High resolution Kelvin-Helmholtz Instabilities observed during the 2018 PMC-Turbo flight

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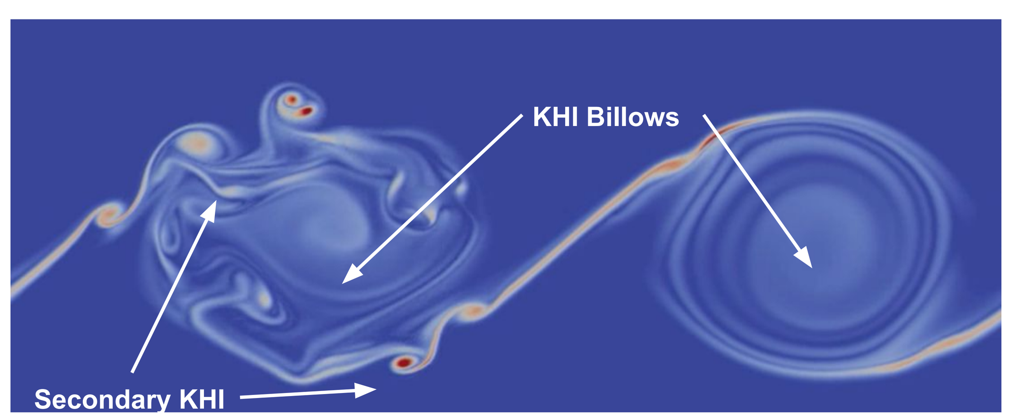
Introduction

The mesosphere and lower thermosphere (MLT) contains a wide variety of wave dynamics at a range of scales, which dictate the structure of the region. Gravity waves (GWs) and their associated instabilities are dominant at medium and small scales (< 15 km).

GWs transport energy and momentum from the lower atmosphere to higher altitudes. Below the turbopause momentum and energy deposition occurs through instabilities and their evolution to turbulence. GWs influence the structure of the mesosphere and lower thermosphere (MLT) by initiating various instabilities leading to wave dissipation, turbulence generation, and turbulent mixing.

Kelvin-Helmholtz instabilities (KHI)are an important class of instability initiated by GWs. KHI arises due to sheared flows or perturbations about a sheared region. KHI can be induced by GWs with near-inertial frequencies and by small scale gravity waves which perturb strongly sheared layers. KHI can host a variety of complex dynamics, which increase the rate of momentum and energy deposition. The details of the dynamics of KHI and its impacts on thermosphere and lower thermosphere (MLT) are important to understanding the structure and composition of the MLT.

Polar Mesospheric Clouds (PMCs) located in the MLT provide a sensitive tracer of GW dynamics. PMCs form as trace water vapor condenses at the minimum atmospheric temperature. This occurs over the poles due to adiabatic cooling driven by macroscopic air motion during the polar summers. This cooling causes clouds to form around 82 km altitude, where the spatial scales for GW and turbulence dynamics are large. PMCs are bright and only a couple of kilometers thick, so they are sensitive tracers of dynamics. The reflective ice particles in PMCs are moved by passing dynamics. PMCs make it convenient to study KHI and other GW dynamics in the MLT due to the more easily observable scales, but these processes are broadly relevant throughout the atmosphere, as well as bodies of water.

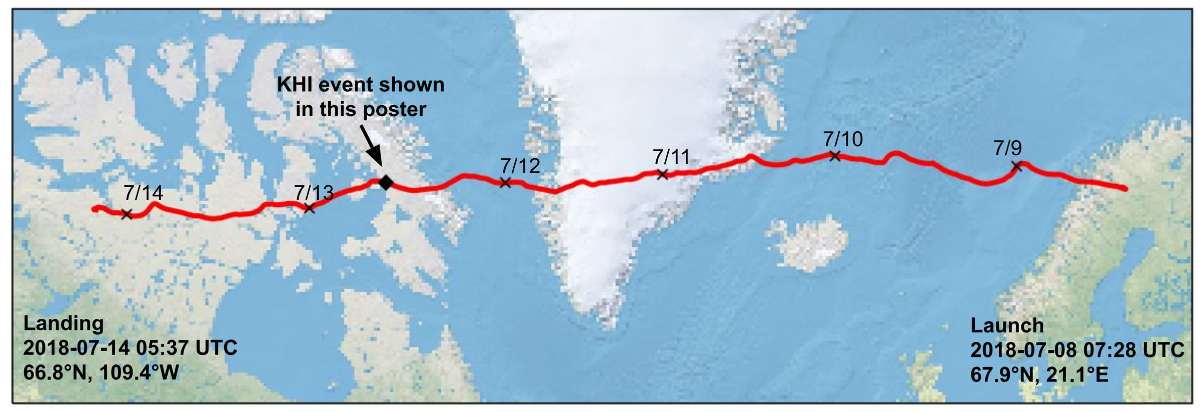


Computational model of KHI exhibiting secondary KHI viewed from the side.

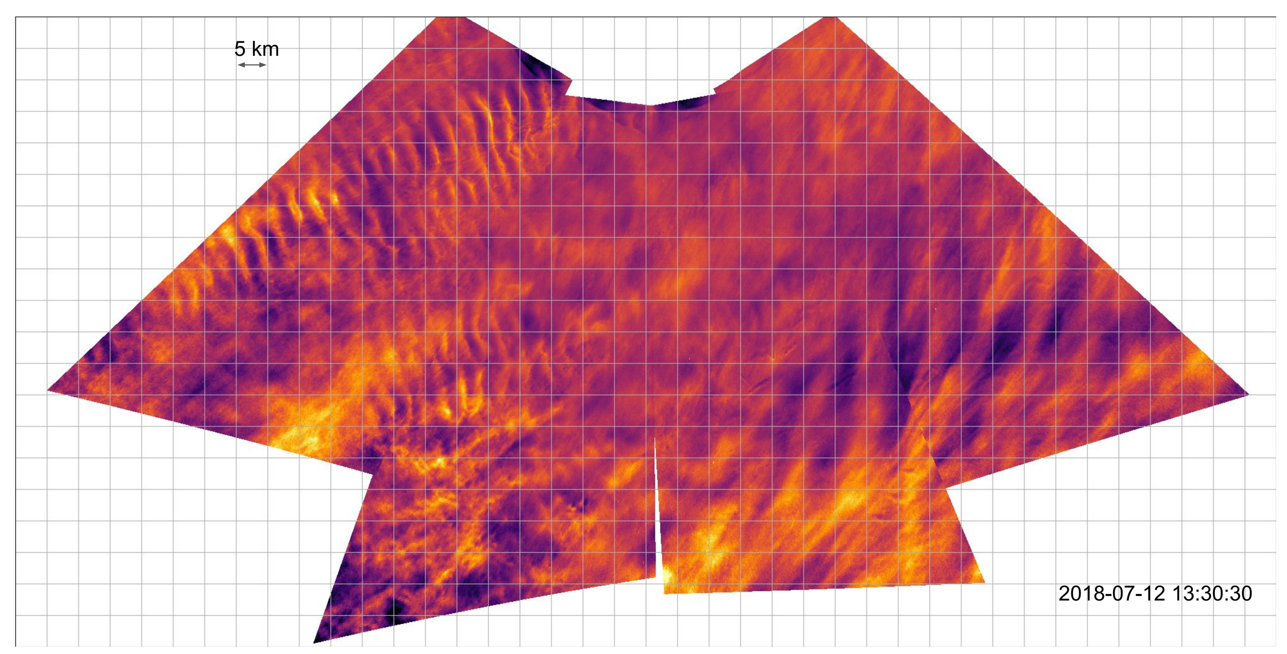
Instrument

- PMC-Turbo is an experiment designed to capture images of PMCs.
- The PMC-Turbo payload hosts seven optical cameras each contained within pressure vessels.
  - Three pressure vessels include a narrow-field lenses, which provided a 10 x 15 degree field of view, and spatial resolution of around 3 meters per pixel on the PMC layer.
  - The remaining four cameras included wide-field lenses which provided a 25 x 40 degree field of view and spatial resolution of 8 meters per pixel.
- The PMC Turbo payload also included a 532 nm 5 Watt Rayleigh lidar.

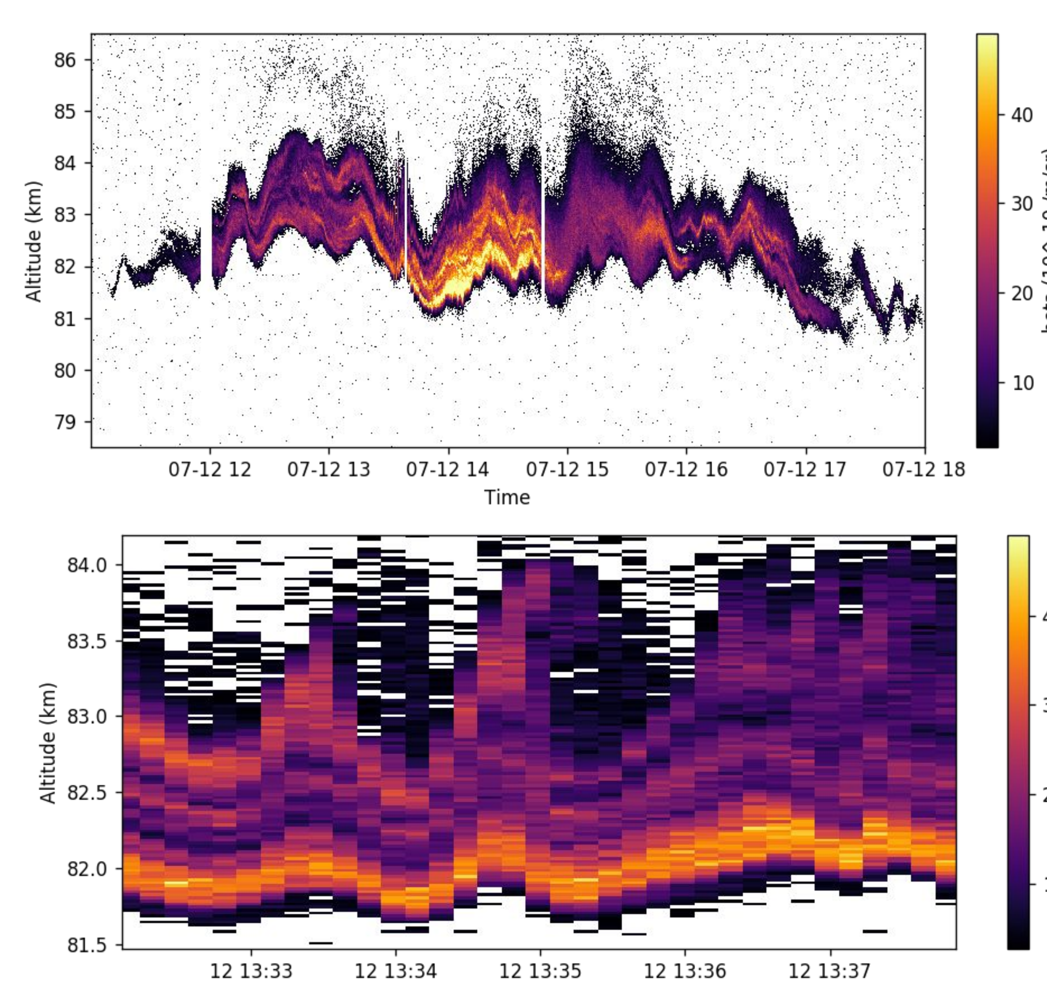
Data Collection and Processing



The PMC-Turbo payload launched from Esrange, Sweden on July 8th, 2018 and landed nearly six days later in Northern Canada. During this time it captured about 6 million camera images, roughly half of which contain PMCs. This poster discusses the dynamics observed during one event on July 12th at 13:30 UTC.

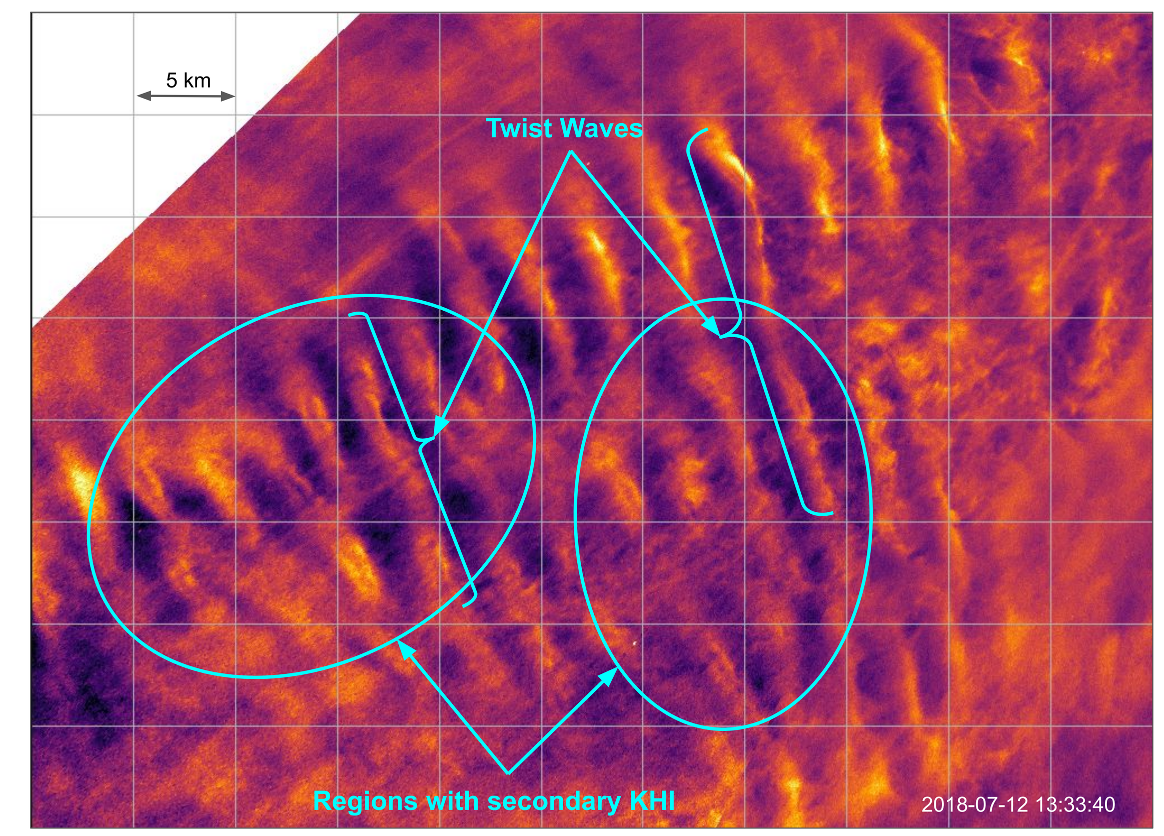


- The image above shows the full field-of-view of the four widefield cameras after image processing and projection.
- Images were processed with a standard flat-fielding procedure. An adjusted image I' was generated from original image I using the standard flat-field equation: $I' = \mu_F(I-D)/(F-D) - S$. Where D is the dark image, F is a mean flat-field image, and S is sky brightness from a model. The adjusted image I' was corrected for exposure time.
- A moving average in time was subtracted from I' to generate the final image I'' to account for scattered light.
- All images were recorded in monochrome - the images displayed have been falsely colored to enhance contrast.
- Images were projected on the sky by finding the pointing of the images using background star fields, and mapping each pixel to the proper location on the sky.
- Pixels have been binned to increase signal-to-noise.



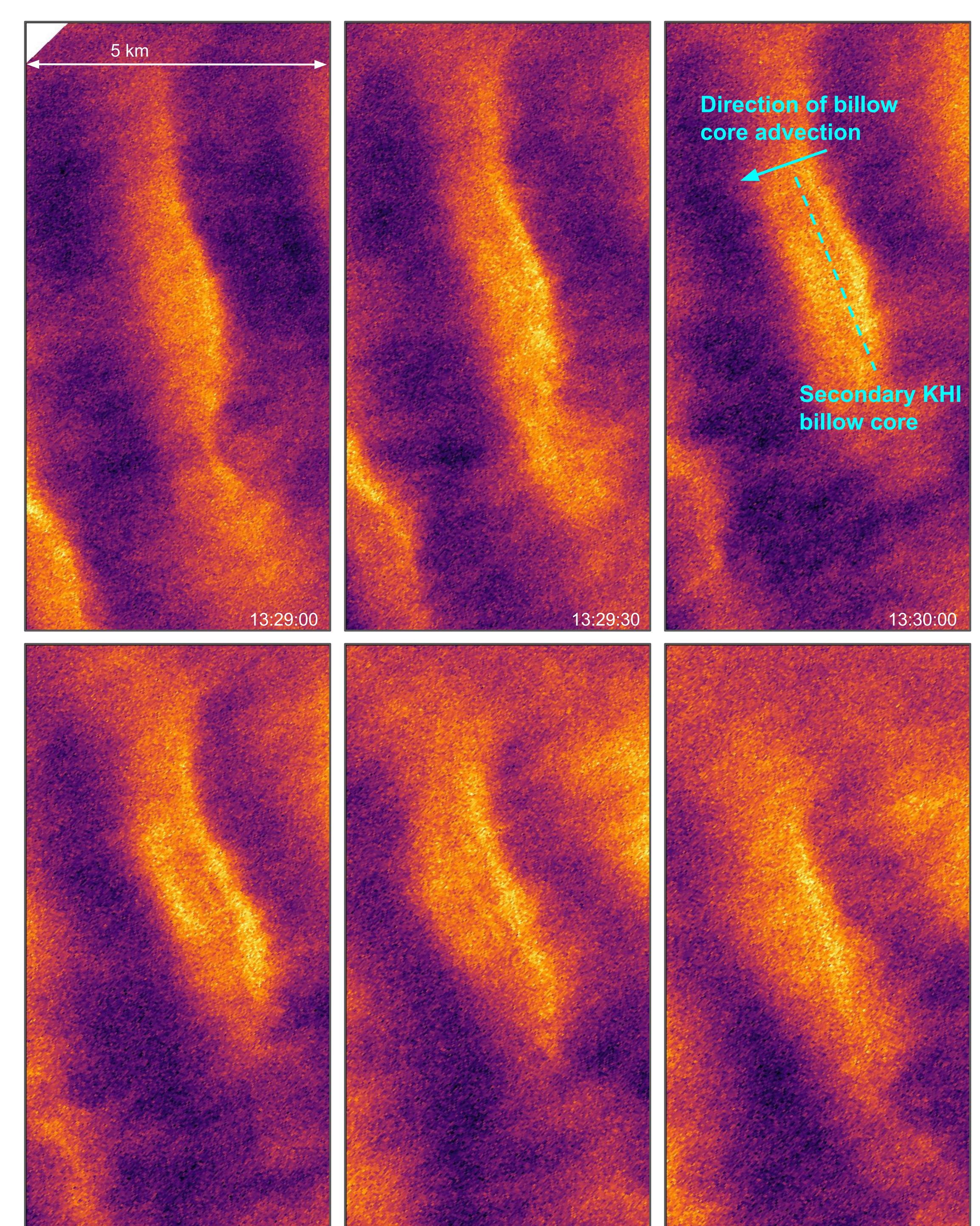
Lidar profiles of the PMC layer during an intense KHI event on 7/12/2018. The top profile shows a slice of the PMC layer for the time PMCs were visible, while the bottom profile shows KH billows traced in the PMC layer.

First Direct Atmospheric Observations of Secondary KHI



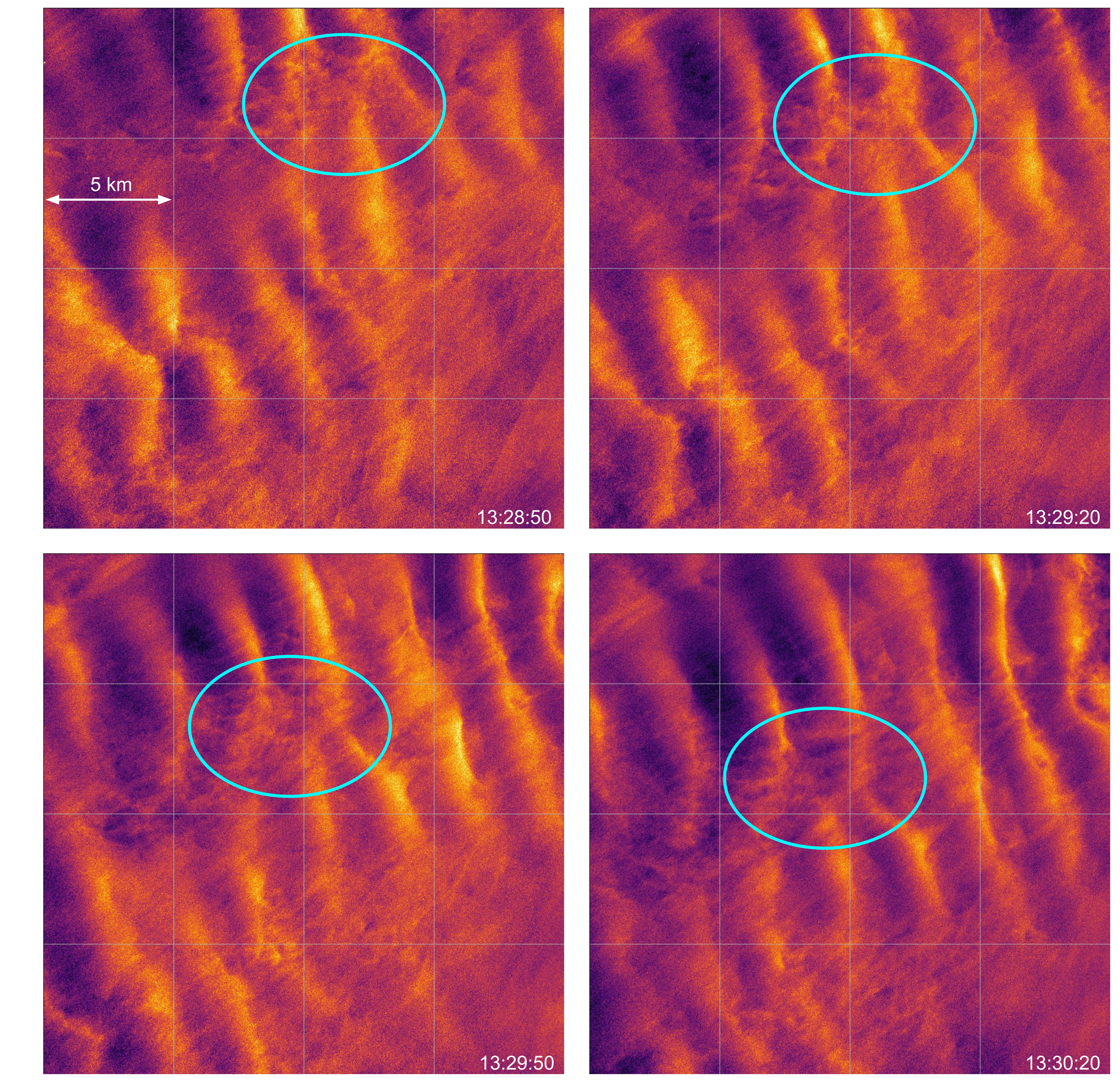
Strong KHI events induce secondary KHI on the strongly-stratified sheets between adjacent billows. Secondary KHI is characterized by counter-rotating vortices with cores parallel to the original KH billow cores. The secondary KHI is advected above or below the original KH billow core, depending on its location relative to the core. In the PMC-Turbo images, secondary KH billows are observed only on the bottom of the KH billows due to the limited thickness of the PMC layer. The PMC-Turbo observations are revolutionary due to their extremely high spatial and temporal resolution. These observations are the first directly observed secondary KHI features in the atmosphere.

KH billow rotation rate can be altered due to underlying GW dynamics, which leads to differential billow rotation along the axis of rotation. This differential rotation can lead to unraveling and undulation of the billow cores, known as twist waves. The secondary KHI observed exhibits both twist waves and the characteristic over-billow advection pattern. The image above contains widespread secondary KHI and several twist waves.



The evolution of a single KH billow fringe exhibiting secondary KHI. Image cadence of 30 seconds. The secondary KH billow advects under the primary KHI fringe over 3 minutes.

Systematic Inter-billow dynamics



The four panels above contain an example of merging KH billows highlighted in cyan. Each image is taken 30 seconds apart. Numerous knots and tubes are involved in the inter-billow dynamics.

Adjacent KH billows have been seen to merge in laboratory studies, which creates additional instabilities linking the billows such as "tubes" and "knots". Knots are regions of numerous tangled vortex lines that extend asymmetrically in three dimensions. Knots have complicated fine structure within and around the vortex lines. Individual tubes within the knots can also contain fine structure such as twist waves. Tubes are vortex lines running between KH billows. They connect neighboring billows and can evolve into knots as billows interact.

While KH billows represent a gradual dissipation of energy and momentum, the fine structure of knots typically dissipates into turbulence on a timescale much smaller than KH billows.
These dynamics have been observed in the lab and simulations, but they had not been systematically observed in nature with sufficient resolution to observe fine structure before PMC-Turbo observations. During the intense KHI discussed in this poster, many billow-merging events were recorded. We are working to use our observations to verify the accuracy of direct numerical simulations of billow interactions within KHI.

Conclusion

The enhanced resolution provided by the balloon-borne observational platform has resulted in the first secondary KHI and systematic billow merging events imaged in the atmosphere. Our results confirm the widespread presence of complex turbulence dynamics within KHI billows and suggest that these dynamics do not manifest in isolation. Secondary KHI forms on many KH billows as suggested by direct numerical simulations and laboratory experiments. The instabilities can be identified as secondary KHI by their advection direction, lifetime, and evolution into twist waves. KH billows are seen to interact and merge through the formation of knots and tubes of vortex lines. We are currently using the measured sky conditions and observed dynamics to refine and verify numerical models that can better describe small-scale features of KHI.

Acknowledgements

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PMC-Turbo overview paper
Fritts, D. C., Miller, A. D., Kjellstrand, C. B., Geach, C., Williams, B. P., Kaifler, B., et al (2019). PMC Turbo: Studying Gravity Wave and Instability Dynamics in the Summer Mesosphere using Polar Mesospheric Cloud Imaging and Profiling from a Stratospheric Balloon. *Journal of Geophysical Research: Atmospheres*, 124. https://doi.org/10.1029/2019JD030298