropospheric fronts,

the authors hypothesized that the formation mechanism of mesospheric fronts could be similar to tropospheric fronts (i.e., different airmasses, gust fronts or dynamic instabilities such as roll clouds), however due to the lack of simultaneous observations of background conditions, this could not be evaluated further. Dalin et al. (2013) reported on a mesospheric front event in PMCs using ground-based digital cameras where the length of the front was ~ 322 km and the elevation of the front jump showed a spectacular height of 12 km from the undisturbed PMC at about 84 km to 96 km. Simultaneous temperature observations showed a large temperature difference of 20–25 K at 85 km between the two different air masses, which the authors concluded was responsible for the observed front. A temperature difference of 20 K between a cloud region and cloud free region separated by a PMC front was also recently reported by Thuraijrah et al. (2021).

In this study, we present a case study of a large mesospheric front structure observed simultaneously in PMC by the CIPS instrument and the Optical Spectrograph and InfraRed Imager System (OSIRIS) on the Odin satellite. The latter operated in a tomographic mode. CIPS PMC measurements provide two-dimensional horizontal information in high resolution of the PMC brightness and microphysical properties, and thus give detailed information about the morphological features of the front. OSIRIS tomographic PMC measurements, on the other hand, provide vertical and horizontal cuts through the PMC layer and are thus complementary to CIPS which does not provide any vertical information. We additionally use common volume observations of temperature and water vapor from the Sub-millimetre Radiometer (SMR) also onboard Odin to study the relationship between the state of the mesospheric environment and the observed front structure.

In section 2 the instruments are presented together with an overview of the common volume observations. Section 3 presents the PMC observations of the front structure from CIPS and OSIRIS and the mesospheric environment in terms of SMR temperature and water vapor in the close vicinity and surroundings of the structure. Section 4 describes CIPS wave analysis. Section 5 presents a broader view of the background environment in terms of planetary wave analyses based on the Aura Earth Observing System (EOS) Microwave Limb Sounder (MLS), and mesospheric winds. In section 6 we discuss the findings in relation to mesospheric fronts previously reported on in airglow and PMC. Finally, we provide our conclusions in section 7.

2. INSTRUMENTATION

2.1. CIPS ON AIM

The AIM satellite (Rusch et al., 2009) was launched in 2007 into a sun-synchronous orbit near 600 km. AIM

has two operating instruments, the Solar Occultation for Ice Experiment (SOFIE) (Gordley et al., 2009) and the high-resolution UV panoramic imager CIPS (McClintock et al., 2009; Russell et al., 2009) consisting of four CCD detectors with a combined field of view of $120^\circ \times 80^\circ$. The camera suite images radiance scattered from PMCs and the background atmosphere in the UV centered at 265 nm. CIPS observes the clouds from up to seven different scattering angles which provide a direct measurement of the cloud scattering phase function used to derive particle size information (Bailey et al., 2009, 2015). The individual images are combined into about 15 orbit swaths per day separated by 95 min, where each swath covers about 8000 km along orbit track and 900 km across orbit track. CIPS PMC data products include cloud albedo, ice water content and particle size. Albedo is defined as the ratio of the scattered radiance to the incoming solar irradiance (10^{-6} sr^{-1}) (Rusch et al., 2009) and ice water content is the column ice mass (g km^{-2}). Detailed descriptions of CIPS retrieval algorithm and error analysis are provided by Lumpe et al. (2013) and Carstens et al. (2013). In the current work, we use CIPS version 5.20 level 2 cloud products albedo and ice water content which use a grid resolution of 7.5 km in the nadir.

2.2. OSIRIS AND SMR ON ODIN

The Odin satellite (Murtagh et al., 2002), launched in 2001, traverses a sun-synchronous polar orbit at around 600 km with ascending node at 18:00 LT. The orbit period of Odin is 95 minutes, allowing the satellite to complete 15 full orbits each day. Odin carries the Optical Spectrograph and InfraRed Imager System (OSIRIS) (Llewellyn et al., 2004) and the Sub-millimetre Radiometer (SMR) (Urban et al., 2007). OSIRIS consists of an atmospheric limb-scanning spectrometer that covers the 275–810 nm spectral range with a resolution of about 1 nm. By scanning the stratosphere and mesosphere, vertical profiles of atmospheric trace gases and ice layers are provided. PMCs are detected through enhancements of limb scattered sunlight and spectroscopy is used to infer particle size information (Karlsson and Gumbel, 2005; von Savigny et al., 2005).

In the current study, we use the Odin OSIRIS and SMR tomographic data sets. In a special tomographic mode, the Odin instruments were co-aligned and operated to only scan the mesosphere with short limb scans. By only covering the mesosphere, the distance between the subsequent limb scans decreased and a larger set of lines of sight through the PMC layer was provided. The extended information allows for an inversion of the data through a tomographic inversion technique (Lloyd and Llewellyn, 1989; D. Degenstein, 1999; D. A. Degenstein et al., 2003, 2004). The PMC properties are reported in terms of local cloud scattering coefficient, ice mass density, number density, and the Gaussian mode radius. The local cloud scattering coefficient ($\text{m}^{-1} \text{ sr}^{-1}$) is reported

in seven different wavelength bands between 277.3 and 304.3 nm (see Table 1 in Karlsson and Gumbel, 2005) and ice mass density is the *local* ice mass in unit ng m^{-3} . Detailed descriptions of the OSIRIS tomographic retrieval algorithm and error analysis are provided by Hultgren et al. (2013) and Hultgren and Gumbel (2014). Megner et al. (2018) provides an evaluation of the OSIRIS PMC properties to model simulations and Broman et al. (2019, 2021) provide comparisons of OSIRIS PMC albedo, ice water content, and particle sizes to CIPS together with an extended error analysis of the tomographic dataset. The grid used for the tomographic PMC data is $(0.5^\circ \times 500 \text{ m})$ (Angle Along Orbit $\times$ altitude), where the Angle Along Orbit (AAO) denotes the position of the OSIRIS tangent point along the satellite orbit and the altitude ranges from 76 km to 90 km. The OSIRIS tomographic PMC data are available for selected days over the northern hemisphere PMC seasons 2010, 2011, and 2012 and for southern hemisphere PMC seasons 2012, 2013 and 2014.

The Odin Sub-Millimetre Radiometer (SMR) (Urban et al., 2007; Lossow et al., 2009) passively measures thermal emissions at the atmospheric limb in several microwave bands. Temperature and water vapor concentrations in the middle atmosphere are retrieved based on the emission line at 557 GHz. Tomographic SMR scans cover altitudes between 70 km and 90 km, which results in a vertical and horizontal resolution of 2.5 km and 200 km, respectively. The tomographic retrieval of water vapor and temperature from an optimal estimation method results in a precision of 0.2 ppmv for water vapor and 2 K for temperature (Christensen et al., 2015, 2016).

2.3. CIPS, OSIRIS AND SMR COMMON VOLUME

The Odin tomographic orbits during 2010 and 2011 were planned to provide optimal temporal coincidence between Odin and AIM to deliver true common volume observations of PMCs and their background atmosphere at about 80°N . At this latitude the instruments perform common volume observations within the narrow coincidence criteria of only 5 minutes for 45 satellite overpasses during 3 consecutive days each month during June, July and August when the satellites are in ascending node. At 80°N , the orbits cross almost perpendicular, producing a common volume where the vertical-horizontal footprint of OSIRIS and SMR are within the horizontal image plane of CIPS. The reader is referred to Broman et al. (2019) for details on the CIPS/OSIRIS common volume definition and uncertainties. The front structure was identified in the CIPS PMC level 2 orbit swaths during four consecutive orbits on 16 July 2010 (AIM orbits 17554, 17555, 17556 and 17557) over the Arctic Ocean north of Siberia. The same structure has also been identified in the OSIRIS PMC data in the coinciding Odin orbits (51234, 51235, 51236, 51237). Common volume observations with SMR provide complementary information of temperature and humidity inside the front structure and are also used to analyse the general state

of the background atmosphere during the front event. The common volume observations with CIPS, OSIRIS, and SMR occur at a local time around 15.45, implying that the combined observation volume progresses westward with time.

3. MESOSPHERIC FRONT OBSERVATIONS

3.1. CIPS PMC FRONT OBSERVATIONS

The four panels of [Figure 1](#) show CIPS PMC albedo in the four orbit swaths in which the front structure has been identified, each separated by 96 minutes. The orbit start times of these orbits are 02:11 UTC, 03:47 UTC, 05:24 UTC and 07:00 UTC, respectively. In orbit 17556, the front structure displays the most distinctive appearance as a very sharp edge in the cloud field that clearly separates a cloudy region from a cloud free region. In the rest of the paper, we will refer to the sharp cloud border as the ‘front edge’ and the whole cloud free region as the ‘front’ or the ‘front structure’. The front structure is identified in the first panel (orbit 17554) as the dark cloud free region extending from 70°N to 78°N . The extent could possibly be larger. However, the observation of the structure is limited by the coverage of the orbit strip. In the second panel (orbit 17555) a clockwise rotation of the structure has positioned it further westward, which enables a latitudinal view from 70°N to 85°N . In the third panel (orbit 17556), the front edge is sharp and horizontally aligned with a second cloud edge. The part of the front structure that CIPS covers has a width of $190 \pm 50 \text{ km}$ and a length of about 1800 km. The clockwise rotation of the structure prevails in combination with a westward movement. The latitudinal extent ranges from 75°N to 85°N . In the fourth panel (orbit 17557), the clockwise rotation has positioned the front to between approximate 78°N and 83°N . Like in the first orbit, the CIPS coverage does not allow a complete picture of the structure here. The boundaries to the surrounding cloud field are more diffuse, indicating mixing between the cloud free and the cloudy region or overlapping cloud layers. [Figure 2](#) shows the approximate location and extent of the front structure. A more detailed display of the progression of the front in the cloud field observed by CIPS is given in [Figure 3](#). The yellow dashed line marks the leading edge of the front at each time step, and the white line marks the trailing edge.

3.2. OSIRIS AND SMR FRONT OBSERVATIONS

The Odin satellite orbit crosses the front structure almost perpendicular to the crest of the front (as simultaneously observed by CIPS), i.e., along the propagation direction of the front. In [Figure 4](#), CIPS ice water content in the four consecutive orbits swaths is shown in color, focusing on the front region. The black crosses mark the center of each OSIRIS/SMR retrieval grid point of the coinciding Odin orbit. OSIRIS and SMR provide 2D fields (vertical

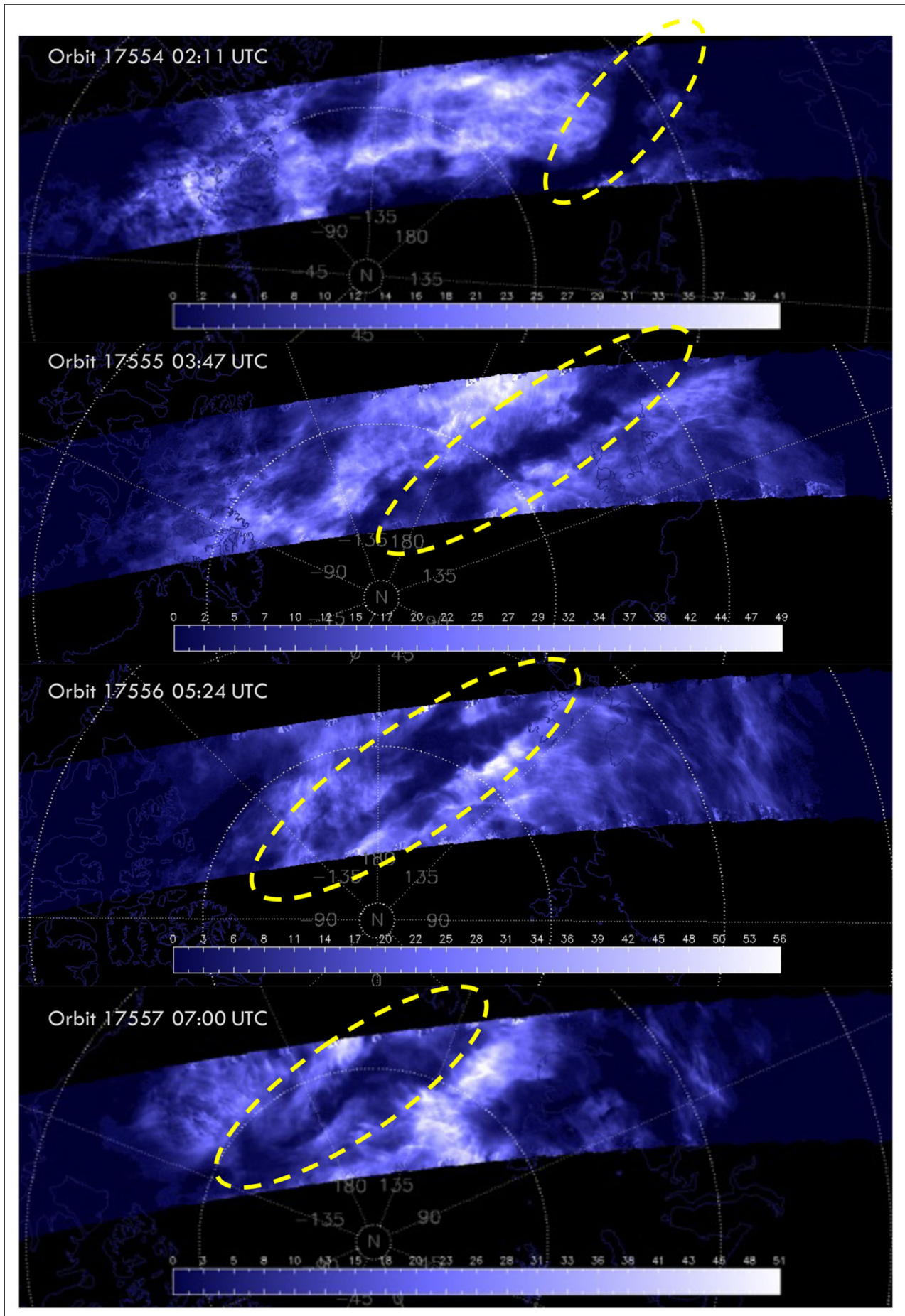


Figure 1 CIPS PMC cloud albedo observations during four consecutive orbits on 16 July 2010. The yellow dashed ovals indicate the dark front-like structure. Note the sharp front edge to the surrounding cloud field in orbit 17556.

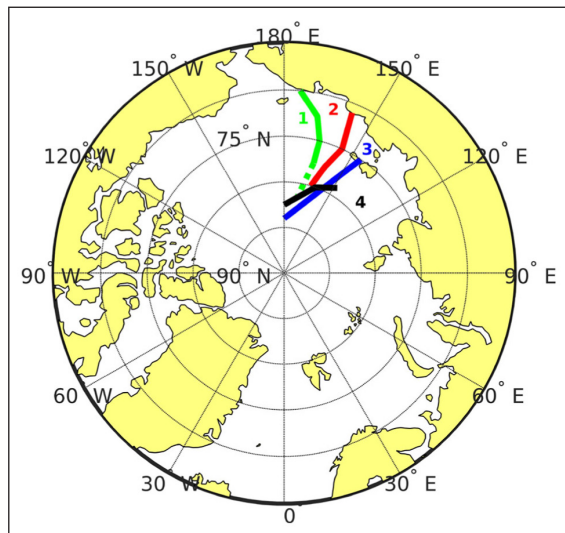


Figure 2 Approximate position of the front structure as observed in CIPS albedo. The numbers refer to the orbits in Figure 1, and the colored lines mark the position of the dark ice free region in each orbit. The view is limited by the CIPS coverage in each orbit swath, and the sketch shows only the part of the structure that is clearly visible. In the first orbit, we use the complementary OSIRIS PMC observations of the front to extend the front position to 78°N (indicated by dotted line).

and horizontal) of PMCs, temperature and water vapor in both the cloudy and cloud free regions on each side of the front edge. At the same time, CIPS provides nadir observations of the front and the surrounding cloud field. In order to relate the state of the background atmosphere to the front structure in the PMC field, it is convenient to combine the PMC ice water content as observed by OSIRIS with the background temperature and water vapor as observed by SMR in one figure. Since the tomographic OSIRIS and SMR observation grids are slightly different, the tomographic SMR temperature and water vapor data were first interpolated into the OSIRIS grid. **Figure 5** shows SMR temperature as filled colour contours combined with OSIRIS PMC ice mass density as black contours during the four consecutive Odin orbits (51234–51237) that coincide with the CIPS observations shown in **Figure 4**. The data presented in the four panels of **Figure 5** shows the time evolution of both PMC structure and temperature field in and around the structure. Note that the observation of the front occurs in ascending node for both satellites. The data presented in **Figure 5** is sampled along the satellite orbit shown in **Figure 4** and the direction of the x-axis is for this reason

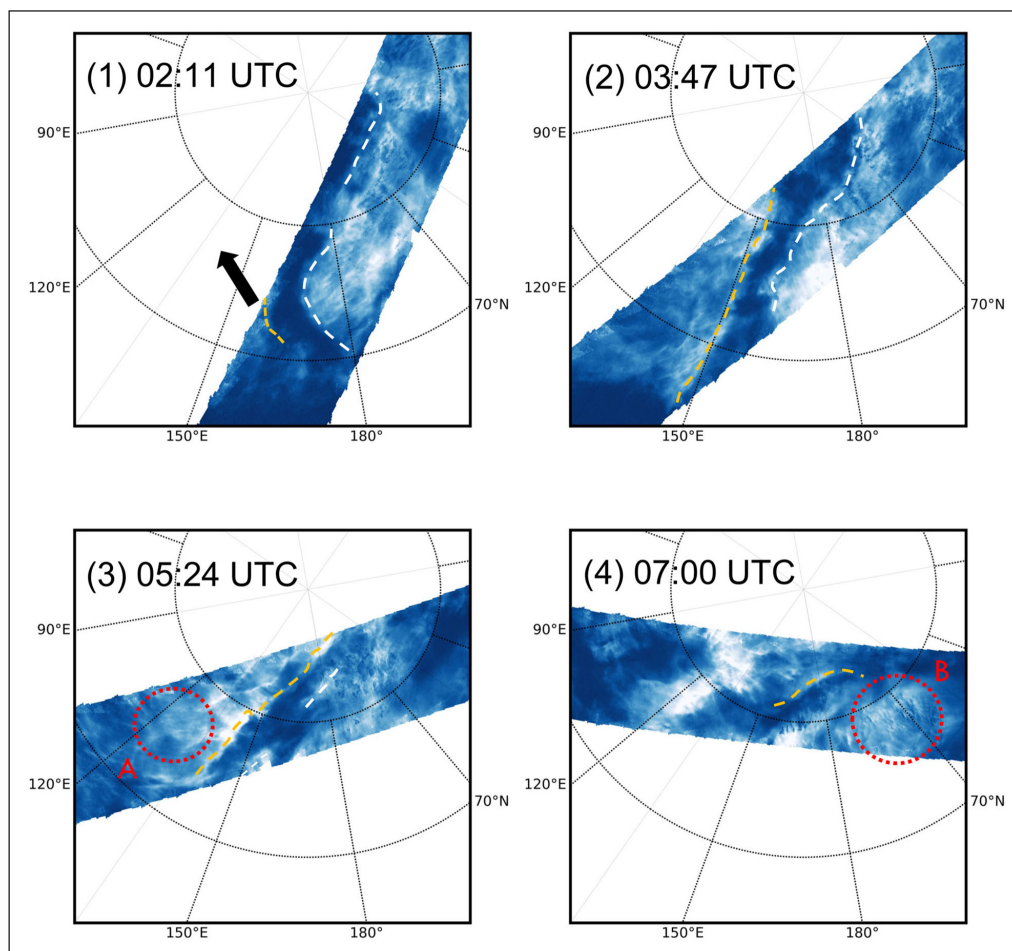


Figure 3 CIPS PMC albedo L2 data projected onto polar map plot centered at 170°E for 4 consecutive orbits showing the progression of the front region and location of regions with small scale waves. The yellow dashed line marks the leading edge of the front, and the white dashed line marks the trailing edge of the front. Red circles (A, B) marks regions of GW activity. The estimated background northwestward wind from tidal climatologies is indicated in top left plot.

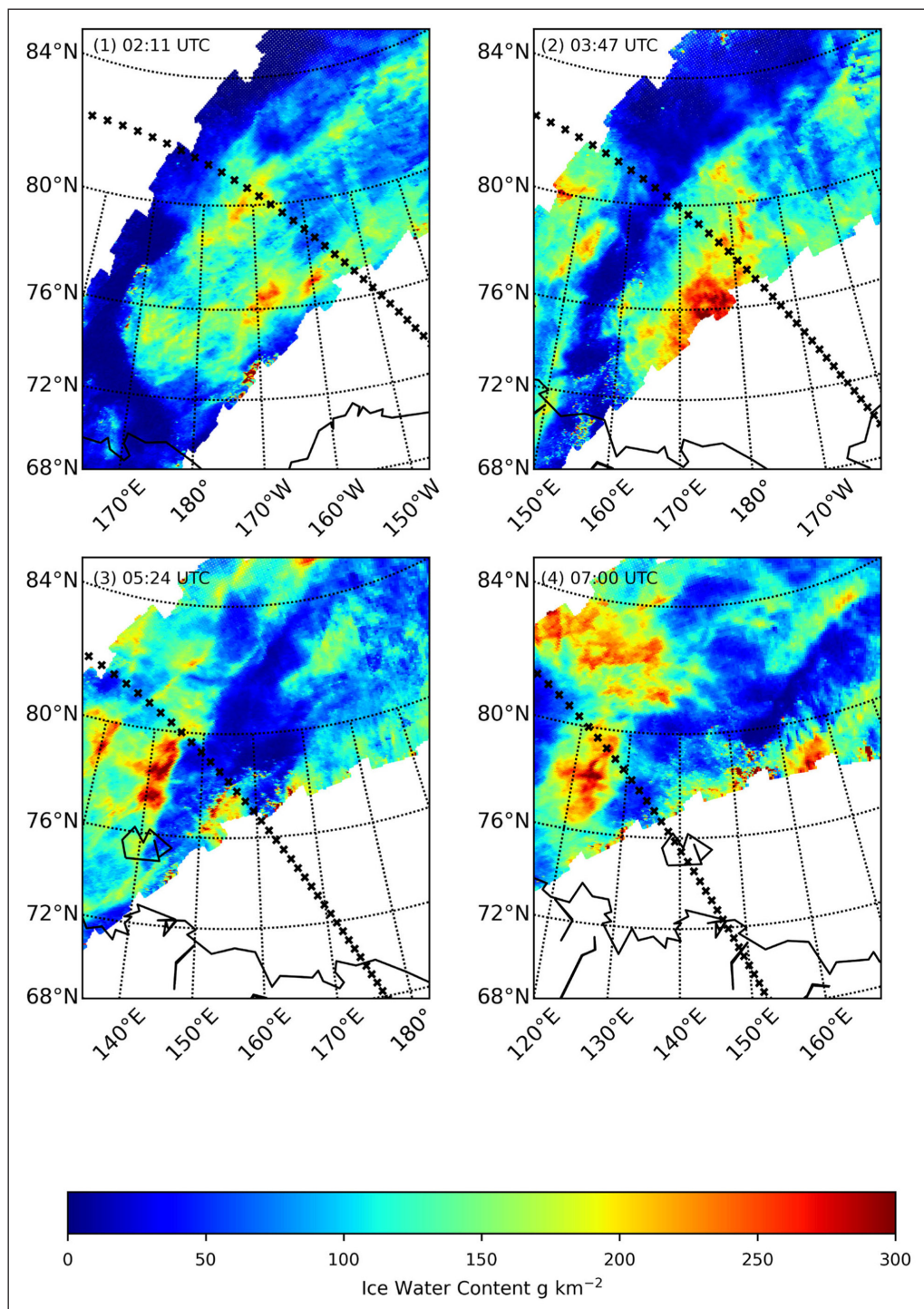


Figure 4 PMC ice water content obtained from CIPS for the four consecutive orbits swaths on 16 July 2010. The orbit start time for CIPS is indicated in each plot. The black crosses mark the position of the coinciding Odin orbit track.

reversed compared to [Figure 4](#). The dotted lines indicate the edges of the ice free (or almost ice free) region as observed by CIPS. Mean ice water content within the CIPS/OSIRIS common volume is shown with yellow (CIPS) and green (OSIRIS) lines for guidance only.

In the first panel (orbit 51234), the PMC field observed by OSIRIS consists of two extensive cloud regions, clearly separated by the same cloud free front region as identified in CIPS PMC albedo between 81.0°N to 82.4°N. Outside of the common volume with CIPS, the cloud layer between longitude 110°E and 150°E shows a tilted

structure. The temperature field indicates the presence of a relatively warm air mass situated at high latitudes between longitude 120°E to 210°E at altitudes about 78 km to 82 km. Also noteworthy in the front region at altitudes above about 85 km is the presence of a cold air mass. In the second panel (orbit 51235) OSIRIS observes the same ice free region as CIPS as indicated by the absence of ice contours between the dashed black lines. However, a thin ice layer at high altitudes is observed by OSIRIS in the front region. Again, the front region is coinciding with warmer air compared to the surroundings

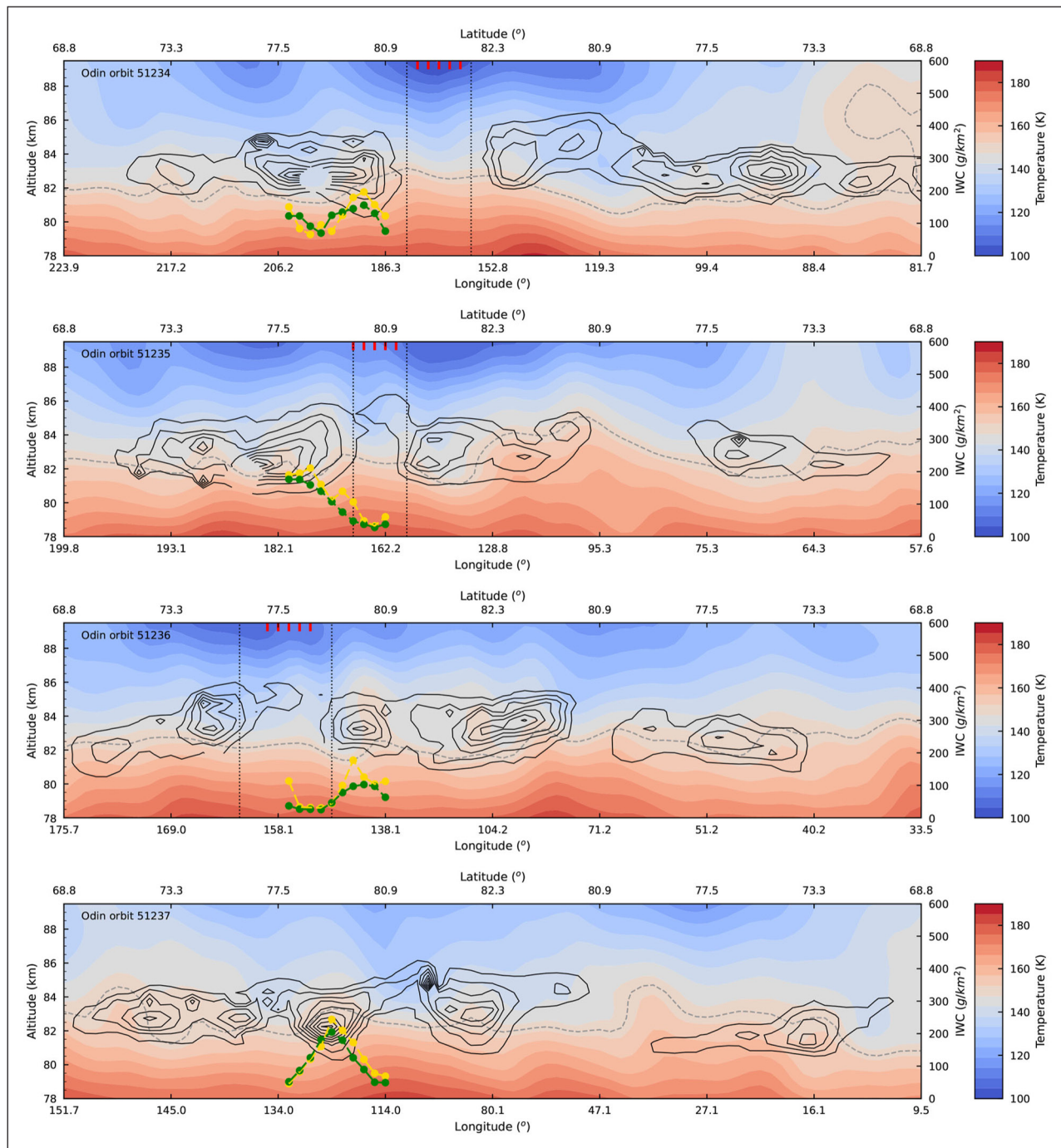


Figure 5 Temperature field from Odin SMR as filled contours combined with simultaneous observations of PMC ice mass density (IMD) from OSIRIS on July 16 2010 for the consecutive orbits 51234–51237. The dashed isoline marks 150 K, where cloud likely sublimates. The black IMD contours correspond to 10 ng/m³. The missing parts of the IMD contours imply missing data. For these retrieval pixels, the microphysical retrieval cannot provide cloud properties using the Ångström relation. CIPS IWC in the common volume is plotted with yellow line and OSIRIS IWC is plotted with green line (right y-axis). Red ticks on upper x-axis denote profiles used in Figure 8.

at lower altitudes, and a cold region at higher altitudes. The results presented in the third panel (orbit 51236) are interesting. OSIRIS provides complementary vertical information to the sharp front edge at 144°E. The cloud patch on the other side of the cloud free frontal exhibits a slope with increasing cloud altitude towards higher latitudes. Furthermore, the temperature field indicates several short scale fluctuations in the front region at altitudes above the clouds and lower temperatures at the sharp front edge. In the fourth panel (orbit 51237)

OSIRIS ice mass density show an increase in clouds. The front structure is still present in CIPS PMC albedo over a large spatial domain in the orbit swath, however, this is outside of the common volume with OSIRIS.

Figure 6 displays SMR water vapour as coloured contours combined with OSIRIS ice mass density contours for the same orbits. During the first front observation (Odin orbit 51234) high concentrations (above 8 ppm) of water vapour are present in the front region at 81–84 km altitude and extend under the elevated cloud layer towards lower

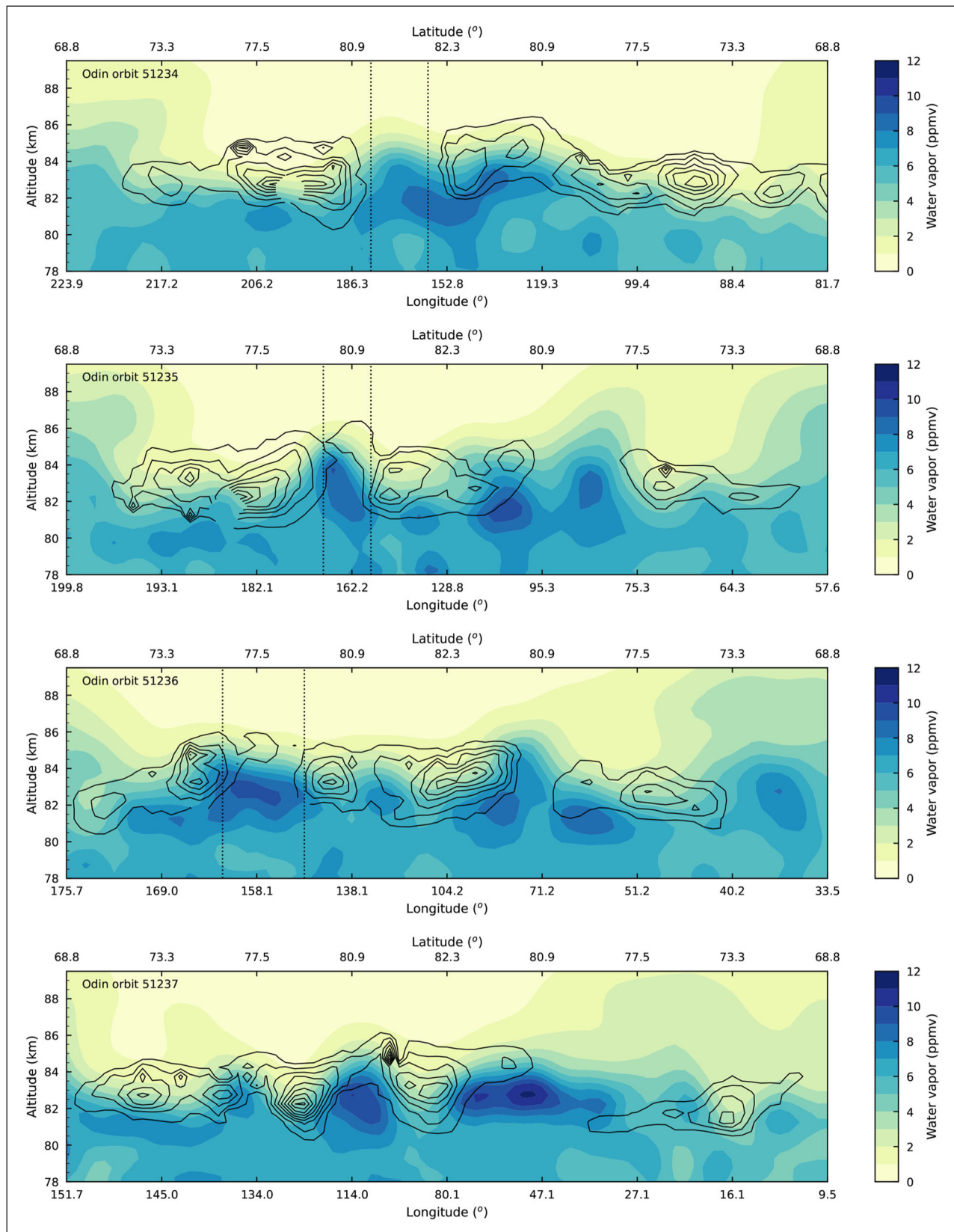


Figure 6 Odin SMR Water Vapor as coloured contours combined with OSIRIS ice mass density as black contours. The dashed lines indicate front (ice free) region as simultaneously observed by CIPS. The missing parts of the IMD contours imply missing data. For these retrieval pixels, the microphysical retrieval cannot provide cloud properties using the Ångström relation.

latitudes. Since the enhanced water vapour concentration coincides with a relatively warm air mass, we consider it likely that the increased water vapor concentration is caused by a recent or ongoing sublimation of PMC ice

particles. In the two subsequent orbits (51235 and 51236), the air in the front region remains considerably more moist compared to the cloudy region which indicates that the sublimation likely continues.

3.3. SMR TEMPERATURE STRUCTURES

The tomographic SMR temperature data, as shown in [Figure 5](#) are presented on a grid of 500 m in the vertical direction and 56 km in the horizontal direction (along the satellite orbit). The ability to resolve vertical structures such as waves and temperature inversions is however limited by the vertical resolution of the instrument which is 2.5 km. Transects of temperature at constant altitude obtained from SMR combined with OSIRIS ice water content (vertical integral of ice mass density) for each

orbit is shown in [Figure 7](#). The altitude levels, one high level at 84.25 km and one low level at 82.25 km are chosen to display the differences in the background conditions at different heights of the cloud layer. The front region is easily identified in each of the first three Odin orbits as the ice free region in each panel and marked by the vertical lines. In the first observation (orbit 51234), a pronounced warming of about 15 K is the dominating structure at the front at low altitude. 90 minutes later during the second observation (orbit 51235), the environment at the front

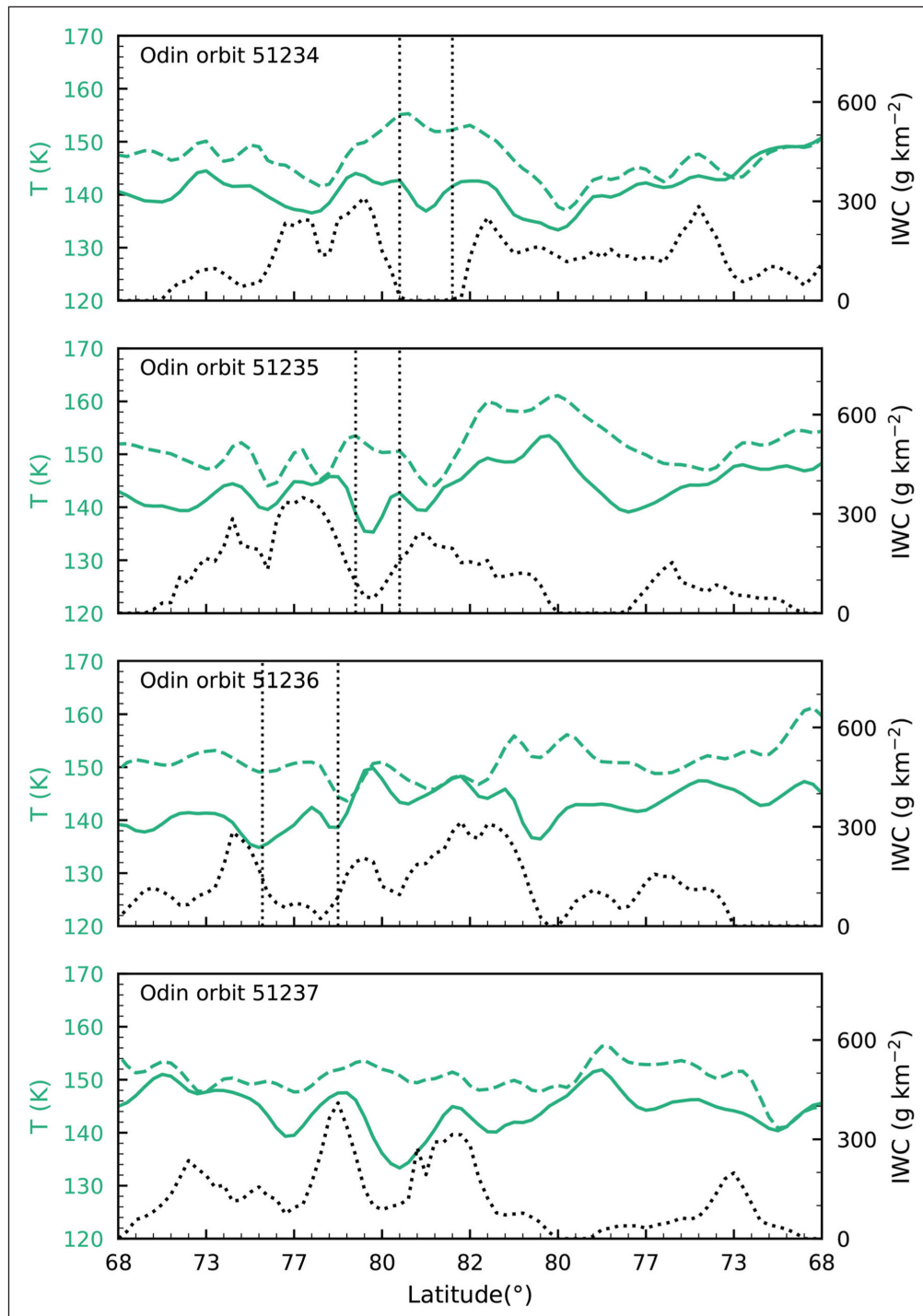


Figure 7 SMR Temperature observations on July 16 shown as transects at constant altitude 84.25 km (dashed line) and 82.25 km (solid line) versus latitude for the four Odin orbits (51234, 51235, 51236, 51237). Common volume observations of OSIRIS ice water content (dotted black line) show the vertically integrated ice mass density. The vertical lines show the edges of the front.

is still characterized by warm air at the low altitude. In the third observation, we note that the sharp cloud edge coincide with a local distinct temperature minimum at low altitude. In the fourth Odin orbit, the front is located outside of the common volume with CIPS and the exact position along the Odin orbit cannot be confirmed from CIPS.

Analysing the vertical temperature structure in the cloud free region in terms of deviation from the mean state provides insights into the presence of waves and temperature anomalies. The mean state is represented by the mean temperature profile along the AAO-dimension for 3 days around 16 July 2010. Since we use a 3-day mean and calculate the mean in terms of AAO instead of latitude, the mean represents the temperature variability over time scales less than 3 days. Furthermore, since Odin's orbit is Sun-synchronous, calculating the mean in terms of AAO is a simple method to remove the effect of the solar tides, such as the diurnal and semidiurnal tides (discussed in greater detail in section 5.2). However, a deviation from the tidal mean amplitude or phase would still appear in the deviation profile. Temperature profiles within the cloud free region for each orbit are shown in the left panel of [Figure 8](#). Each profile represents the mean of 5 profiles within the front region in each orbit. The selected profiles are marked with red ticks on upper x-axis of [Figure 5](#). The right panel of [Figure 8](#) shows the temperature deviation from the mean state. In the second observation (51235), the profile indicates the presence of wave motions with shorter wavelengths. At the time of sharpening of the

front during the third observation (51236), oscillations with uniform spacing having temperature maximum at altitude 73.5 km, 79.5 km and 85.5 km reveal the possible presence of a single wave with $\lambda_z \sim 6$ km. The increase in amplitude with height is consistent with the decrease in density with altitude.

4. CIPS WAVE ANALYSIS

The cloud field surrounding the front structure is bright and indicates the presence of multiple waves and small scale structures. In particular, the cloud field in the third and fourth CIPS swath (orbit 17556 and 17557) is characterized by bands of almost ice free regions to each side of the front structure, indicative of a large quasi-periodic perturbation in the cloud albedo at these times. [Figures 9a](#) and [10a](#) show cropped versions of CIPS orbit swaths in terms of PMC ice water content for the same orbits. Ice water content is used here instead of albedo since PMC wave structures are easier to detect in ice water content.

To further characterize these periodic structures in the cloud field a single pixel wide scan along the center of the orbit in the x-dimension (along the orbit swath) was made to determine the ice water content variation along the orbit for these two orbits, and is plotted with a solid line in [Figures 9b](#) and [10b](#). The scans reveal two distinct horizontally extended ice water content structures with two peaks in each orbit. To analyse the wavelength

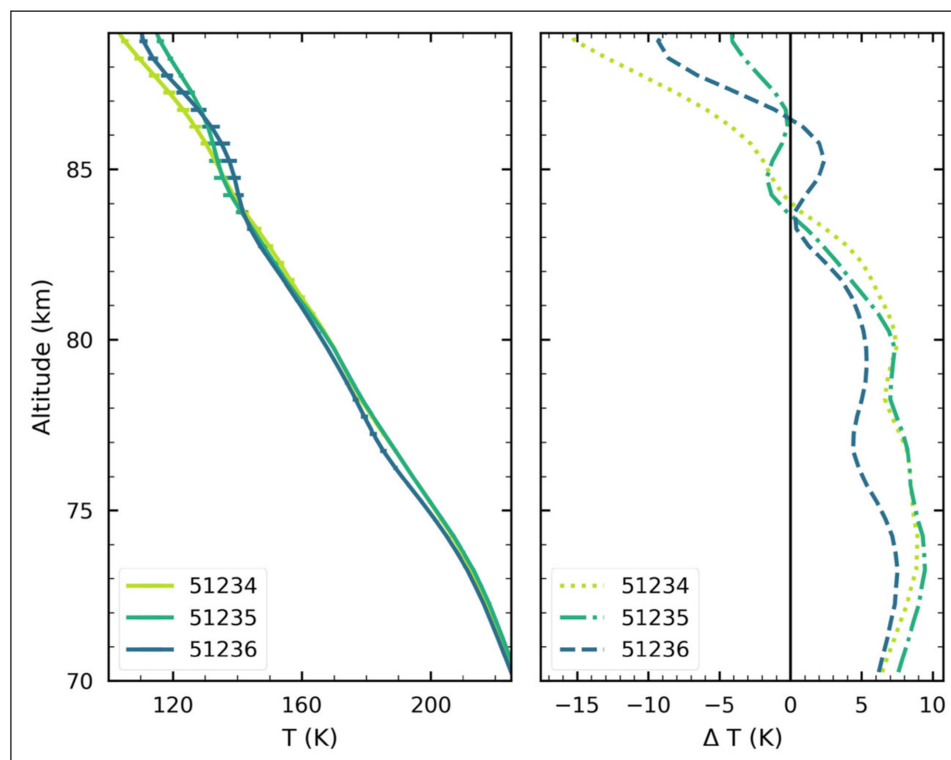


Figure 8 Temperature inside the cloud free region obtained from SMR tomography during the mesospheric front event for the Odin orbits (51234–51236). Left panel shows the temperature profiles where each profile is an average of 5 profiles within the cloud free region. Right panel shows the deviation compared to a 3-day average around the time for the observation for 75°N.

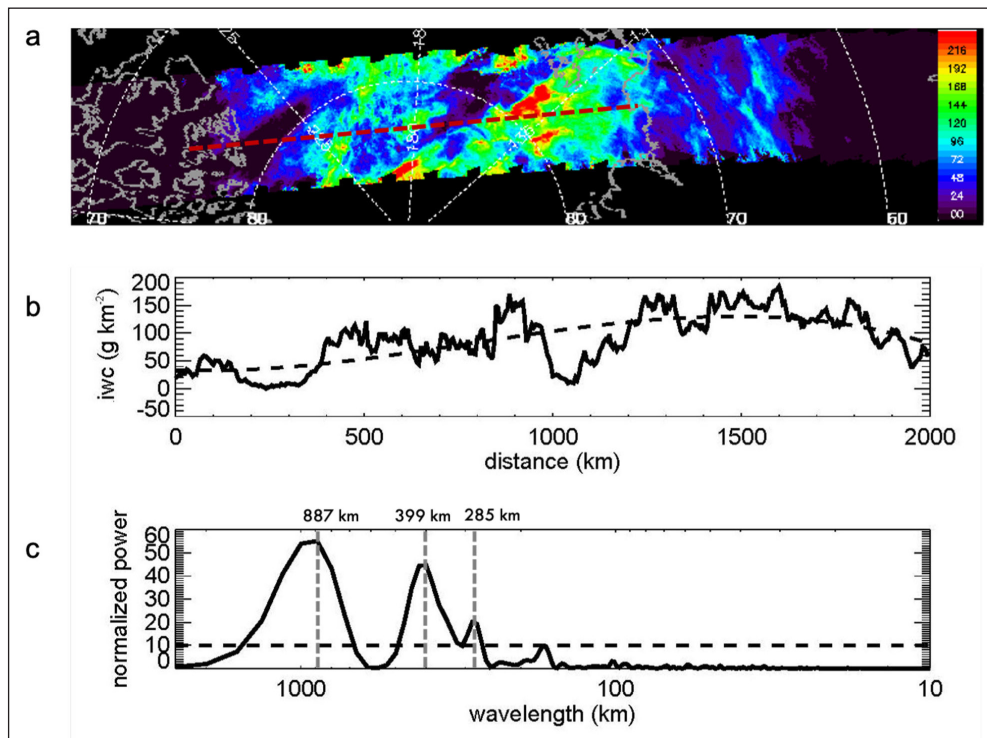


Figure 9 (a) CIPS PMC ice water content for orbit 17556 observed on July 16, 2010. (b) Ice water content along a scan cross the quasi-periodic structures marked by the red dashed line in (a) as a solid line and a polynomial fit (dashed line) to the data to represent the background. (c) Horizontal wavelength against the normalized power spectra of the event. The dashed horizontal line shows the 95 confidence level of the analysis.

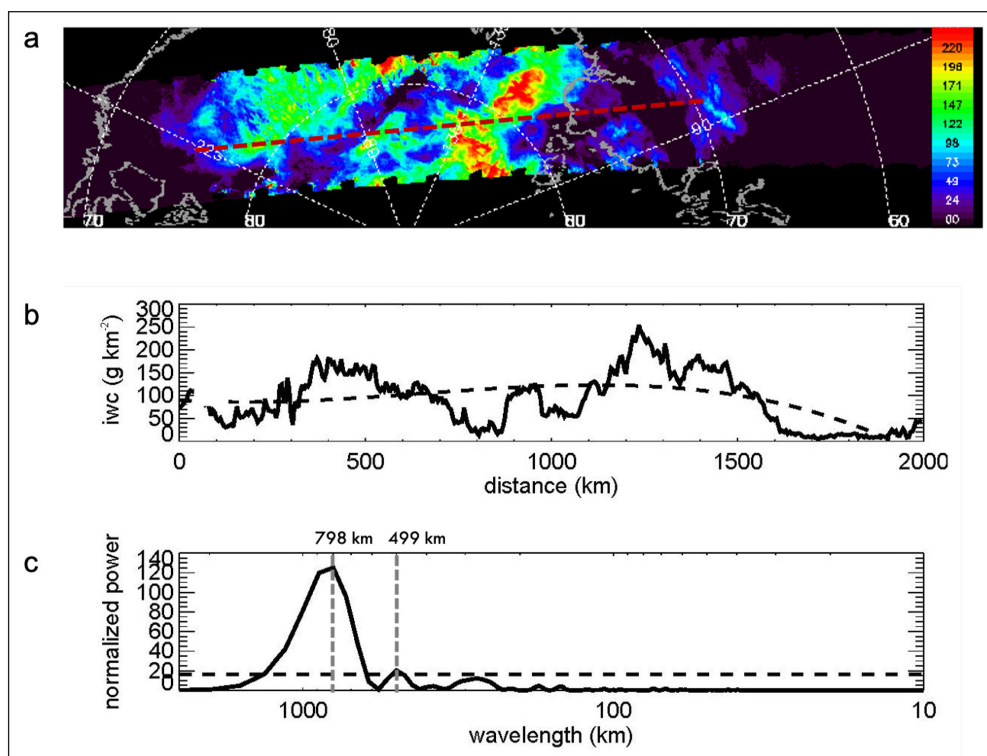


Figure 10 Same as Figure 9 but for CIPS orbit 17557.

of periodic structures from data that are unevenly sampled, we use a Lomb-Scargle periodogram analysis (Press et al., 2007). Lomb-Scargle is a standard technique to determine periodic structures from data that are not continuous and this method has previously been used to

derive wave characteristics from horizontal structures in CIPS PMC data (e.g. Chandran et al., 2010; Thuraijah et al., 2017). A third order polynomial fit is applied to the ice water content variation along the scan to represent the background and is plotted with the dashed line in

Figures 9b and **10b**. The ice water content perturbation is retrieved by subtracting the background polynomial fit from the observed ice water content variation. The results of this method are shown in **Figures 9c** and **10c** which plot the horizontal wavelength up to 2000 km on the x-axis against the normalized power of the wave event on the y-axis. The dashed horizontal line shows the 95 percent confidence level of the analysis, indicating that the peaks above this line have only a 5 percent risk of being noise.

The scan in **Figures 9c** and **10c** reveals multiple waves. The dominant wavelength of the large wavelike structure varies between about 800–900 km. Other smaller waves are also present. Note that the wavelength derived by this method is dependent on how the scan is drawn and is approximate. The derived wavelength can be larger than the true wavelength depending on how the wave crests are oriented relative to the satellite orbit as discussed by Carbary et al. (2000). We additionally perform a shorter scan only across the front (perpendicular to the elongation of the front) in each CIPS observation of the front in orbits 17554, 17555, 17556 and 17557, and get a dominant wavelength with an average horizontal wavelength of about 500 km (not shown).

CIPS orbit swaths also reveal the presence of much smaller-scale, GW features in orbits 17556 and 17557, in regions marked with red circles in **Figure 3**. **Figure 11** shows CIPS ice water content in enlargements of regions labeled A in (a) and B in (b) in **Figure 3**. To analyse the horizontal wavelength of the features in regions A and B, we scan across the red dashed line in (a) and (b) and analyse the ice water content perturbation using Lomb-Scargle periodogram analysis. We find multiple waves in A with dominant wavelengths of about 18, 33, and 23 km (not shown). In region B, we find multiple waves with dominant wavelengths of about 54, 33, and 23 km (not shown).

5. ATMOSPHERIC BACKGROUND CONDITIONS

The meteorology of the mesosphere, in terms of temperature, humidity, and winds, is mainly governed by planetary waves, tides, and GWs. A thorough analysis of the phases of the dominating planetary waves and tides, as well as conditions for GW propagation, is useful to better understand dynamics and transport processes during the occurrence of the front.

5.1. MLS PLANETARY WAVE ANALYSIS

The influence of planetary waves on PMC formation and destruction has been studied using both observations and models (e.g. Merkel et al., 2008; France et al., 2018). Merkel et al. (2008) showed that PMC occurrence frequency and brightness are highly correlated with the 5-day wave and the 2-day wave. Cloud formation is enhanced in the cold phase of the wave while cloud destruction is enhanced in the warm phase of the wave. In order to investigate the state of the planetary waves during the occurrence of the front, we use temperature observations from the Earth Observing System Microwave Limb Sounder (MLS) on the Aura Satellite (Waters et al., 2006). In this study we use version 4.2 of MLS temperature data (Schwartz et al., 2008; Yan et al., 2016). The planetary wave analysis has been carried out during a 40-day period (day of year (doy) 182–212 during 2010) centered around the observation of the front structure (doy 197 = July 16, 2010) for both the 5-day planetary wave and the 2-day planetary wave and the results are shown in **Figure 12**. The horizontal line corresponds to the time of the front observation, and the vertical lines correspond to the longitude range within which the front is observed. During the occurrence of the mesospheric front, the 5-day wave is in a positive phase with an amplitude of about 0.2 K while the 2-day wave is between the positive and negative phase. From

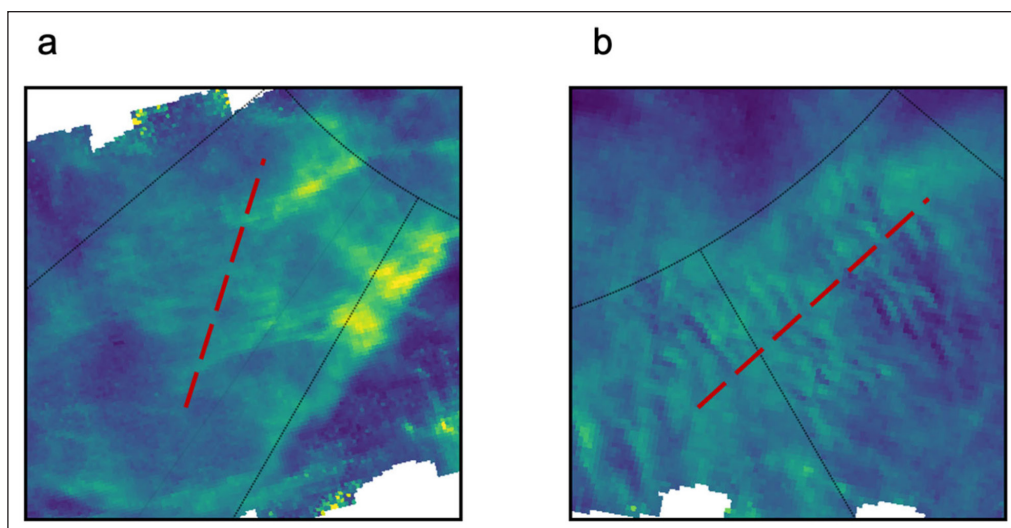


Figure 11 Enlargement of CIPS PMC ice water content for orbit 17556 and 17557 observed on July 16. (a) and (b) are regions marked A and B in Figure 3. Red dashed line marks scan across wave structures.

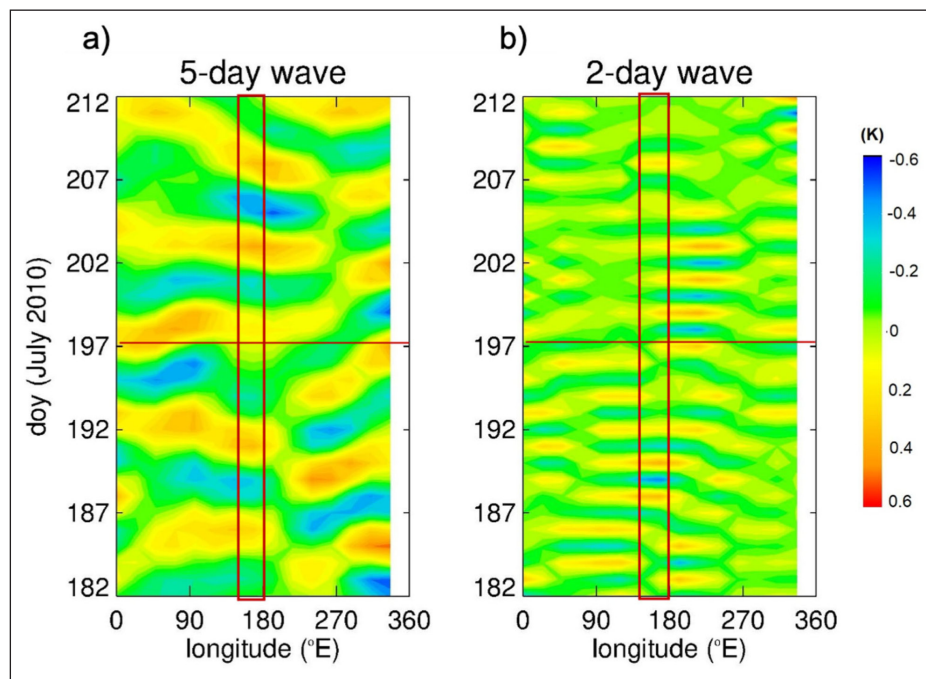


Figure 12 Longitude-time plots of temperature amplitude for the 5-day wave (a) and for the 2-day wave (b) for day of year 182 to 212 2010 from MLS temperature. The red lines denote the occurrence of the mesospheric front.

these observations, we conclude that the 5-day wave is dominating over the 2-day wave during the occurrence of the front and that a decrease in cloud frequency and brightness are expected due to the warm phase of the 5-day wave.

5.2. MESOSPHERIC WINDS

To study the observed movement of the front in relation to the background wind situation we now continue with a brief discussion of the estimated winds. Mesospheric winds are governed by tides, planetary waves, and GWs. On the timescale from hours to a day, the zonal and meridional winds are mainly governed by migrating and non-migrating tides. The westward migrating (sun-synchronous) tides are large scale waves with periods that are harmonics of 24 hours that are excited by absorption of solar radiation in Earth's atmosphere. The two dominant migrating tides in the upper mesosphere are the diurnal and semidiurnal tide. While the diurnal tide is dominant for equatorial regions, linear theory suggests that the semidiurnal tide becomes important for mid and high latitudes (Lindzen and Chapman, 1969). The dominance of the semidiurnal tide over the diurnal tide at high polar latitudes in summer has been confirmed by tidal climatology from meteor radar studies (e.g. Lukianova et al., 2018; Wilhelm et al., 2019). Satellite observations have shown that the migrating diurnal and semidiurnal tide have a strong yearly and seasonal variation (Hays et al., 1994; Burrage et al., 1995). In addition, non-migrating tides, driven by longitudinal differences in radial heating (Hagan and Forbes, 2002), have also been identified to reach large amplitudes in the mesosphere (Talaat and Lieberman, 1999; Oberheide

et al., 2002). The non-migrating tide can be stationary relative to the surface of the ground or propagate westward or eastward with other phase velocities than the migrating tides.

Due to the remote location of the front structure over the East Siberian Sea, there is, unfortunately, no direct observation of mesospheric winds available in the vicinity that the authors know of, so we refer to tidal climatologies at high northern latitudes to study mesospheric wind conditions during the occurrence of the front. The actual day-to-day variability of the tides is modulated both by the variability in the forcing of the tides and the interaction between tides and other waves. However, for the purpose of our study, the wind information from a tidal climatology at high northern latitudes provides valuable insights into the wind variation over the course of a day. Wilhelm et al. (2019) show that for high latitudes (Andenes, 69°N, 16°E) at PMC altitudes, the zonal component of the diurnal tide maximizes in mid/late July, while the meridional component of the diurnal tide generally increases during all the summer months. From this study, we infer that large fluctuations in the zonal winds at high latitudes could be expected over the course of a day during mid/late July compared to earlier and later in the PMC season. Kishore-Kumar and Hocking (2010) studied mean winds and tides in the MLT at Resolute Bay (75°N, 95°W) from 82 km to 94 km using almost 12 years of meteor radar data. The 12-year climatology includes specific tidal parameters (their Table 3) and amplitudes and phases of the diurnal, semidiurnal, and terdiurnal tides (their Figure 4). We will focus on the diurnal and semidiurnal tide since these two have the largest amplitudes at PMC altitudes and

impose the largest wind variations on the PMC layer. Over Resolute Bay at PMC altitudes, the diurnal tide has a clockwise rotation during summer, while the semidiurnal tide has an anti-clockwise rotation.

We now make the approximation that the diurnal and semidiurnal migrating tide patterns over high northern latitudes in July are zonally symmetric and infer an estimate of the tidal wind pattern during the occurrence of the front, centered around the same high latitude but at a different meridian. The first front observation takes place at 16.45 LT, we are thus interested in the tidal wind pattern around this local time. In the afternoon hours between 13.00 LT and 17.30 LT, we infer from the Resolute Bay climatology (Kishore-Kumar and Hocking, 2010) that for 75°N, July, at 82 km, the zonal component of both the diurnal and semidiurnal tides are westward. The meridional component of both tides are northward between 15.00 LT and 19.00 LT. For the times before and after this time window, the diurnal and semidiurnal tidal wind directions are opposite to each other and thus we cannot conclude climatological wind directions. We thus infer from climatology that during the first observation of the front structure, the tidal winds are expected to be northwestward and in the same direction as the observed progression of the structure. However, the day-to-day variability in the phase and amplitude of the semidiurnal tide should be noted and is a source of uncertainty to this statement.

6. DISCUSSION

The length of the mesospheric front in the current study of at least 1800 km is in line with, or longer than, previously reported mesospheric fronts in PMC (e.g. Thurairajah et al., 2013; Dalin et al., 2013). Apparent similarities exist also to the 2200 km long mesospheric wave front of the bore observation recently investigated by Hozumi et al. (2018) using the Visible and near-Infrared Spectral Imager on the International Space Station (ISS). The structural resemblance of the current mesospheric front to airglow observations of mesospheric fronts suggests that the mechanism responsible for the formation could be the same. In order to investigate the possible relationship between the observed mesospheric front to previously reported mesospheric fronts and large scale gravity waves in both airglow and PMC we now continue with a comparison of the observed front characteristics and observed state of the mesospheric environment to previous studies.

From the extent and orientation of the front in consecutive CIPS orbits, we are able to obtain apparent horizontal propagation speed and rotation. Based on the propagation of the structure at 75°N, we calculate the propagation speed in the zonal direction to 50 +/- 5 m/s. Similarly, based on the rotation of the azimuthal angle

of the front in CIPS orbits 17555 to 17556 at latitudes higher than 75°N, we are able to estimate a rotation speed. We find that the rotation is approximately 12° per hour clockwise. The propagation speed is somewhat larger than the speed of the PMC front described by Dalin et al. (2013) which travels towards northwest in the upper mesosphere with a speed relative to the ground of 31.1 m/s. It is also somewhat smaller than typical propagation speeds of 60–80 m/s as reported for mesospheric bores and fronts using airglow observations (e.g. Taylor et al., 1995; Bageston et al., 2011). Furthermore, the observed rotation of 12° per hour is larger but of the same order of magnitude as values from previous studies of mesospheric bores in the NH reporting on clockwise rotation between 6–8° per hour (Smith et al., 2003; Li et al., 2013). However, these bores were observed at lower latitudes and also in wintertime when different wind conditions are expected due to the seasonal variations of tidal winds which would explain the differences in rotation. Previous studies of mesospheric bores have described the presence of phase-locked trailing waves to the initial front (Bageston et al., 2011; Taylor et al., 1995; Hozumi et al., 2018). Using a 3D model, Fritts et al. (1997) estimated the wavelengths of these small scale ripples behind the leading front to 5–10 km. In the CIPS front observations, no trailing waves are detected parallel to the front that could confirm the typical bore characteristics. However, this could possibly be related to the resolution of CIPS v 5.2 which cannot resolve waves with a horizontal wavelength smaller than 15 km. The CIPS images do however present evidence of small scale GW activity with wave crests situated ahead of the front with wavelengths in the order of about 20–30 km ([Figure 3](#) in region A and [Figure 11a](#)). Behind the front, small scale GW activity is found with wavelengths in the order of about 20–50 km. Mondal et al. (2021) recently presented a case study of a mesospheric bore front over the Western Himalayan region observed in airglow with a maximum horizontal elongation of about 450 km. In connection with the bore front, they identified both trailing waves with wavelengths of about 22 km that lasted for about 1.5 h and more short lived (about 25 min) small scale ripples head of the front. One possible interpretation of the observed small scale GWs in the present case is that these GWs are triggered by dynamic instability associated with the front similar to the case presented by Mondal et al. (2021).

As already pointed out, the presence of an inversion layer or wind shear acting as a ducting layer is a necessary criterion for a mesospheric bore to be able to propagate horizontally. For our current case study, it is thus essential to know if a duct was present. Temperature observations in the front from SMR in the 70–90 km altitude range show a pronounced warming of about 15 K at low PMC altitude (82.25 km) compared to the surrounding cloud field at the same altitude ([Figure 7](#)). The region with high

temperatures in the lower PMC layer is closely connected to a larger region with high temperatures that extends upwards from the middle mesosphere at 70 km to at least 85 km as seen in [Figure 8](#). The temperature at 89 km (4 km above the top cloud at 85 km) is as low as 103 K during the first observation, which is about 15 K lower than the measured 3-day average temperature for the same altitude. We consider it likely that this is a downward extension of the mesopause. However, since SMR does not measure at higher altitudes this cannot be analysed further. In summary, analysis of the vertical temperature structure shows extensive temperature anomalies but no obvious sign of an inversion layer during the front observation that could serve as a duct. It is possible that narrow inversions with an extent less than 2.5 km could still be present, but these would not be observed by SMR run in tomographic mode owing to the vertical resolution of the instrument. Due to the lack of coincident mesospheric wind observations, we do not know if a Doppler wind duct was present. It is however interesting to speculate that wind shear caused by tidal winds could produce such a duct. As discussed in the previous section, the front occurs during the time of year when the amplitude of the semidiurnal tide can be of similar magnitude as the diurnal tide, and when the amplitude of the diurnal tide maximizes at PMC altitudes at high northern latitudes.

At the time of the third observation of the front structure (at 144°E, CIPS orbit 17556), the planetary wave analysis indicates that the upper mesospheric environment was subject to warming due to a positive phase of the 5-day wave ([Figure 12](#)). Previous orbits show that the front was located further to the East, centered at 180°E. At this longitude, we note that the phases of both waves are positive. Planetary waves are considered too large scale phenomena to cause PMC structures such as a mesospheric front. However, they induce significant warming of the PMC region that can alter the PMC brightness. For this reason, we find it interesting to note that the environment where the mesospheric front formed was subject to large scale warming, even though this is not expected to be the main cause of the structure itself.

Relating our findings to previous mesospheric fronts in PMC, we can confirm the hypothesis by [Thurairajah et al. \(2013\)](#), that the air masses on each side of the front structure are two very different air masses. The meteorological conditions obtained from SMR show an increase in water vapor mixing in the cloud free region. We can also confirm that the sharp front coincides with large temperature differences in agreement with [Dalin et al. \(2013\)](#) and [Thurairajah et al. \(2021\)](#). For example, the long mesospheric front (322 km) observed in PMC at 57°N, 115°W described by [Dalin et al. \(2013\)](#) coincides with a strong meridional temperature gradient at PMC height perpendicular to the front propagation. However,

that front constituted of a single wave crest with a width of about 3.4 km followed by trailing GW crests. In comparison, the dimension of the current front is larger and no trailing waves are observed. We conclude that even though the characteristics of the background temperature field are similar, the resulting effect on the PMC layer is different. [Fritts et al. \(2020\)](#) investigated two mesospheric bores in PMC over Canada performed by the PMC Turbo experiment. They proposed that one of these was forced by large amplitude GWs that had horizontal wavelengths of 12–30 km that underwent breaking. Inspired by this finding, we consider whether the current mesospheric front could be forced by large scale GWs. The SMR temperature structure within the front structure during the first two orbits ([Figure 8](#)) does not indicate gravity wave activity. The third orbit, however, shows signs of GW activity with $\lambda_z \sim 6$ km in the cloud free region. This coincides with a sharpening of the front edge visible in [Figure 4](#). We do not attempt to characterize the horizontal wavelength of this wave. The ability to resolve horizontal wavelengths in SMR temperature is limited by the resolution: only wavelengths larger than about 250 km can be observed by SMR. Furthermore, the SMR temperature observations are only performed in the direction along the orbit and not in three dimensions, thus we cannot derive a horizontal wavelength of the structure satisfactorily using SMR. The front structure coincide with several large ice free band regions in the CIPS PMC field (as analysed in Sect. 4) with wavelengths of about 800–900 km. One possible interpretation is that the front structure is caused by sublimation due to a large GW, however this cannot be confirmed from the SMR temperature data.

The physical interpretation of the observed sharpening of the front edge (as observed by CIPS) is not straightforward. [Hart et al. \(2018\)](#) recently presented an interesting method to study vertical structures in CIPS PMC dataset using an intensity-weighted centroid profile and PMC surface map to infer wave induced vertical displacement of PMCs. They showed a high spatial correlation with PMC albedo and wave induced altitude variations, namely bright structures aligning with wave troughs and dim structures aligning with wave crests (see their Fig 8). Connecting their results to the observed sharpening of the present front suggests that large differences in cloud altitude can be expected in the front. Furthermore, this suggests that the brighter cloud edge is located at a lower altitude and the dark (apparent ice-free) region is located at a higher altitude. We propose that the observed sharp front is related to a wave induced altitude displacement of an existing cloud edge that, viewed in nadir geometry, displays a sharp increase in brightness. The local temperature minimum observed by SMR at the sharp front edge (see [Figure 5](#)), possibly related to a GW-induced upward motion and adiabatic cooling, supports the reasoning.

A plausible chain of events leading to the observed structure in the PMC is hypothesized:

1. The PMC region at high latitudes during the first observation has undergone local warming leading to sublimation of ice over a large elongated area resulting in an increased amount of water vapor in the cloud free region. Temperature observations from SMR show pronounced warming of about 15 K and mesospheric wind conditions inferred from meteor radar wind climatology suggest northwestward flow at the location and time of occurrence of the first front observation. We consider that the warming could be connected to transport with and adiabatic warming induced by a large amplitude tide.
2. The front region in the PMC is transported with the tidal background winds towards northwest and rotates clockwise.
3. A vertically propagating GW in the front region with phase front aligned with the pre-existing front region induce vertical motions in the PMC field that causes vertical displacement of the PMC layer leading to increased PMC brightness gradient across the front edge.

7. CONCLUSIONS

The spatial and temporal development of a mesospheric front in PMC has been reported and the background atmosphere during the occurrence of the front has been analysed. The front was observed on 16 July 2010 at $\sim 75^\circ\text{N}$, 144°E during a time period of 4.5 hours as an elongated feature of length ~ 1800 km that separated cloudy and cloud-free air. By combining three different instruments, CIPS on the AIM satellite providing 2D horizontal information of the spatial characteristics of the front in the PMC field and OSIRIS and SMR on the Odin satellite providing 2D vertical + horizontal PMC information and 2D temperature and humidity information across the propagation direction of the front, we have characterized the structure in great detail. A propagation direction from Southeast to Northwest and simultaneous clockwise rotation of $12^\circ/\text{hour}$ was observed and found to be consistent with the expected climatological tidal wind pattern. SMR observations show the presence of a warm air mass and increased amount of water vapor in the cloud-free front region, likely caused by a recent sublimation of PMC particles. SMR temperature perturbation in the front region depicts the presence of a wave-like disturbance 3 hours later, possibly a GW, at an altitude of 70–90 km with $\lambda_z \sim 6$ km that coincides in time with a sharpening of the front edge. We propose that the observed sharpening of the front is connected to GW-induced vertical displacement of the PMC field that leads to enhancement of PMC albedo in

the wave troughs and decrease of albedo in wave crests. Lack of simultaneous wind data limits a more thorough study of a possible wave propagation direction in relation to the observed front extent and propagation. The visual characteristics of the mesospheric front in the current study display similar features as previous mesospheric fronts and bores in PMC (e.g. Dalin et al., 2013; Fritts et al., 2020; Thuraijah et al., 2013) and airglow (e.g. Bageston et al., 2011; Hozumi et al., 2018). Furthermore, common volume observations of the background atmosphere in terms of temperature and water vapor indicate different air masses across the front border which also is in line with earlier findings (Dalin et al., 2013). However, the absence of trailing waves and simultaneous ducting conditions in the form of thermal or wind ducts cannot be confirmed. For future studies of mesospheric fronts on PMC, simultaneous high resolution temperature and wind profiling would be beneficial.

DATA ACCESSIBILITY STATEMENT

AIM CIPS data are openly available at Laboratory for Atmospheric and Space Physics (LASP): <http://lasp.colorado.edu/aim>. Odin OSIRIS and SMR tomographic data used in this study are available at <https://doi.org/10.6084/m9.figshare.14458764.v1>. EOS Aura MLS temperature data are openly available at <https://mls.jpl.nasa.gov>.

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COMPETING INTERESTS

The authors have no competing interests to declare.

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