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Comparison of Stratospheric Gravity Waves in a High-resolution General Circulation Model with 3-D Satellite Observations

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My Abstract (EGU23-14145)

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What is JAGUAR?

Japanese Atmospheric General circulation model (GCM) for Upper Atmosphere Research (JAGUAR) [Watanabe & Miyahara, 2009]:

- Has a model top of ~150 km (lower thermosphere)
- Resolves gravity waves (GWs) explicitly

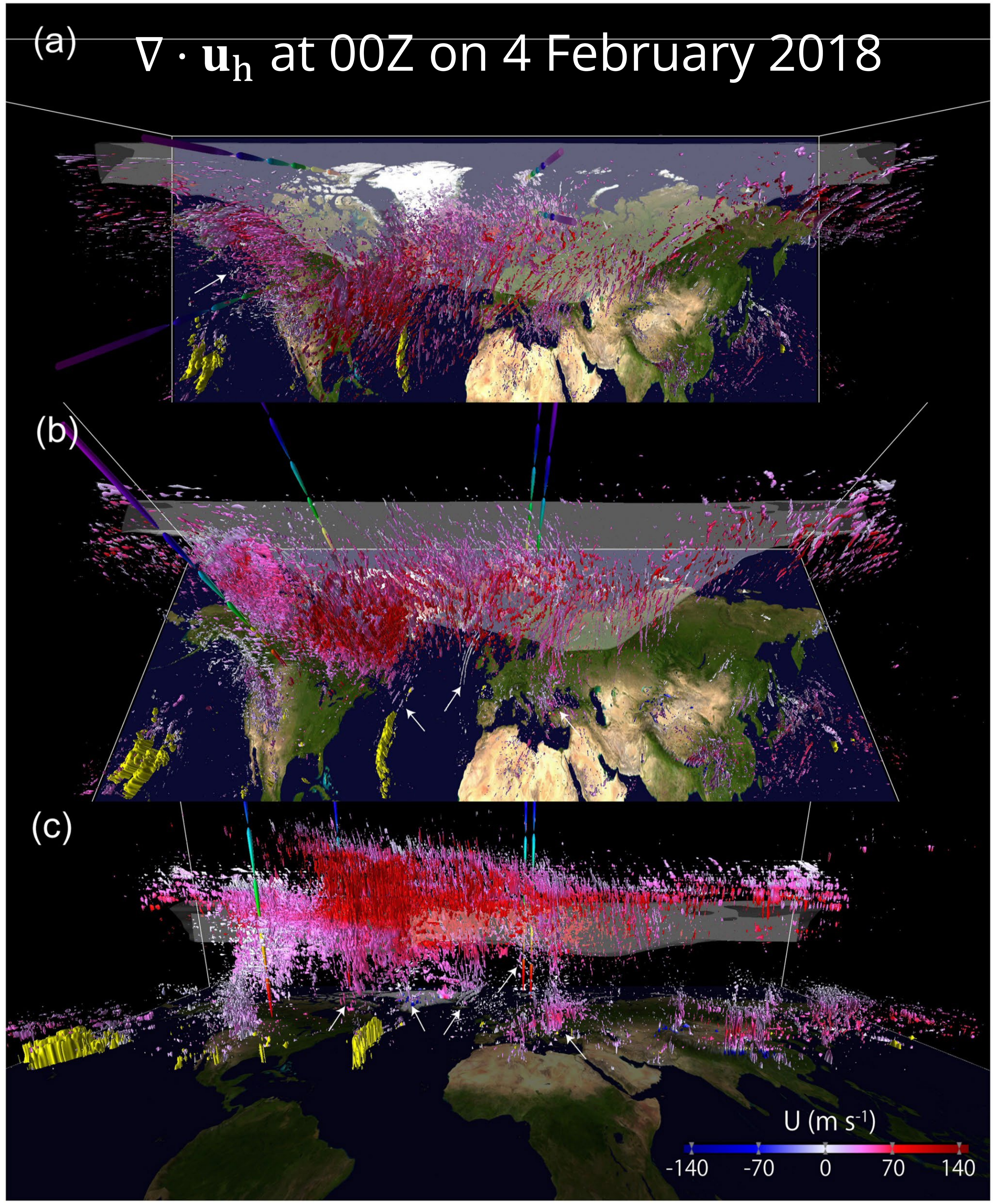
Right figure: GWs in the JAGUAR model

Major Achievements

Performing hindcast simulations for boreal winters with the JAGUAR model, we investigated:

- Roles of GWs in mesospheric response to a stratospheric sudden warming (e.g., the elevated stratopause) [Okui et al., 2021]
- Causes of the steepness of GW vertical wavenumber (m) spectra ($\propto \sim m^{-3}$) in the middle atmosphere [Okui et al., 2022]

How reliable are GWs in JAGUAR?



3-D views of GW signatures in JAGUAR T639L340 at 00:00UTC on 4 February 2018. Isosurfaces of the divergence of the horizontal wind of -6×10^{-5} s^{-1} are displayed, whose colors show the local background eastward winds. [Fig. 1 of Watanabe et al., JGR, 2022]

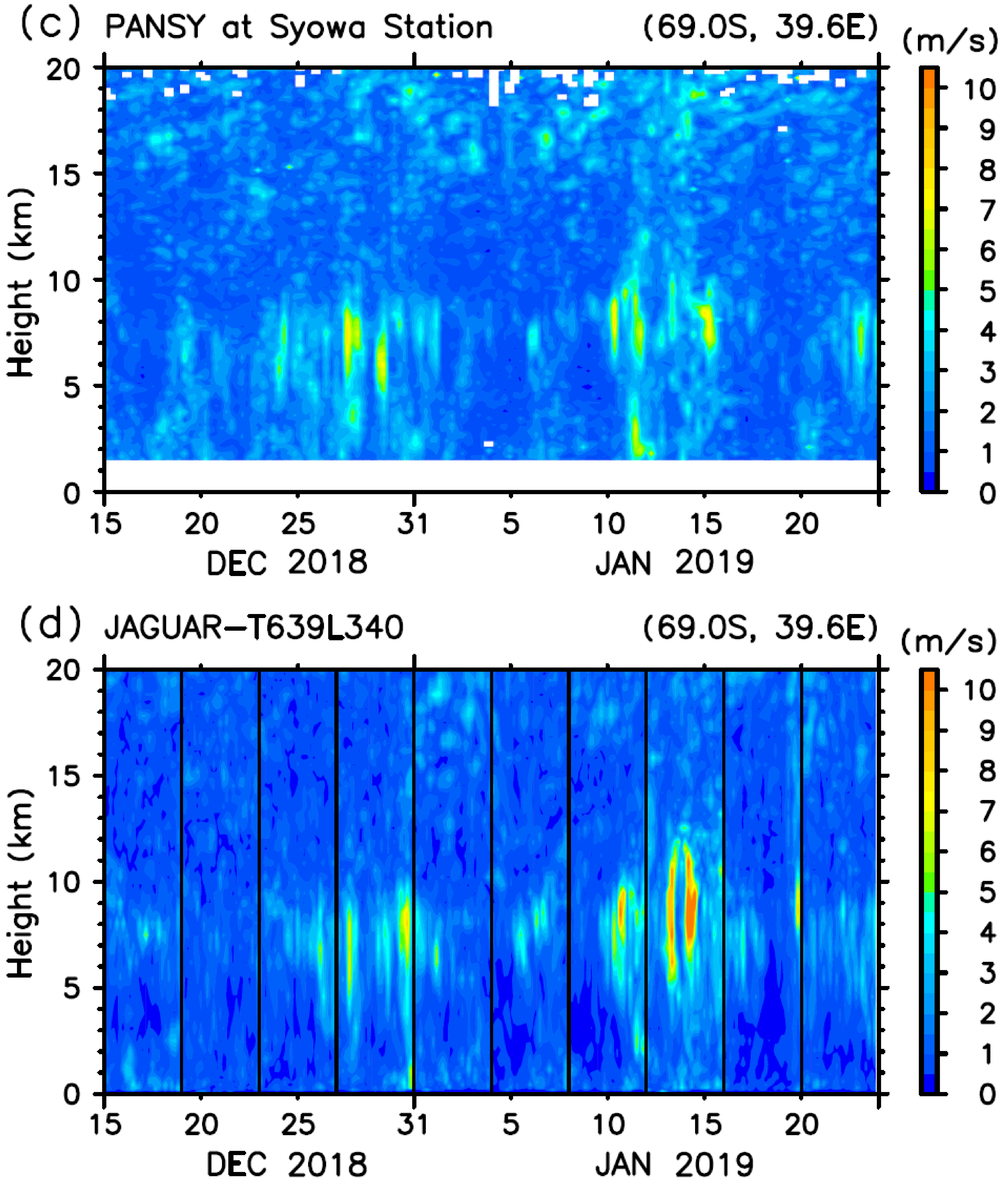
Comparison with Observations

- GWs in the upper troposphere & lower stratosphere (→) in the JAGUAR model are in good agreement with GWs observed by several radars.
- GWs in the upper mesosphere (not shown) are also roughly consistent with radar observations.

► However, these comparisons were done only for several radar stations

► Global comparison of GWs in the model with observations is necessary for further model validation.

► Comparison with high-resolution satellite observations will serve this purpose.



The magnitude of horizontal wind disturbances of GWs at Syowa Antarctic station from 15 Dec 2018 to 23 Jan 2019. (Top) Observed by the PANSY MST/IS radar. (Bottom) Obtained from JAGUAR hindcasts. Vertical lines denote the boundaries between two free-runs. [Sato et al., conditionally accepted by JGR, 2023]

Other High-resolution High-top GCMs & Their Validation of GWs

- Kruse et al. [2022]:
  Showed good agreement of orographic GWs over the Drake Passage in two high-resolution GCMs: IFS & ICON models, whose model tops are ~80 km, with those observed by AIRS

- Becker et al. [2022]:
  Nudged High Altitude Mechanistic general Circulation Model (HIAMCM) to MERRA-2 and demonstrated that the model simulated a GWs over Northern Europe in January 2016 consistently with AIRS temperature measurements

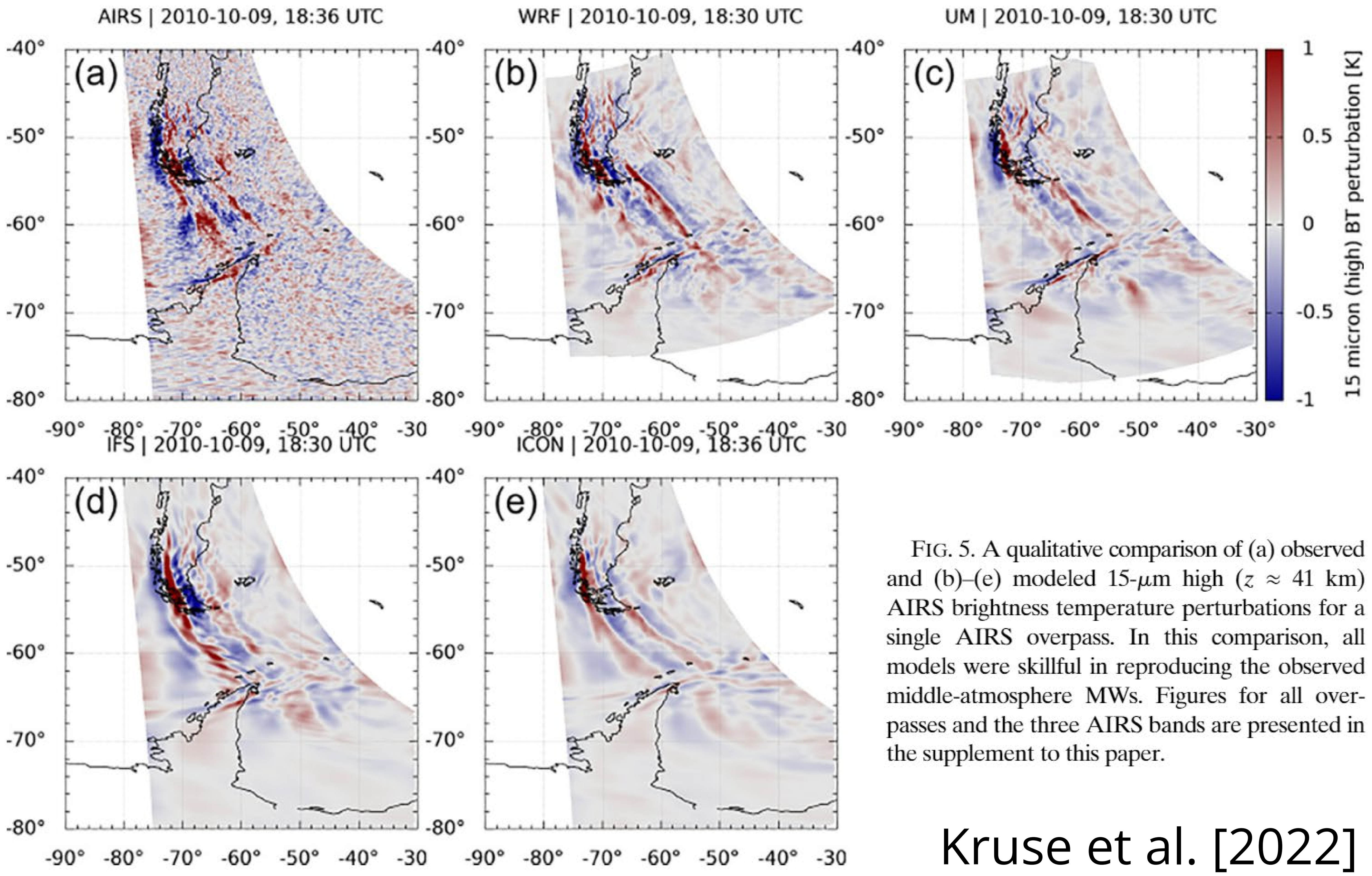


FIG. 5. A qualitative comparison of (a) observed and (b)–(e) modeled 15-μm high ($z \approx 41$ km) AIRS brightness temperature perturbations for a single AIRS overpass. In this comparison, all models were skillful in reproducing the observed middle-atmosphere MWs. Figures for all overpasses and the three AIRS bands are presented in the supplement to this paper.

Kruse et al. [2022]

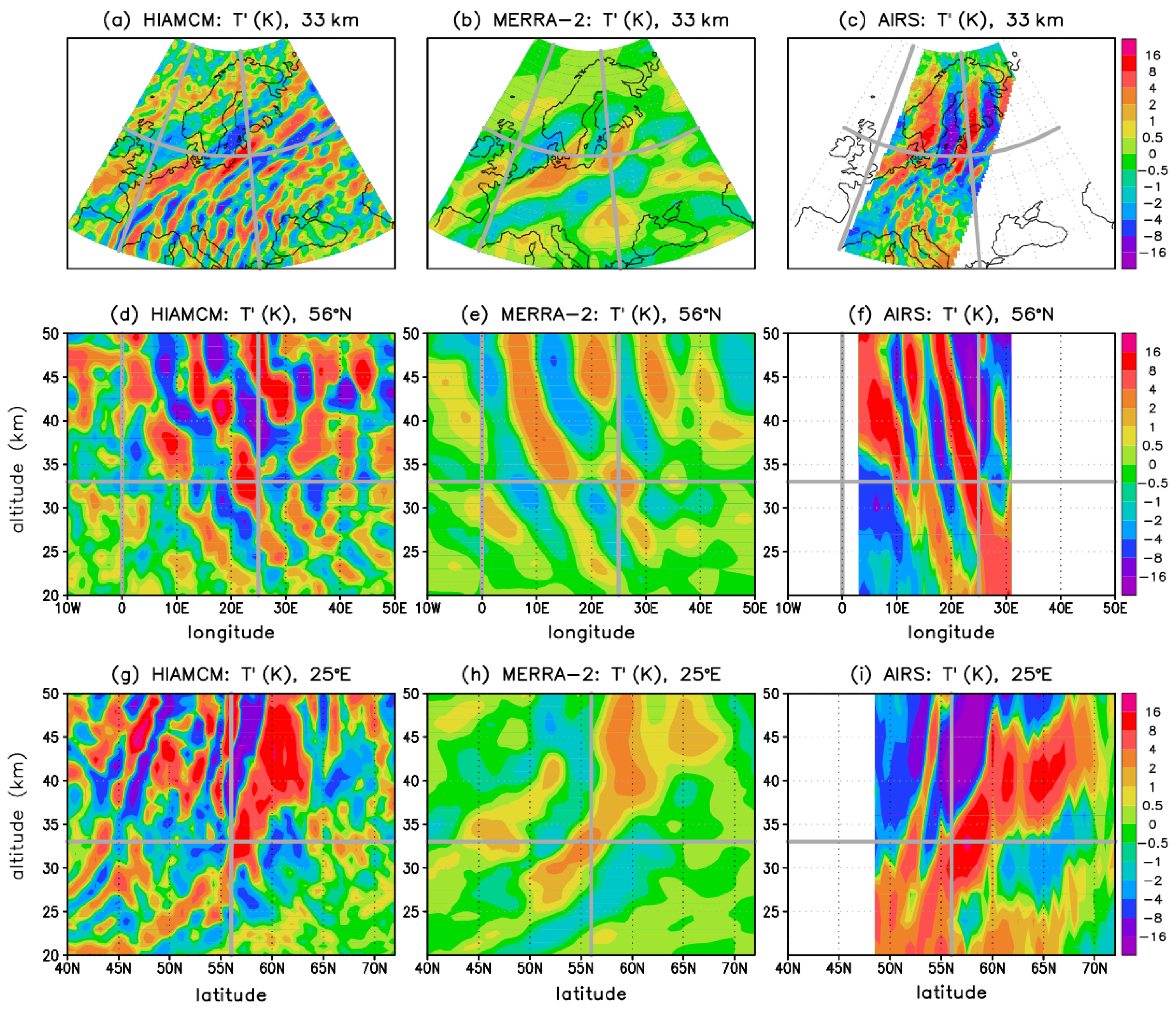


Figure 8. Instantaneous temperature perturbations during a gravity wave (GW) event over Northern Europe at 1:30 UT on 11 January 2016 from the nudged HIAMCM (left), MERRA-2 reanalysis (middle), and AIRS (right). First row: horizontal map segments at 33 km height from 10°W to 50°E and from 40°N to 72°N. Second row: longitude-height cross-sections at 56°N. Third row: latitude-height cross-sections at 25°E. The gray lines mark the longitudes 0° and 25°E, the latitude 56°N, and the height 33 km. These lines are included for better comparison of the different panels.

Becker et al. [2022]

Model & Simulations

- Model description is shown in the right-hand table.
- As the initial values, JAGUAR-Data Assimilation System (DAS) Reanalysis data were used. This dataset was created by using a lower-resolution (T42L124) version of JAGUAR.
  ➡ The free-run simulations are "hindcasts".
- Free runs for 4 days each were analyzed.

Japanese Atmospheric GCM for Upper Atmosphere Research (JAGUAR) [Watanabe & Miyahara, 2009]:

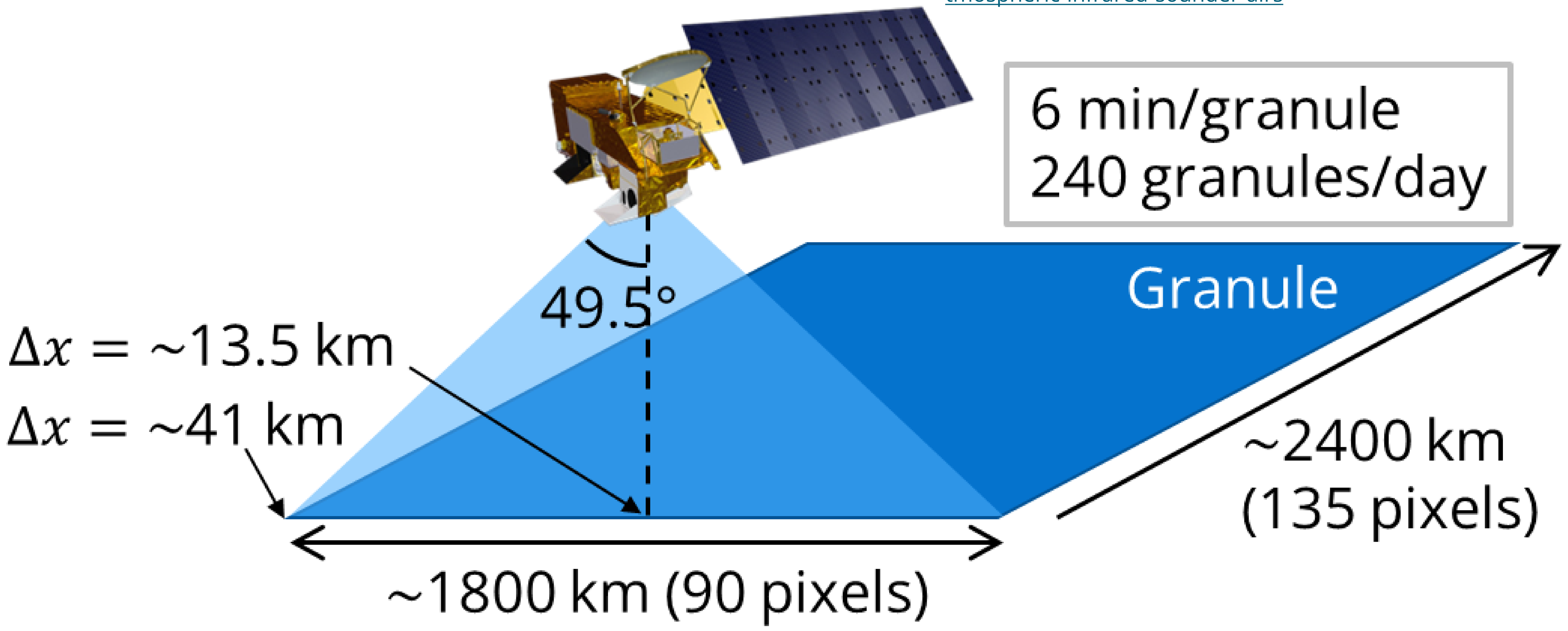
Vertical domain	0–150 km
Resolution	Horizontal resolution: T639 ($\lambda_h \gtrsim$ 60 km) Vertical resolution: 300 m (340 layers)
GW parameterization	Not used
Initial values	JAGUAR-Data Assimilation System (DAS) Reanalysis [Koshin et al. 2020, 2022] ◄ PREPBUFR, MLS, SABER & SSMIS are assimilated by the 4D-LETKF method.
Cycle of simulation	3-day spectral nudging & 4-day free-run
Analyzed period	15 December 2018 – 8 January 2019 * SSW onset: 1 January 2019

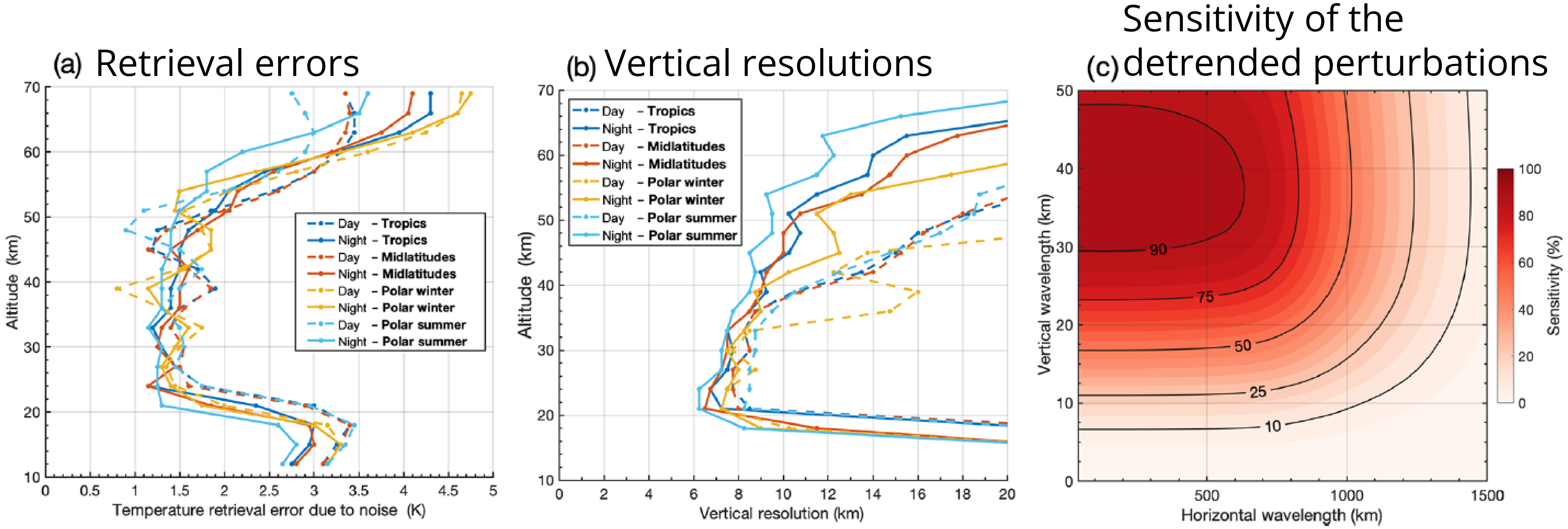
Atmospheric Infrared Sounder (AIRS)

- A nadir-sounding multi-spectral imager aboard NASA's Aqua satellite
- A sun-synchronous near-polar orbit at a height of ~700 km
- Retrieval scheme: [Hoffmann & Alexander [2009]]
- Detrended using a 4th-order polynomial in the cross-track direction to extract GWs

3-D temperature retrieval in a height region of 10–60 km were used in this study. Results are shown mainly for a height (z) of 39 km.

https://www.jpl.nasa.gov/missions/atmospheric-infrared-sounder-airs

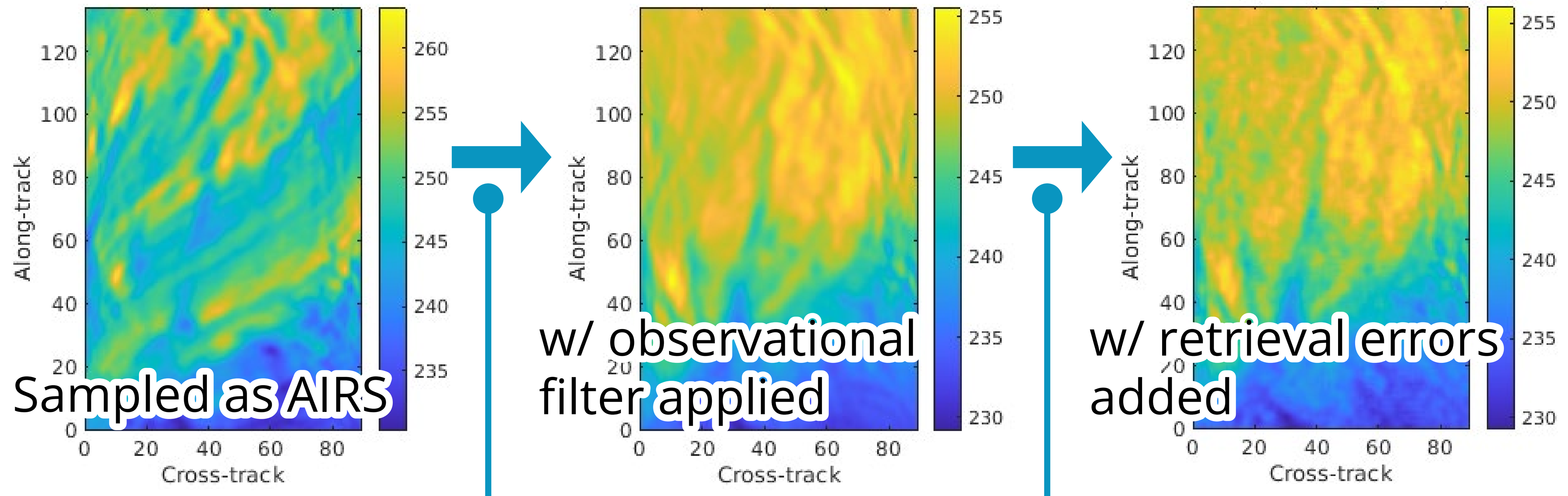


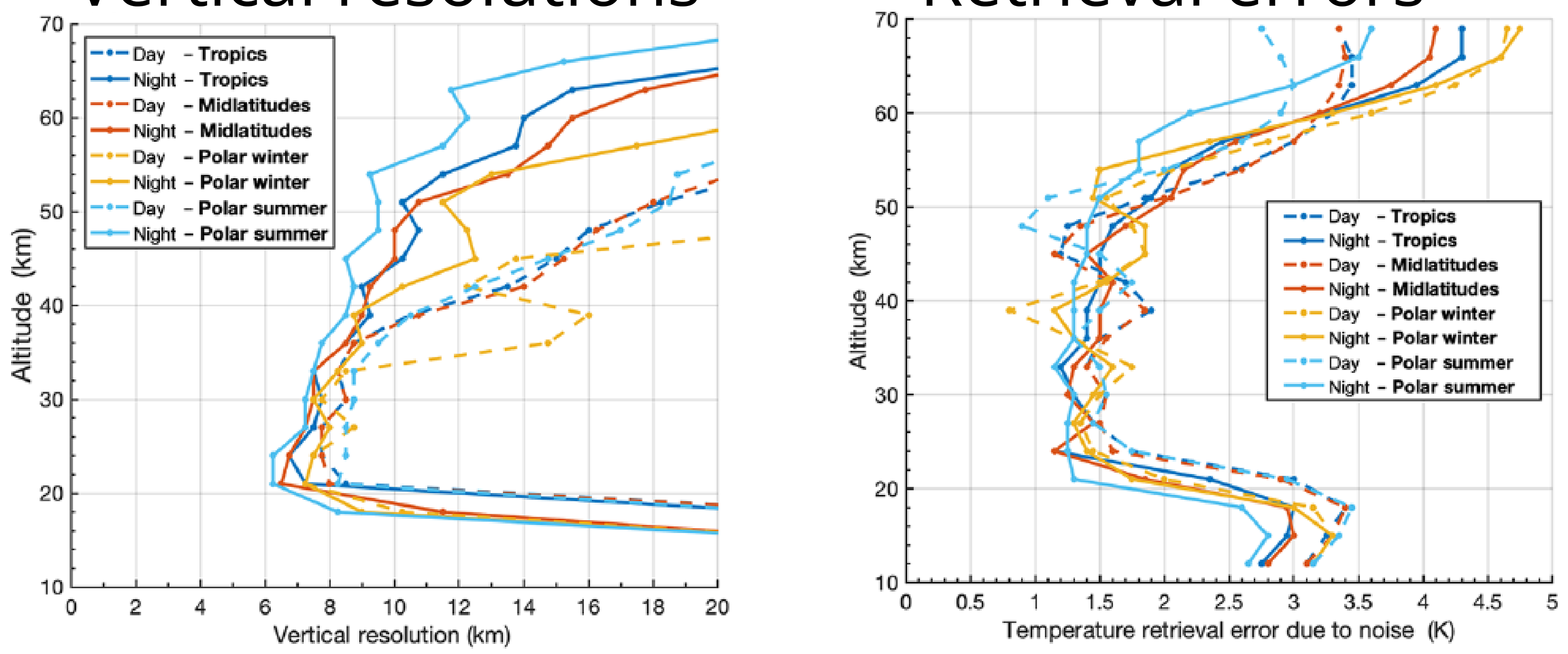


[Fig.2 of Hindley et al., 2019]

Analysis Method

JAGUAR temperature data





[Fig.2 of Hindley et al., 2019]

AIRS 3-D temperature retrieval

Detrend each cross-track row using a 4th-order polynomial

Regrid the data on to a regular grid with grid spacing of 20 km x 20 km x 3 km in x (cross-track), y (along-track), and z (vertical) directions

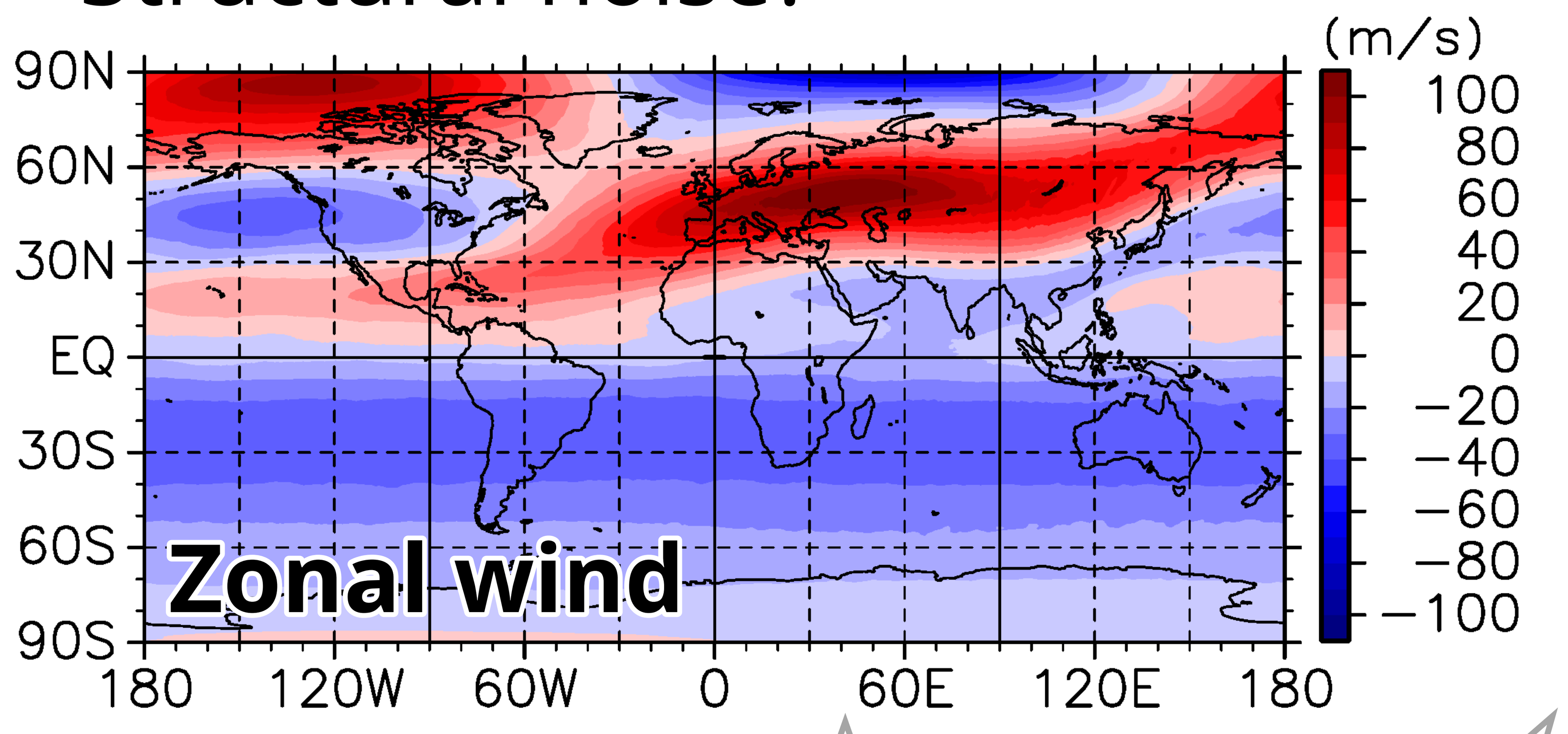
Estimate amplitudes and wavelengths by using the 3-D Stockwell transform [e.g., Hindley et al., 2019]

Global Features at z= 39 km

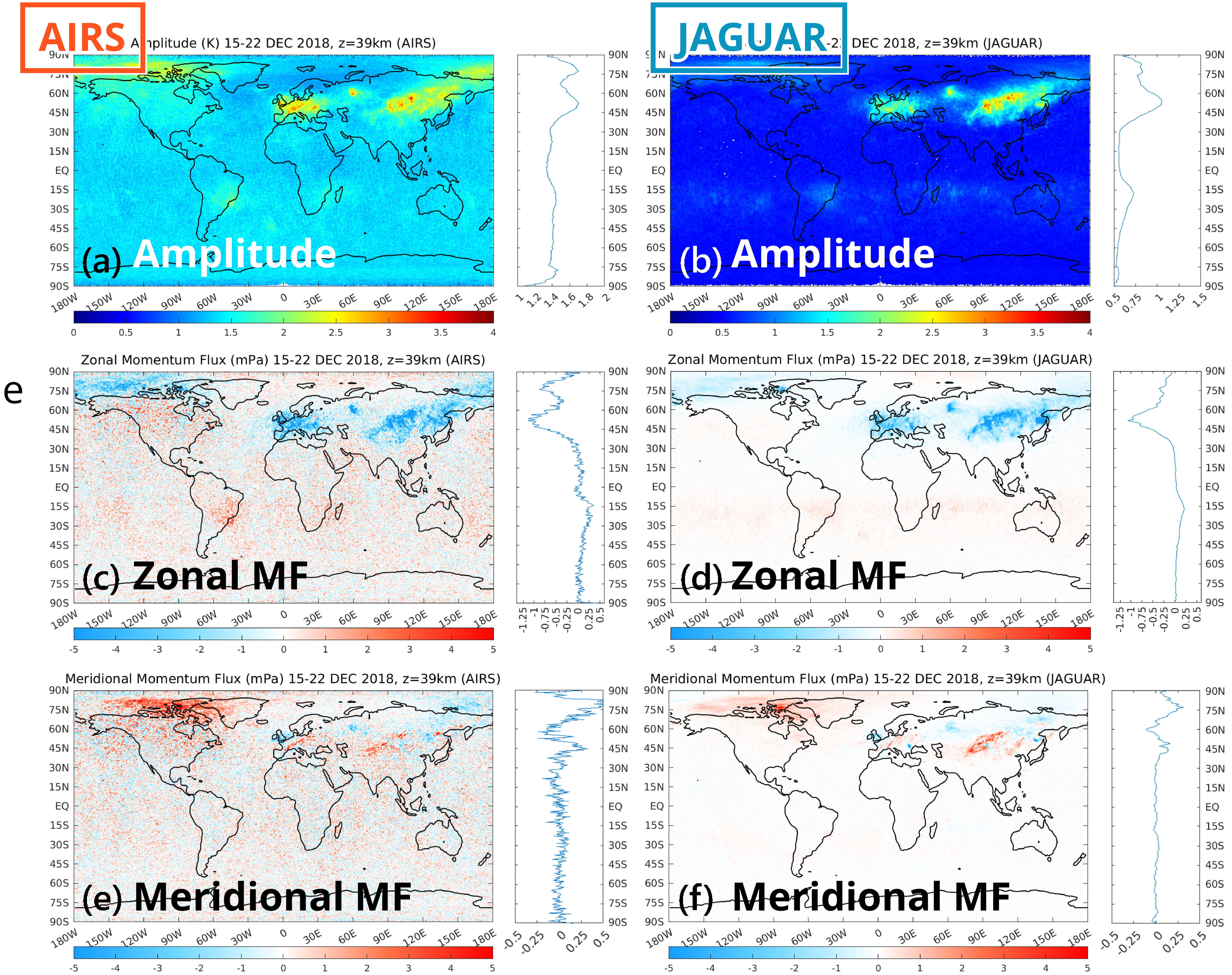
15 – 22 Dec 2018 (Day −17 – −10*)

*Day 0 ≡ SSW19 onset

- The magnitudes and distribution of peaks in amplitudes and momentum fluxes correspond surprisingly well (!)
- A nearly-uniform background amplitude level of ~1.4 K in the AIRS data cannot be seen in the JAGUAR data. Background momentum fluxes are ~0
  - ► Structural noise?



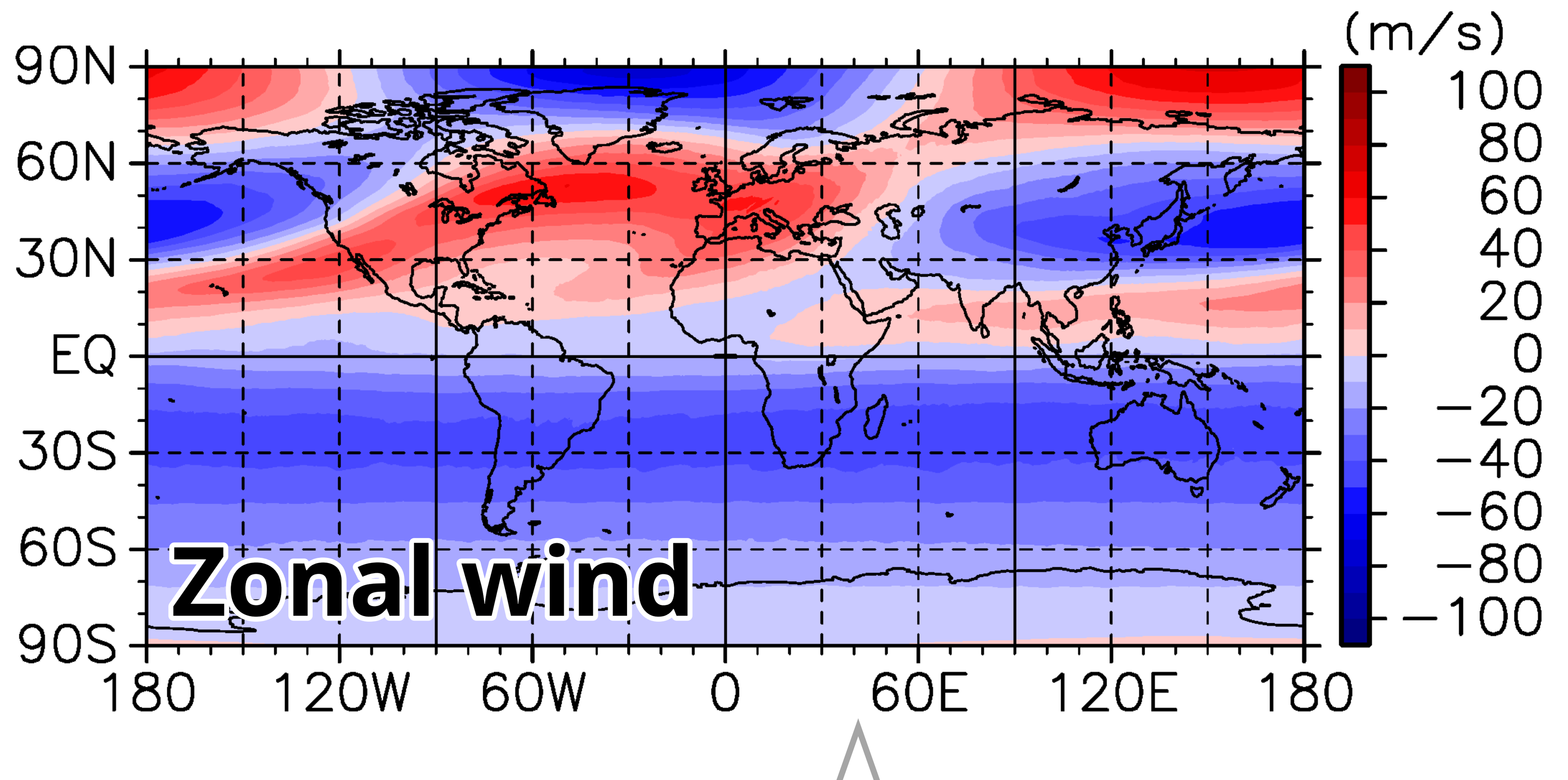
Large amplitudes and westward momentum fluxes are observed along the eastward jet



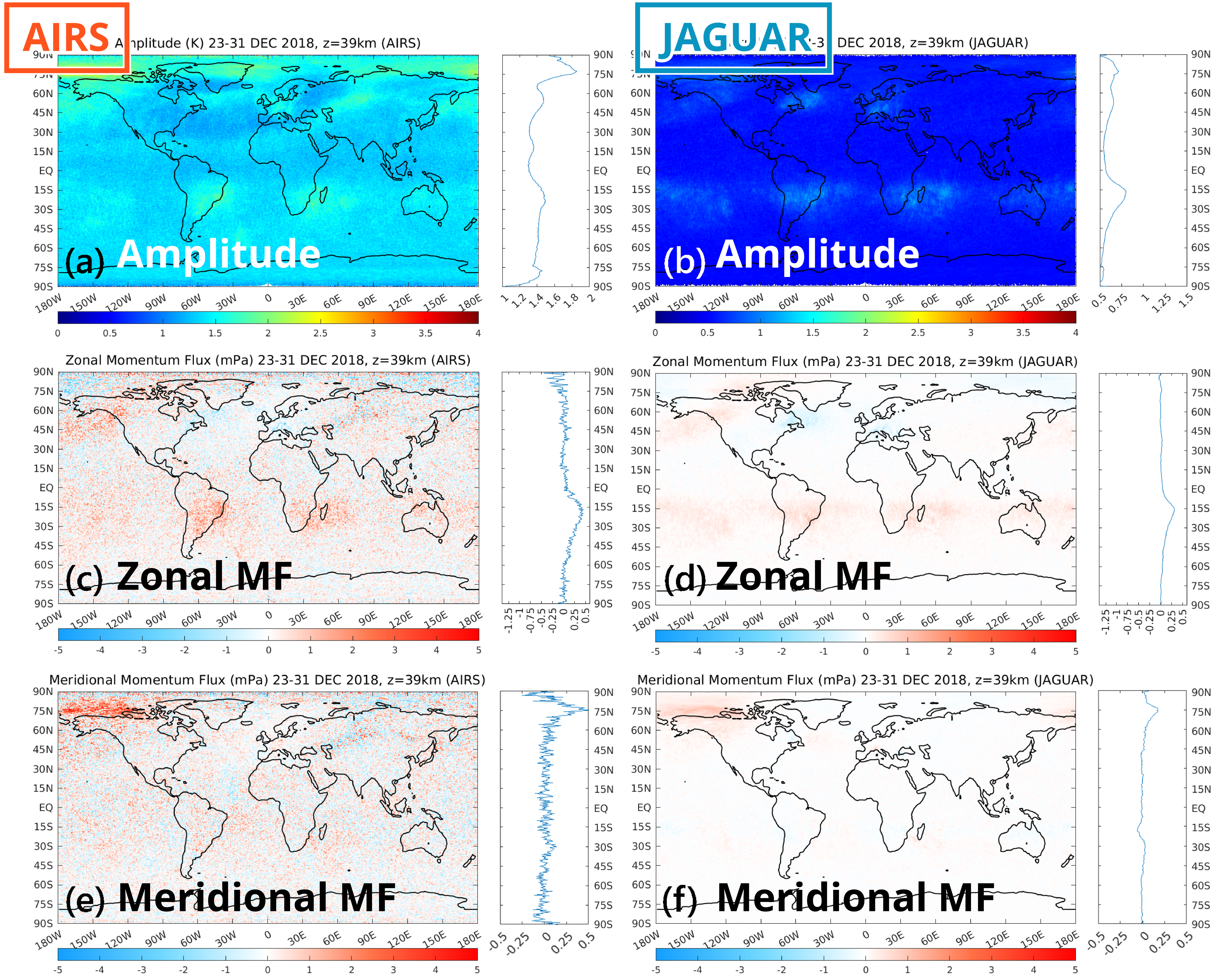
Global Features at z= 39 km

23 – 31 Dec 2018 (Day −9 – −1)

- GW amplitudes in the Northern Hemisphere (NH) become small
- Eastward momentum flux at ~15° S becomes stronger
  - ► Likely due to the enhancement of the westward jet in the SH



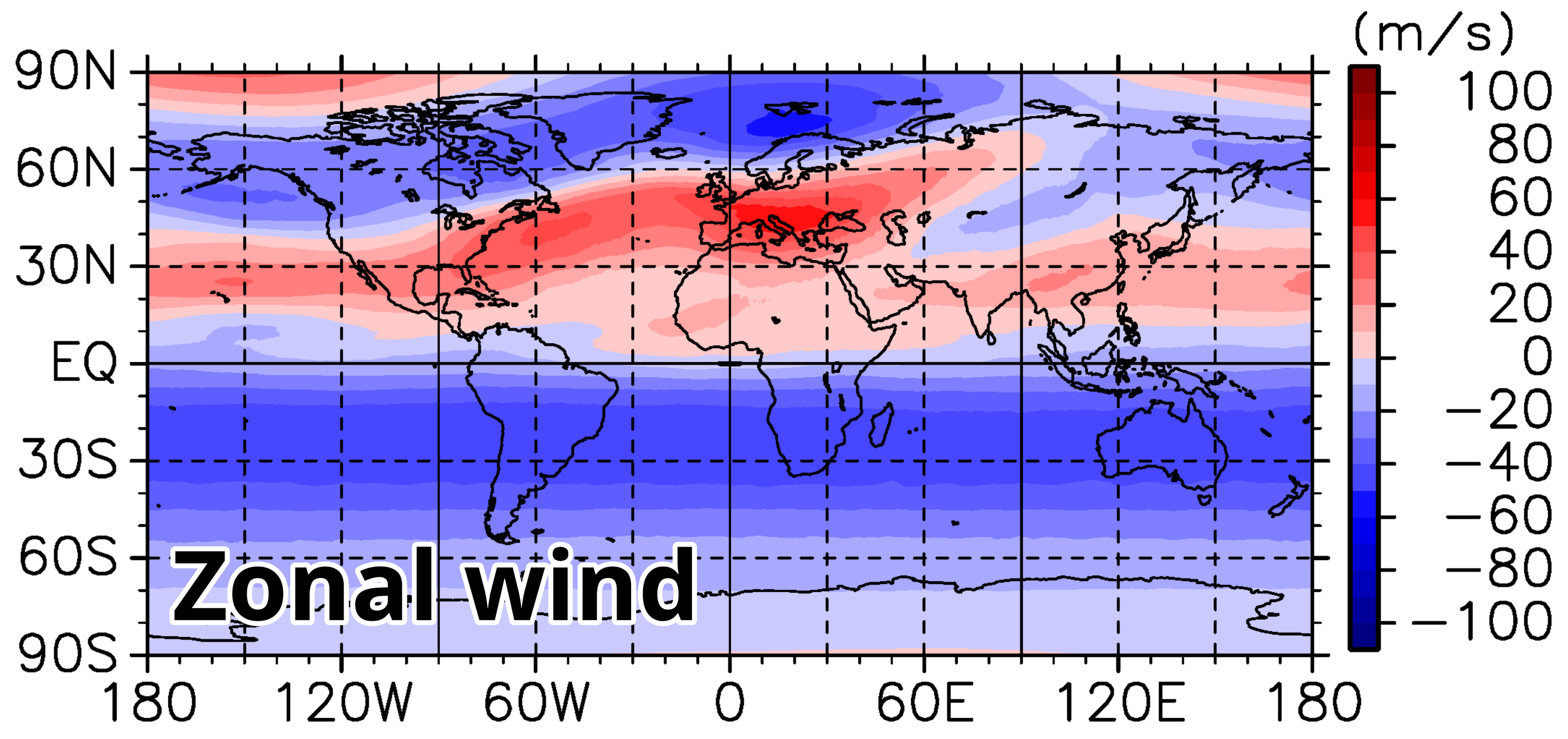
- WN1 structure in the NH
- Stronger SH westward jet

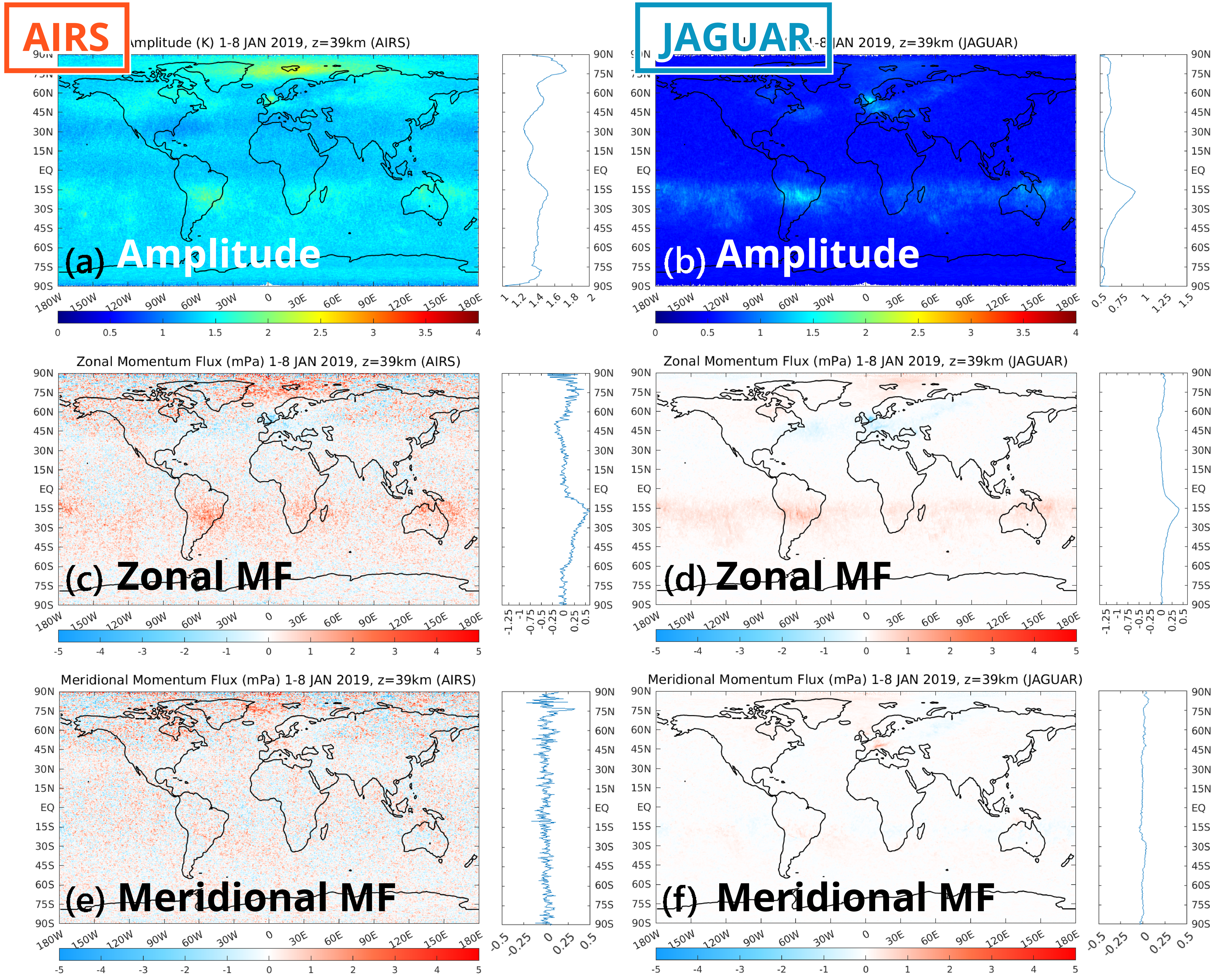


Global Features at z= 39 km

1 – 8 Jan 2019 (Day 0 – 7)

- There is an enhancement of the eastward momentum flux at ~15° S, which is more significant in the AIRS data than in the JAGUAR data

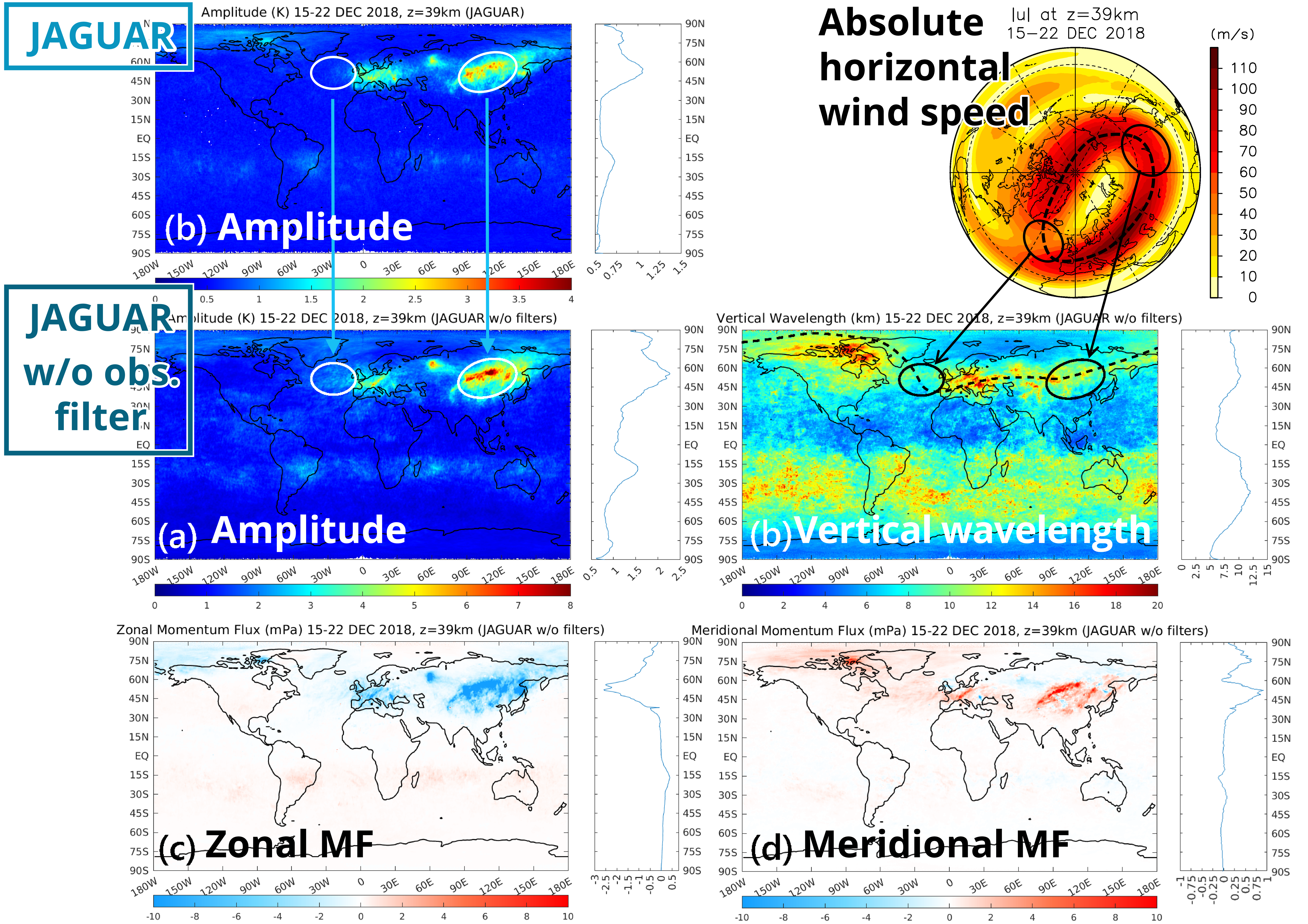




Effects of the AIRS Observational Filter

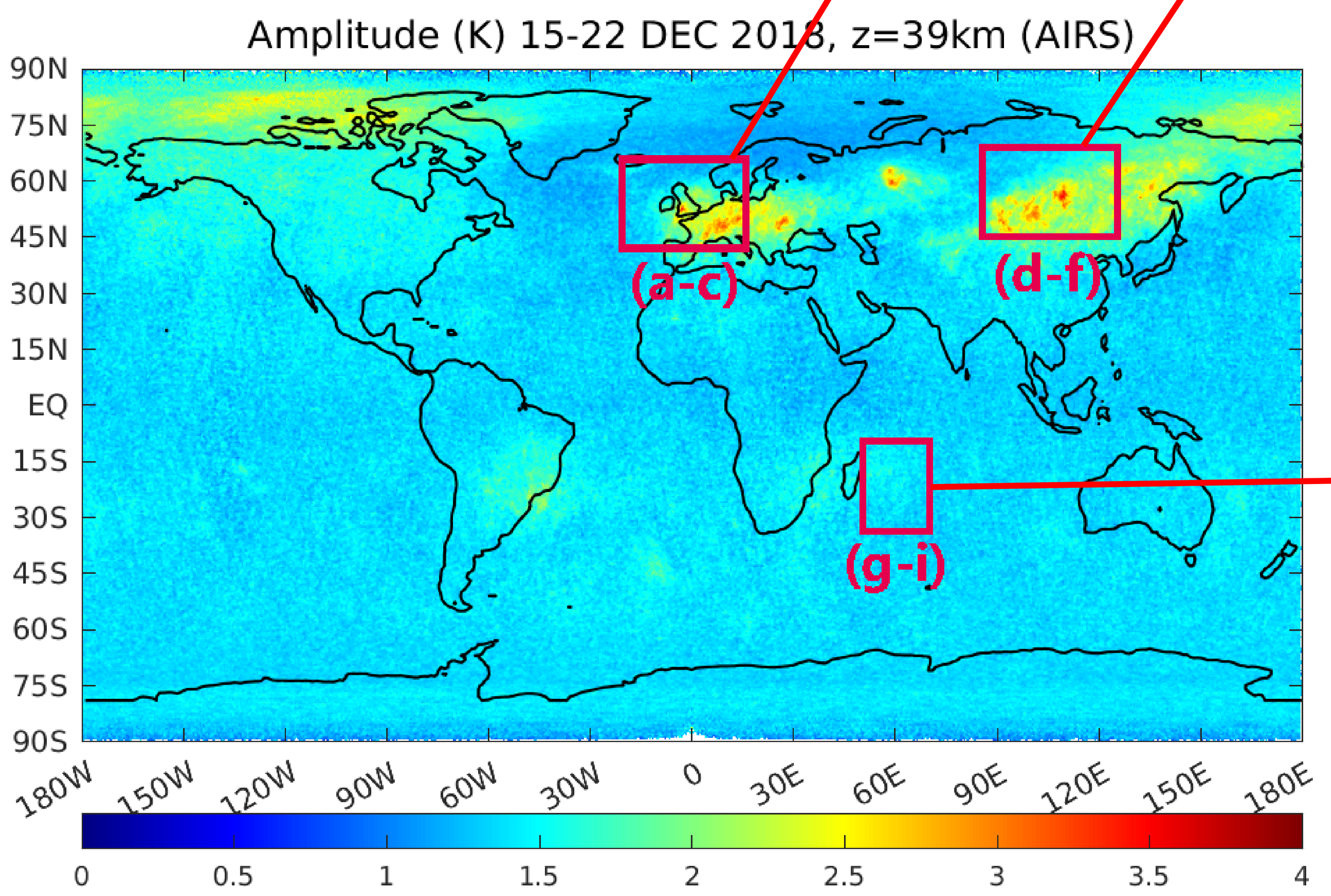
To examine the effect of the low vertical resolution of the AIRS measurements, JAGUAR data without the AIRS observational filter applied.

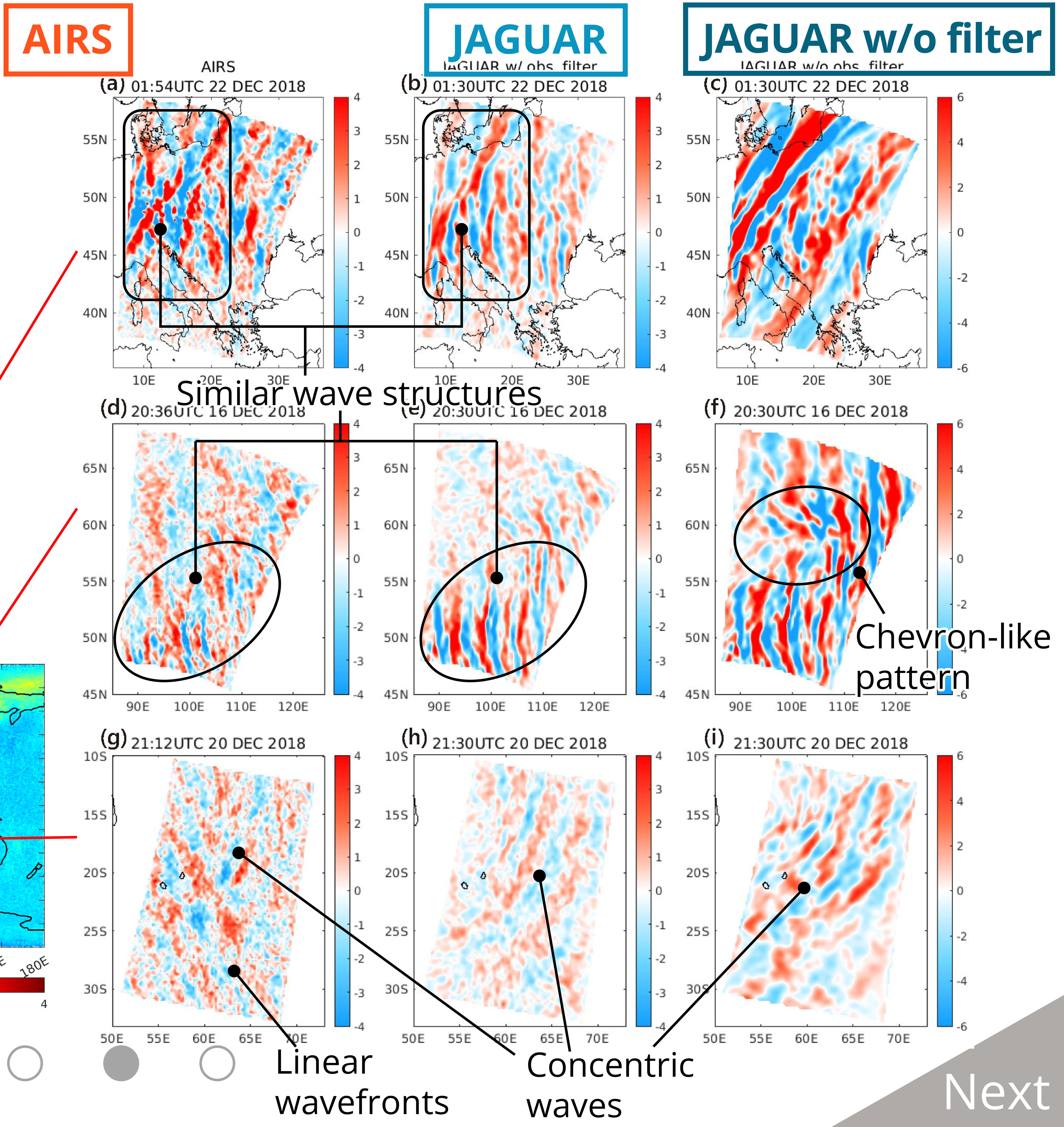
- Around the exits & entrances of the jet streaks, vertical wavelengths (Fig. b) of GWs are relatively shorter compared with GWs along the eastward jet at other longitudes
- In these regions, GW amplitudes have especially larger values than the JAGUAR result with the observational filter



Case Studies

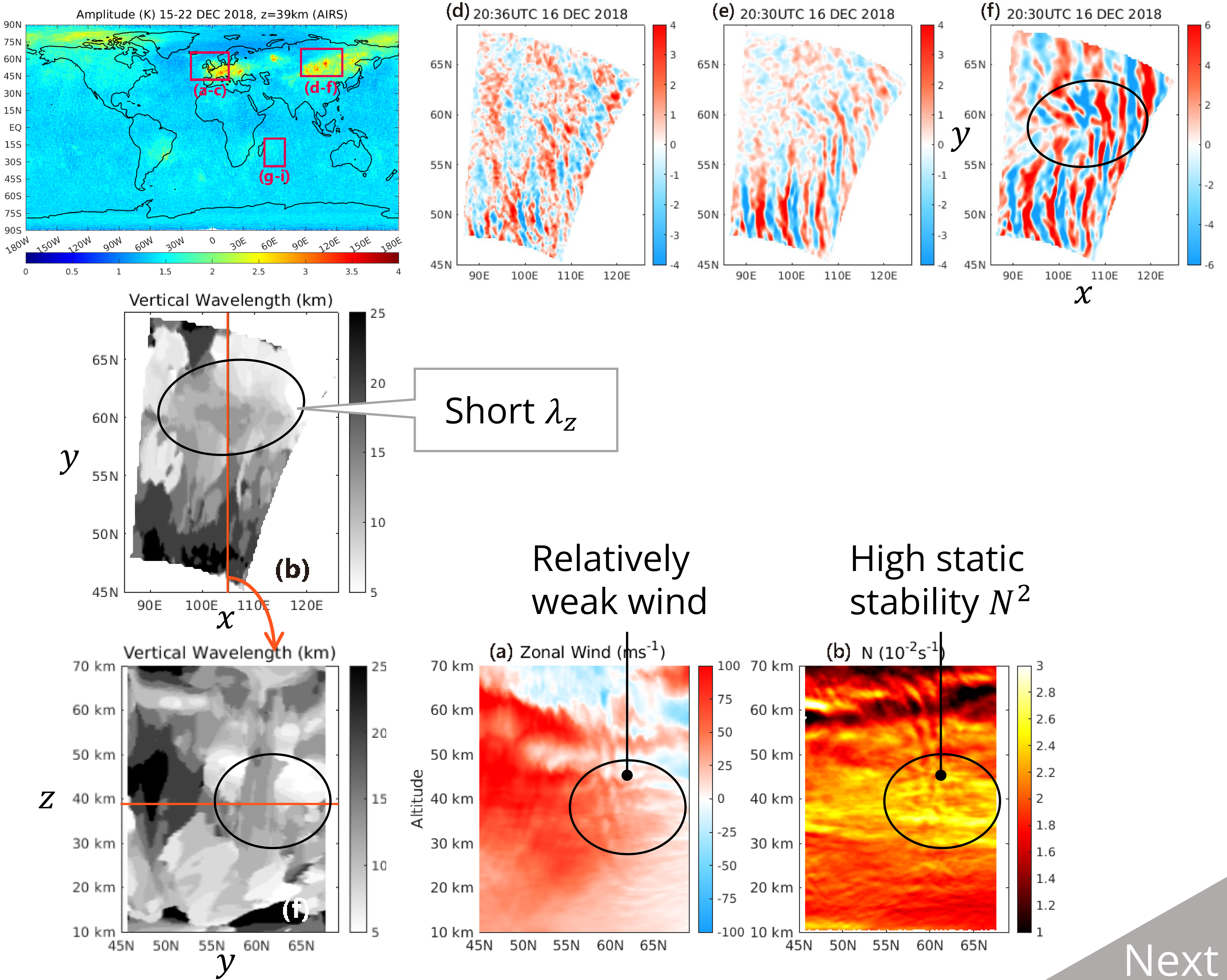
- Over Europe (Figs. a–c):
  - Similar wavefronts distributed meridionally in Figs. a & b
- Over eastern Eurasia (Figs. d–f):
  - Fine horizontal-scale wave structure in the south of Figs. d & e
  - Chevron-like pattern at ~58° N in Fig. f
- In the east of Madagascar (Figs. g–i):
  - Concentric waves in Figs. g–i
  - Linear wavefronts in the south-west of Fig. g are hardly seen in Figs. h & i





Case Studies

- Over eastern Eurasia:
  - Waves having short vertical wavelengths (λ_z) of 5–10 km form chevron-like pattern at ~58° N in Fig. f in the prev. slide
    - ► GWs generated by spontaneous adjustment?
    - ► The vertical resolution of AIRS temperature retrieval seems to be insufficient to resolve all of them
  - Short λ_z are distributed around a region of relatively weak background wind & high static stability
    - ► Typical for the poleward edge of the polar vortex



Summary & Concluding Remarks

A comparison of stratospheric GWs in the **GW-permitting GCM, JAGUAR** with 3-D temperature measurements by **AIRS** has been made for the period of 15 December 2018–8 January 2019.

The two datasets show **surprisingly good quantitative agreement** in:

1. **The peaks** in the amplitudes and zonal and meridional momentum fluxes of GWs
2. **The distribution of GW characteristics**: high GW activity in Europe, over the Ural Mountains, in eastern Eurasia, and in the low-latitude region in the summer hemisphere
3. **The attenuation and reinforcement of GWs** along the winter eastward jet and summer westward jet **during the SSW occurrence**, respectively

Some **differences** have also been observed:

4. **GWs at low latitudes** are underestimated by JAGUAR.
5. **The background level in the AIRS GW amplitudes** cannot be fully explained by the retrieval noise added to JAGUAR GWs. There is almost no net momentum flux associated with the background amplitudes.

► We hypothesize that this is due to the internally-uncorrelated nature of the noise added.

In addition, it is suggested that **GWs near the exit of a jet streak** over eastern Eurasia are **underestimated in the AIRS observations** due to the relatively low vertical resolution of the instrument.

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