Investigating Multi-Scale Gravity Wave Dynamics with the Complex Geometry Compressible Atmospheric Model (CGCAM)

Wenjun Dong[1,2]

David C. Fritts[1,2], Thoms Lund[2], Alan Liu[1], Adam Lund[2], Tyler Mixa[2], Ling Wang[2] , Han-Li Liu[3], Jonathan Snively[2]

[1]Center for Space and Atmospheric Research (CSAR), Embry-Riddle Aeronautical University, Daytona Beach, FL, USA

[2]Global Atmospheric Technologies and Sciences (GATS), Boulder, CO, USA

[3]High Altitude Observatory (HAO), National Center for Atmospheric Research (NCAR), Boulder, CO, USA

2024.06.12

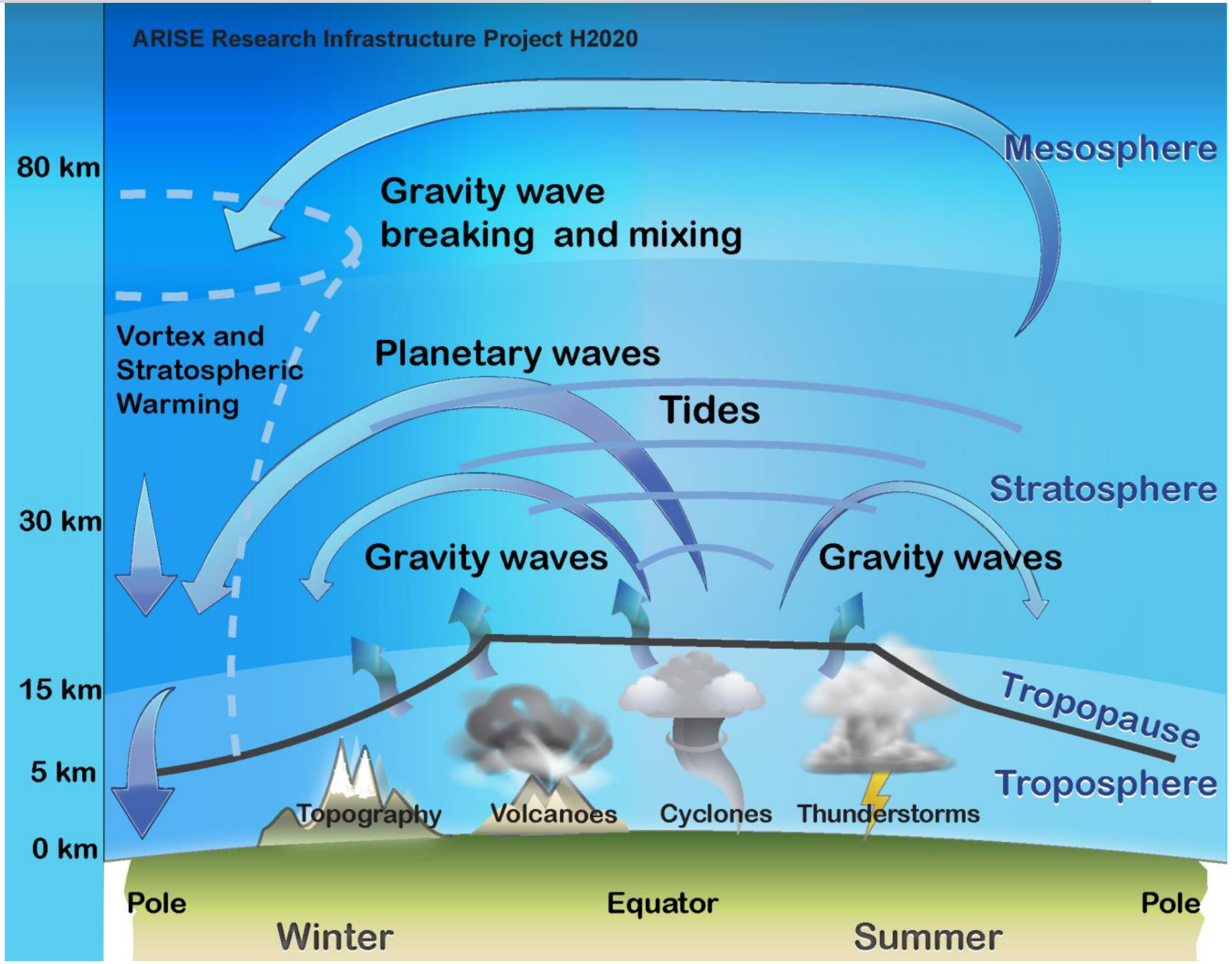
CEDAR Workshop, San Diego

Gravity Wave (GW)

GWs are oscillations in the atmosphere caused by the buoyant restoring force acting on displaced air parcels

Self-Acceleration (SA): GWs can transfer momentum to the mean flow, altering wind patterns and potentially accelerating the GWs themselves.

GW breaking occurs when their amplitude grows large enough to become unstable, leading to their collapse and resulting in turbulent mixing and energy dissipation.



Source:LASP

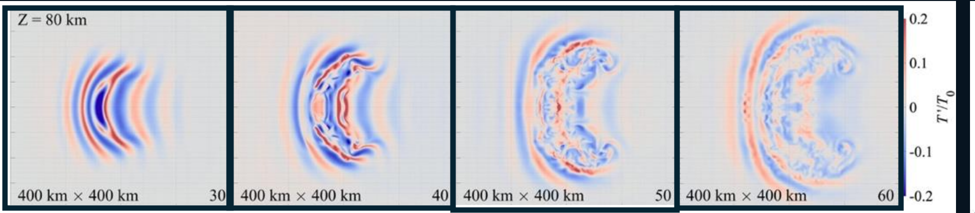
CGCAM Description

- **Numerical Framework:** Uses a finite-volume framework that ensures mass, momentum, total energy, and kinetic energy are conserved globally.
- **Complex Boundaries:** Handles various boundary conditions, making it suitable for simulating different atmospheric phenomena like wind shears, mountain waves, and convective plumes.
- **DNS and LES:** Can operate in Direct Numerical Simulation (DNS) mode to resolve all turbulent scales directly or in Large Eddy Simulation (LES) mode to simulate larger scales directly and model smaller scales.
- **Tracer Variables:** Models both passive and active tracer variables, useful for simulating things like PMC and airglow layer.
- **Data Assimilation:** Has a mode to incorporate data from observations or coarser simulations, imposing large-scale wind and thermodynamic fields as needed.
- **Computational Efficiency:** Uses stretch and block grids and is optimized for efficient performance on parallel computers.

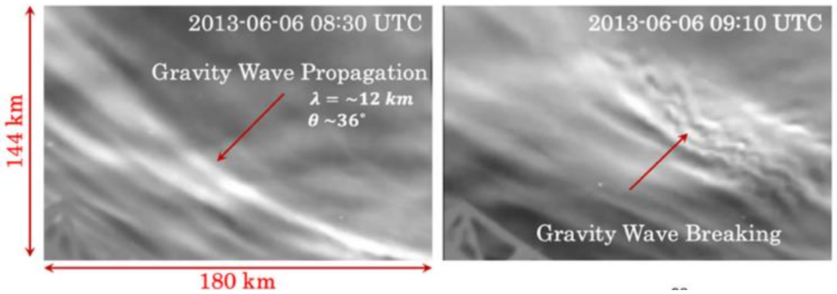
CGCAM is developed and maintained by the GATS team.

Example 1: GW Self-Acceleration and Breaking

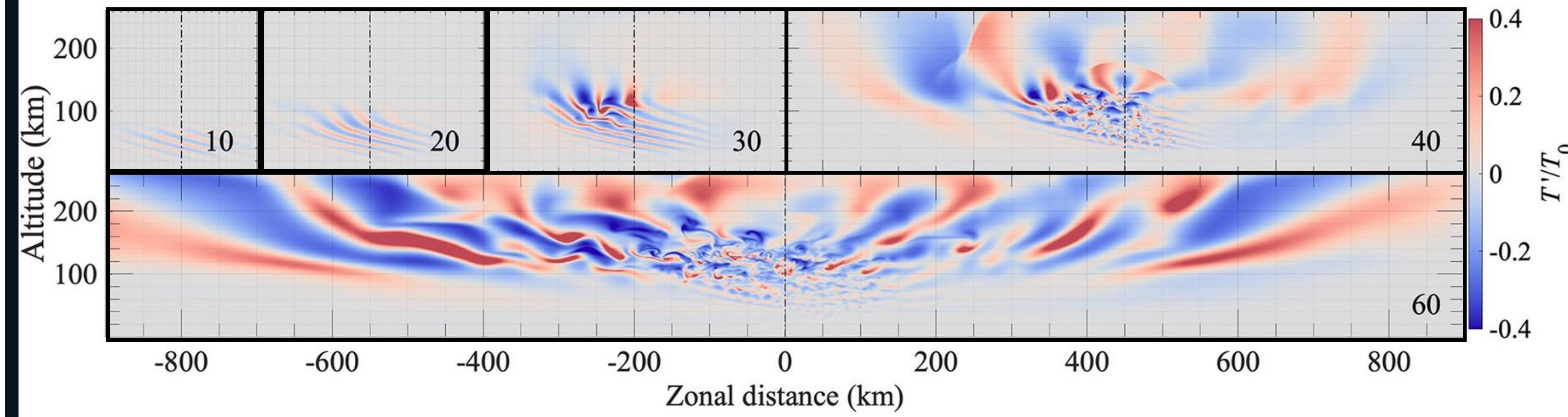
- Initial large-scale SGWs are driven by self-acceleration dynamics, not by GW breaking.
- GW breaking causes strong subsequence SGW and acoustic GW generations at higher altitudes



XY: GW T'/T_0 at 30, 40, 50 and 60 min (left to right) at 80 km altitude



AMTM Observations (Source: Dominique Pautet)



XZ: GW T'/T_0 at 10, 20, 30, 40, and 60 min (clockwise from upper left in each).

Dong et al.,2020, JGR (AGU EOS Highlight) and Fritts et al., 2020,JGR

Example 2: GW impacts on PMCs

- GWs can induce significant PMC advection, large-scale transport, and sublimation, which eventually leads to voids.

Dong et al., 2021,JGR

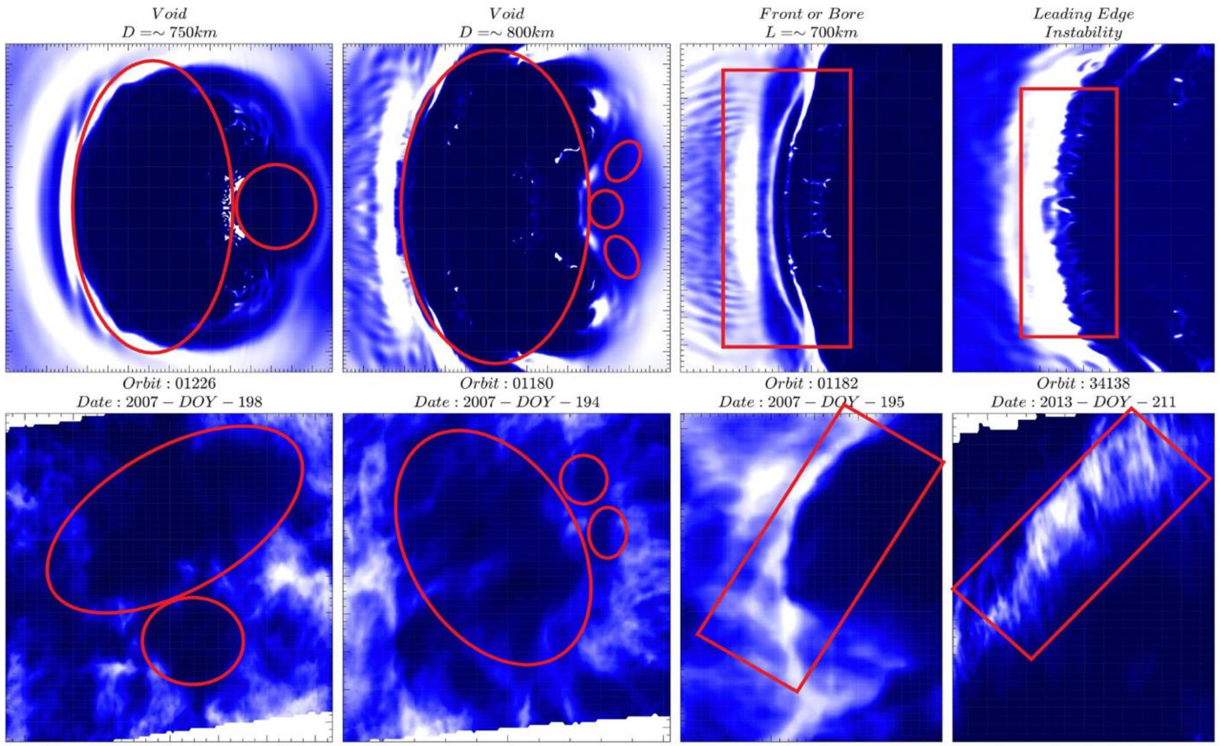
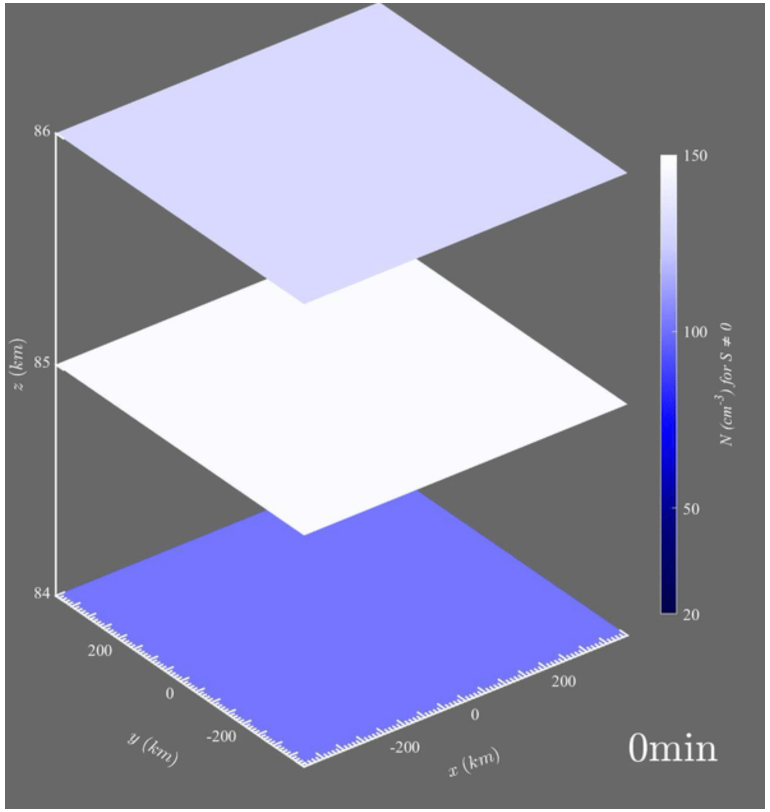


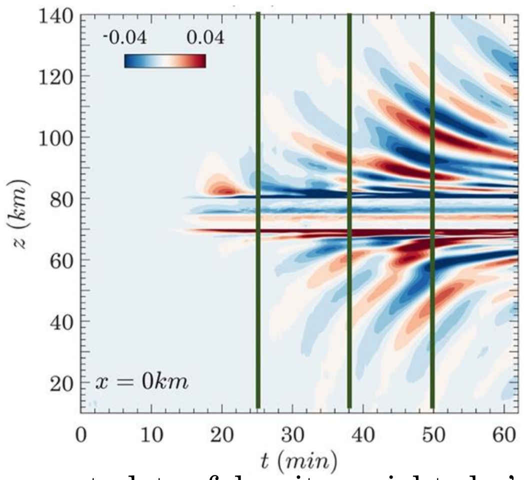
Figure 14. Modeled voids (columns 1 and 2) and leading-edge phase structures and instability dynamics (columns 3 and 4) (top, see text for details) and seen in example Cloud Imaging and Particle Size (CIPS) polar mesospheric cloud (PMC) imaging (bottom). Void diameters and front lengths are ~700–800 km. D and L denote void diameter and front length, respectively.



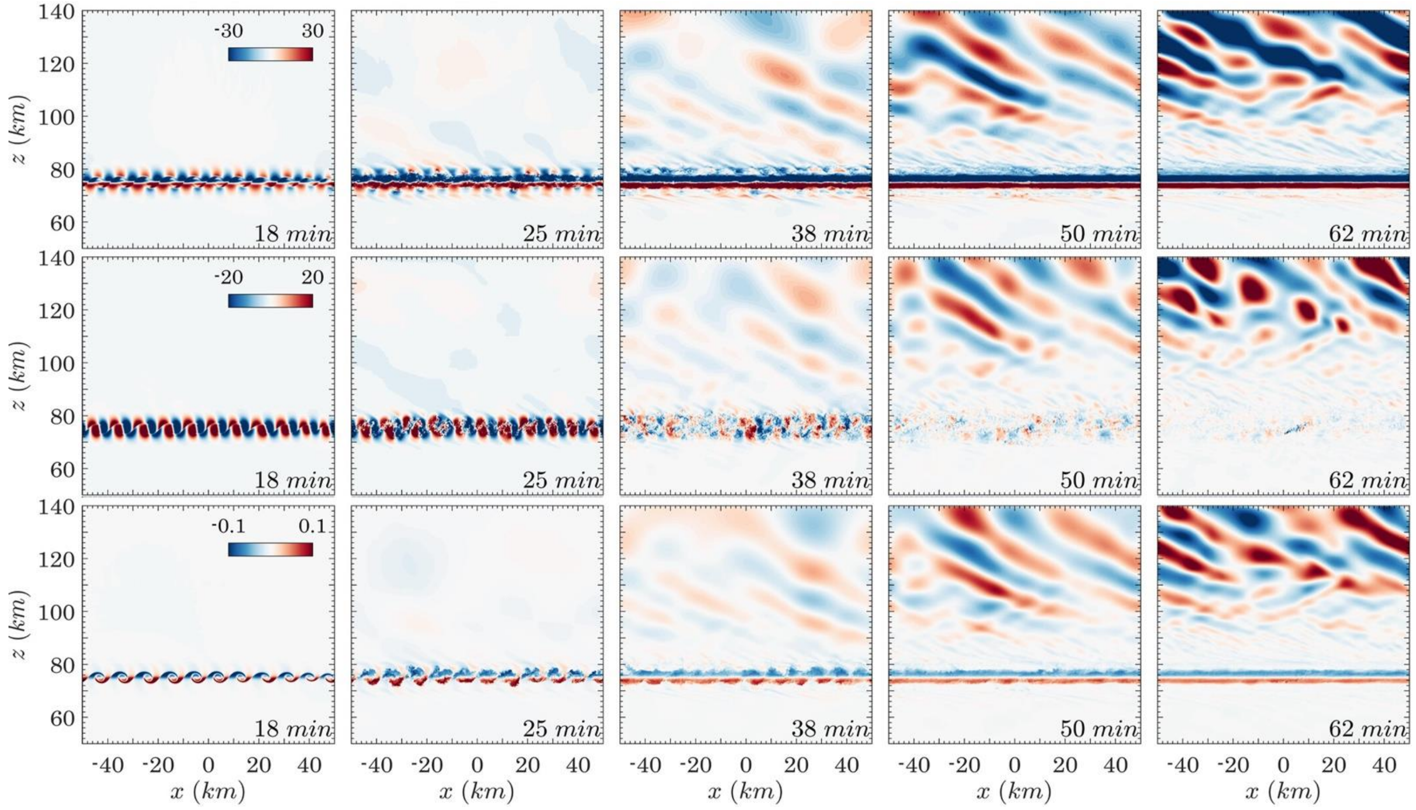
PMC ice particle number density x-y cross-sections at z = 84 km, 85 km, and 86 km

Example 3: KHI as GW source (Upscale Energy Cascade)

- Strong KHI results in the emission of high-frequency (~10-20 mins) and small-scale (~20 km) GWs.
- The density-weighted amplitudes of the KHI-radiated GWs give rise to a "fishbone" structure in z-t plots.



z-t plots of density-weighted u’

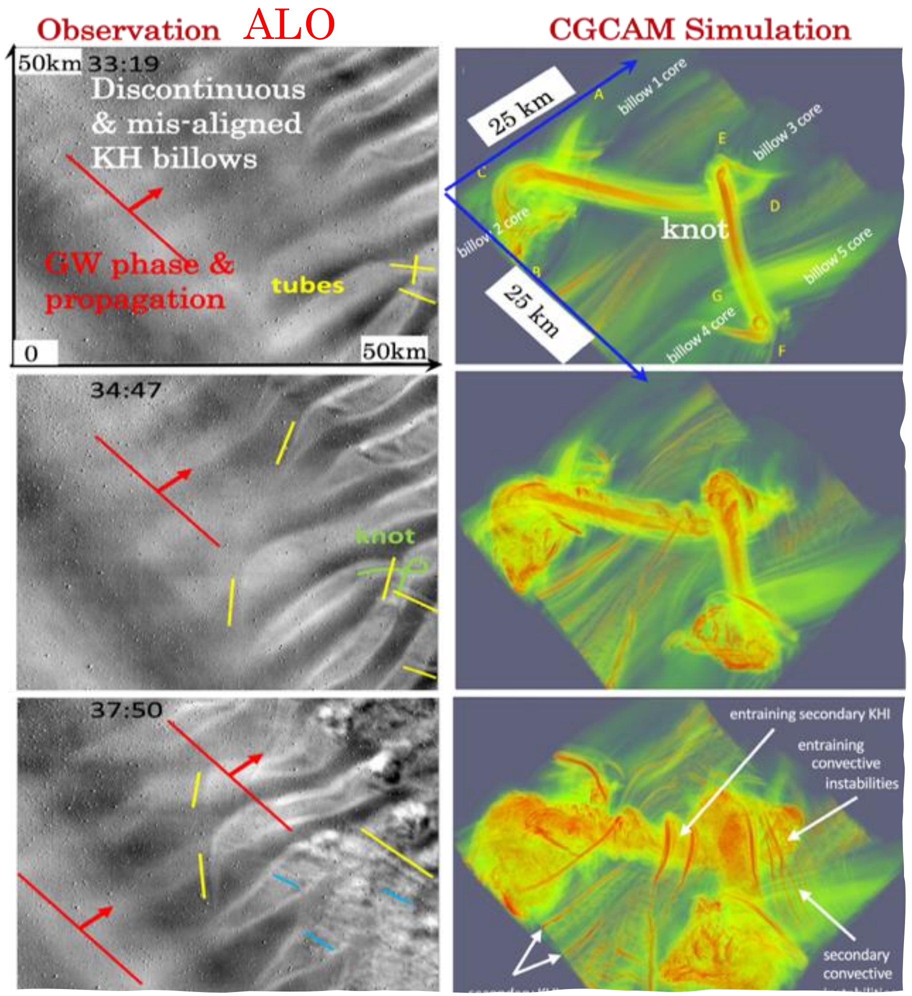


x-z cross sections of (top to bottom) u'(m/s), w'(m/s), and T/T0 at 18, 25, 38, 50, and 62 min (left to right).

KHI occurs at the interface between two layers moving at different velocities.

Dong et al., 2023, GRL (AGU EOS Highlight)

Example 4: KHIs Contribute to T&K (Downscale Energy Cascade)



Tube and Knot (T&K) indicates intense turbulence.

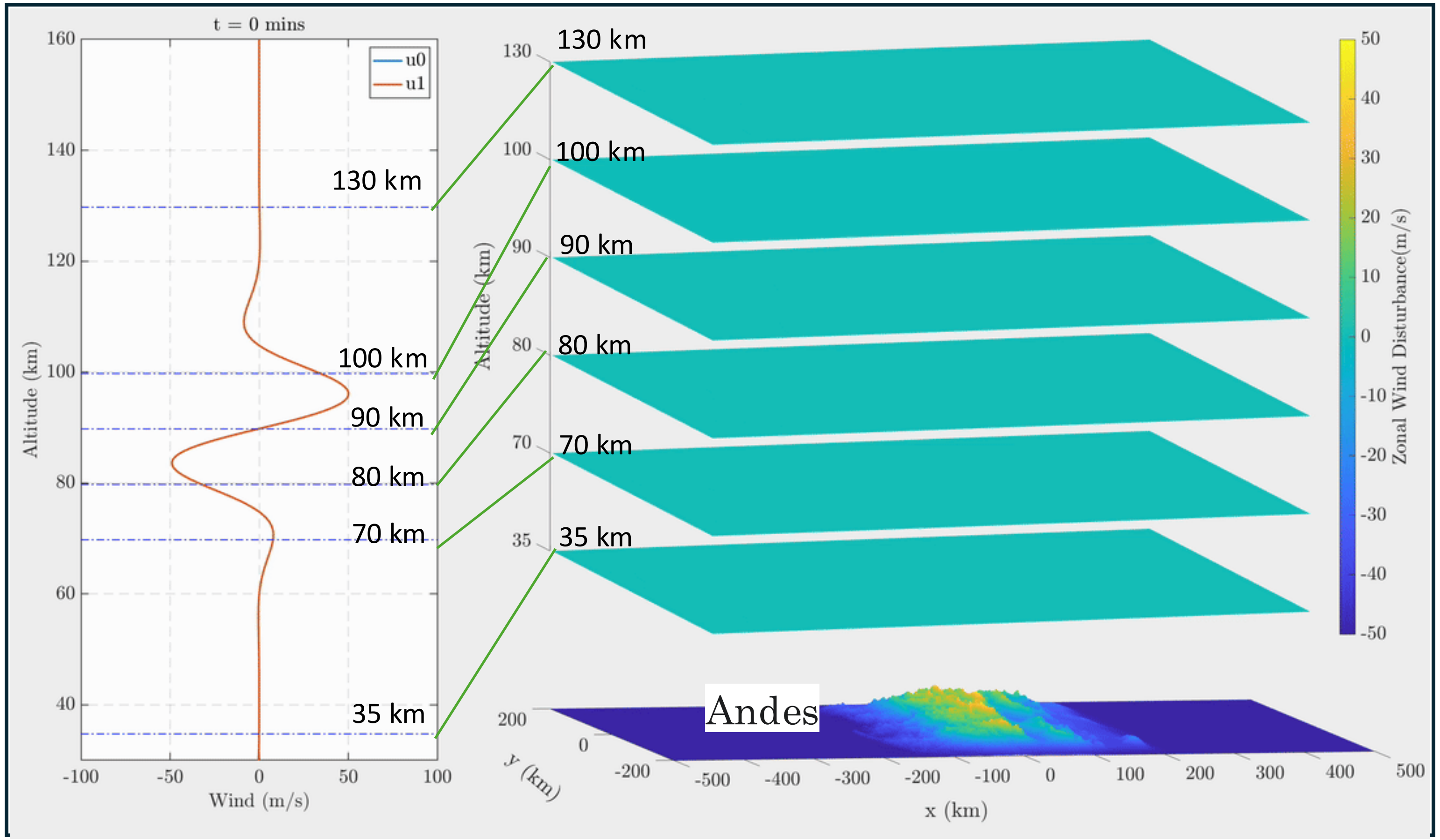
KHI are elongated into tube-like structures by wind shear, while the KHI breaking and the resulting turbulence twist and knot the KHI into complex shapes.

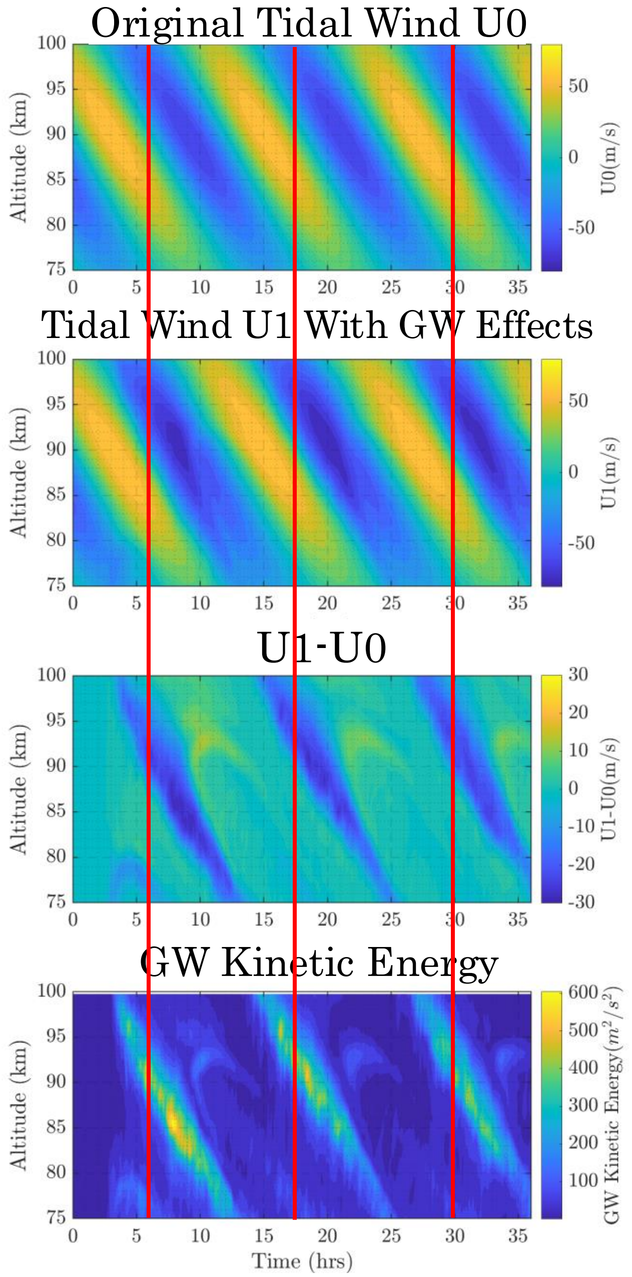
- Observations revealed intense KHI including T&K dynamics in the MLT.
- CGCAM modeling has reproduced these events and been used to study T&K.
- KHI can cascade energy upward to gravity waves and downward to turbulence, significantly impacting atmospheric mixing processes .

Hetch et al., 2021,JGR; Fritts et al., 2021,JGR

Example 5: GW-Tide Interaction

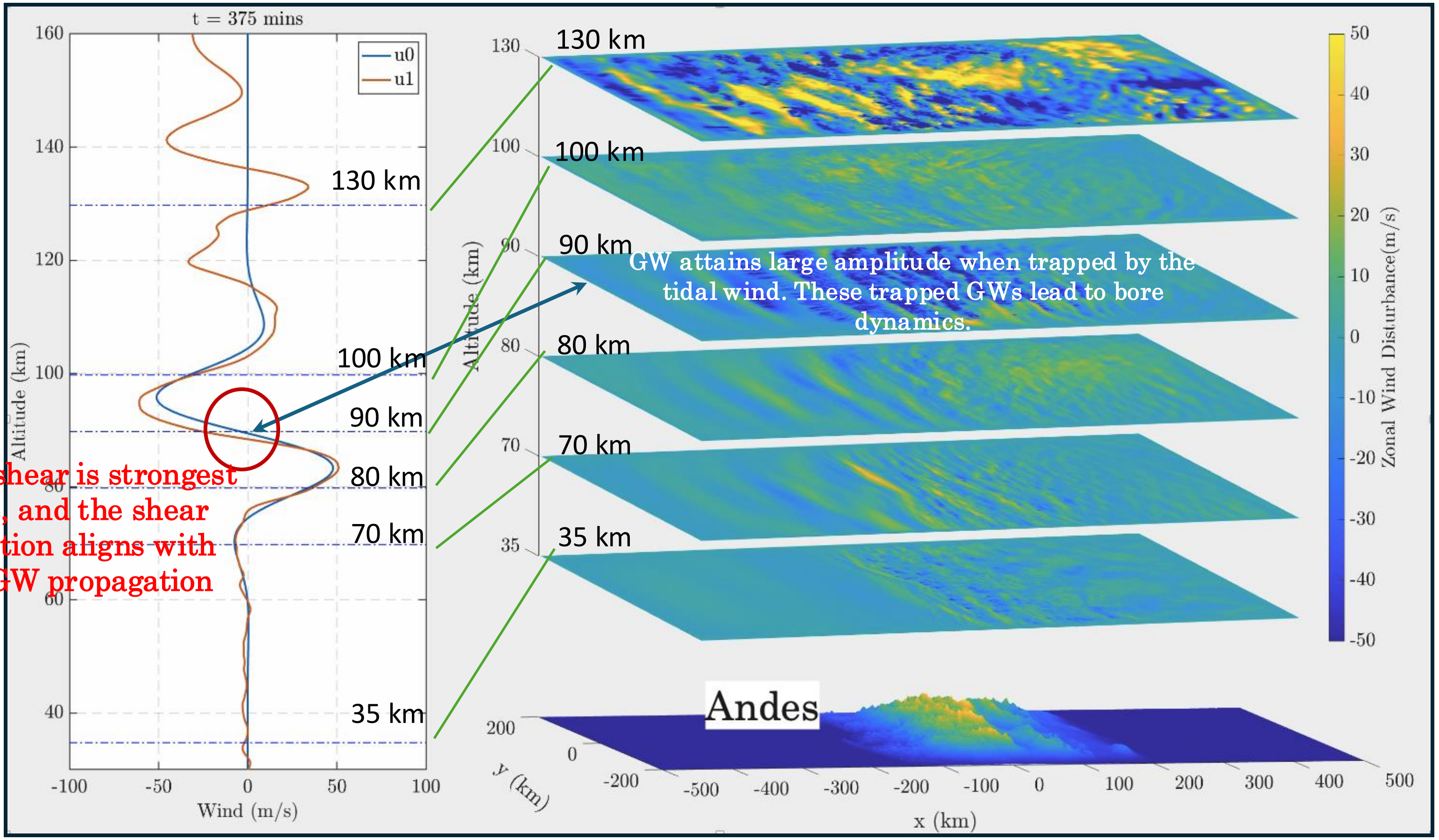
- Tidal winds can modulate GW by capturing their energy and inducing bore dynamics.
- Tides cause the GW energy to oscillate in a tidal cycle, In turn, GWs can enhance tidal amplitude.
- There is an approximately 90-degree phase difference between the tides and GW energy. The GW is more easily captured when wind shear is large, occurring where the wind speed is zero and located between the tidal peaks

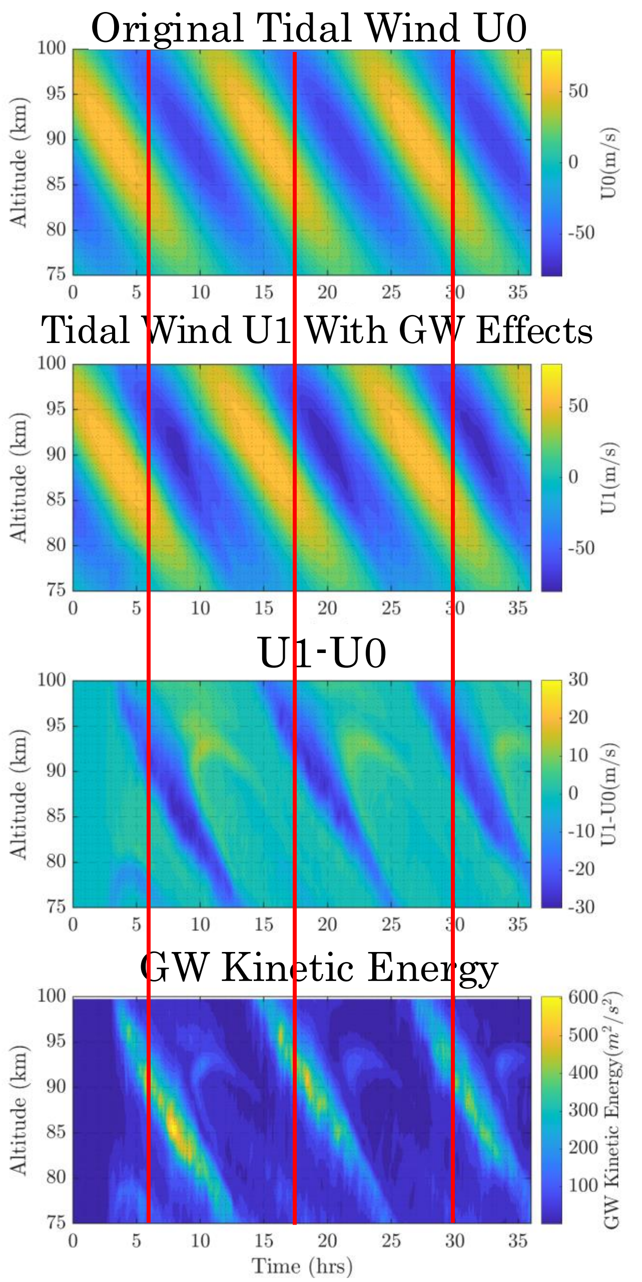




Example 5: GW-Tide Interaction

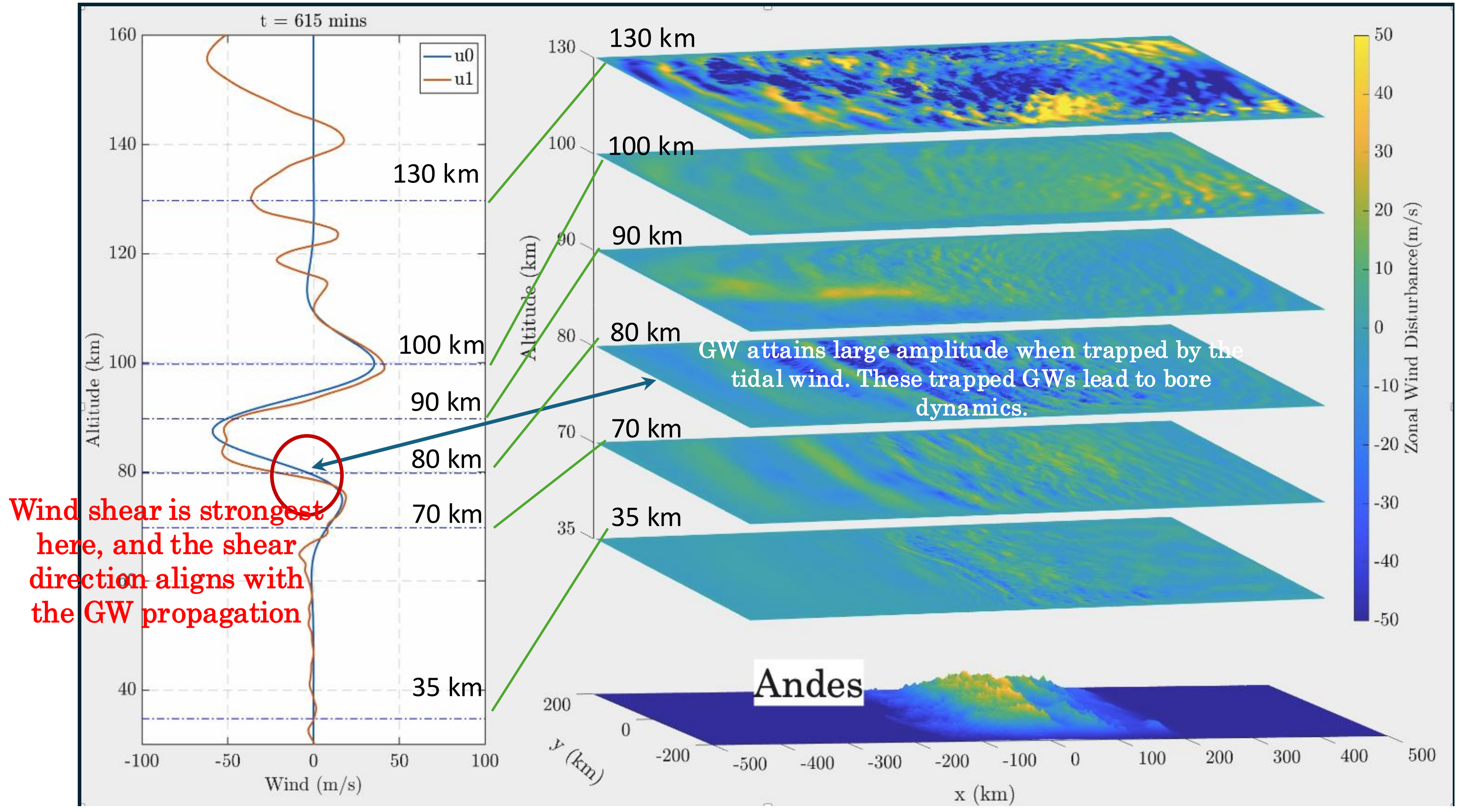
- Tidal winds can modulate GW by capturing their energy and inducing bore dynamics.
- Tides cause the GW energy to oscillate in a tidal cycle, In turn, GWs can enhance tidal amplitude.
- There is an approximately 90-degree phase difference between the tides and GW energy. The GW is more easily captured when wind shear is large, occurring where the wind speed is zero and located between the tidal peaks

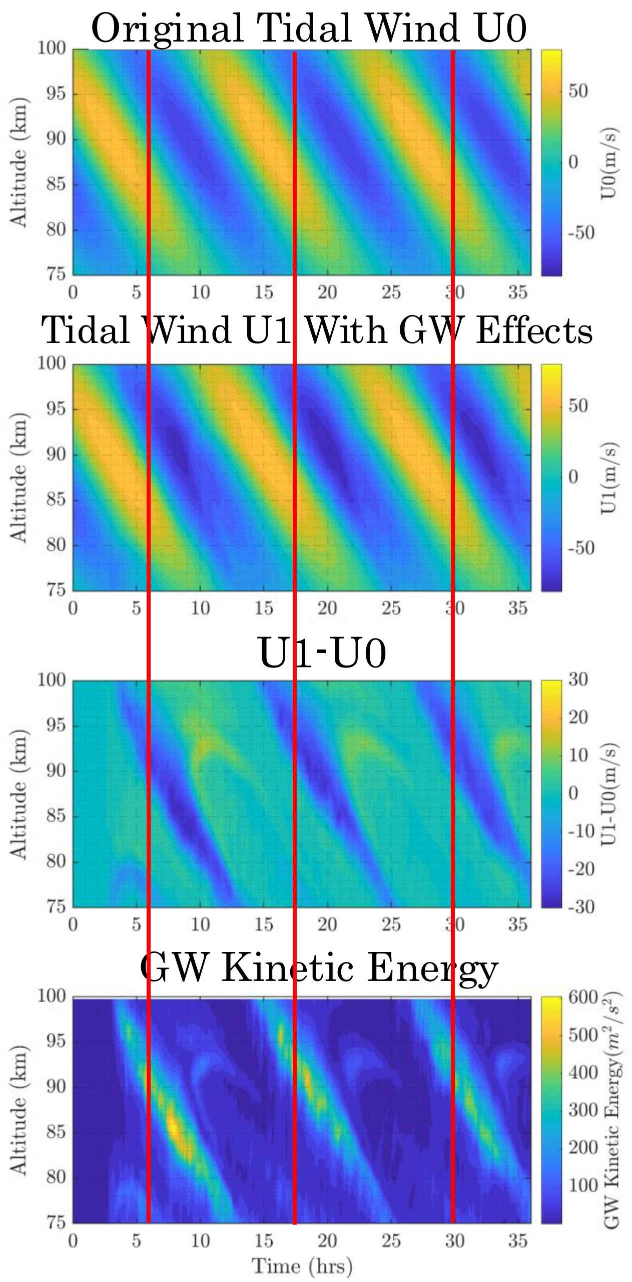




Example 5: GW-Tide Interaction

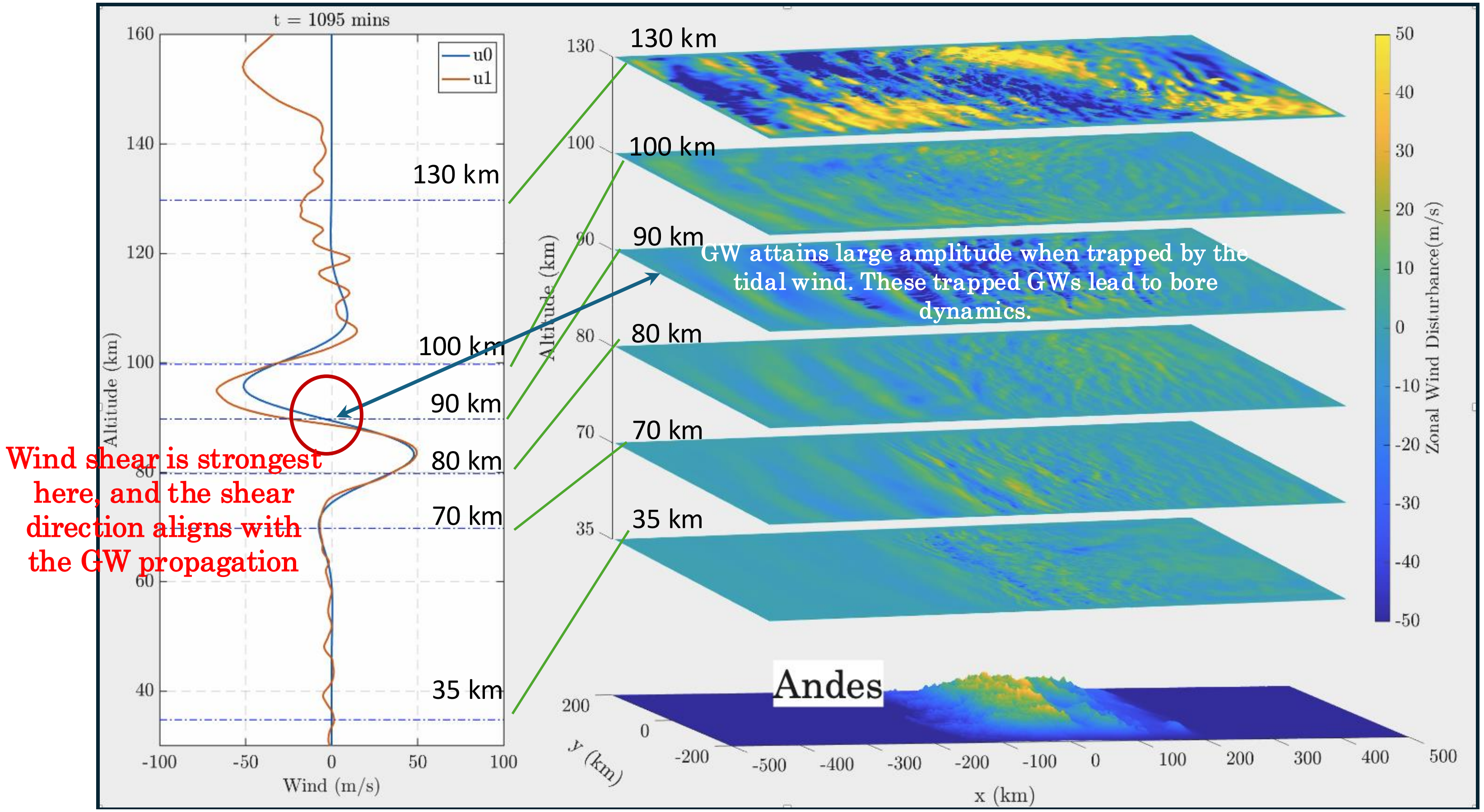
- Tidal winds can modulate GW by capturing their energy and inducing bore dynamics.
- Tides cause the GW energy to oscillate in a tidal cycle, In turn, GWs can enhance tidal amplitude.
- There is an approximately 90-degree phase difference between the tides and GW energy. The GW is more easily captured when wind shear is large, occurring where the wind speed is zero and located between the tidal peaks

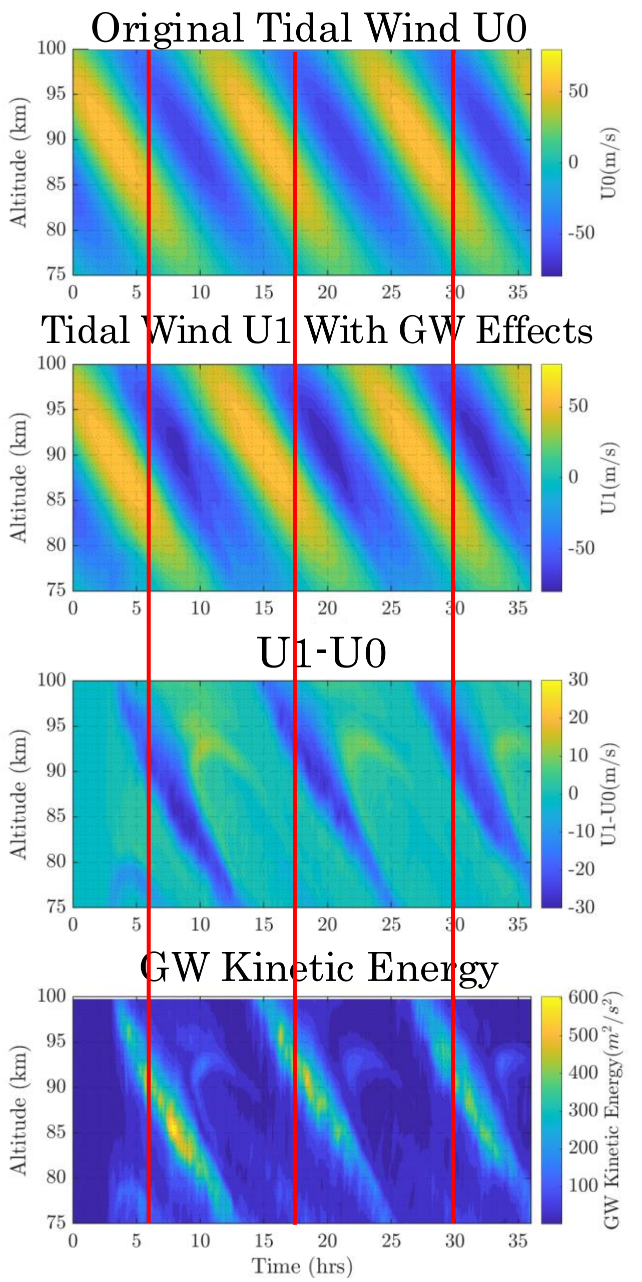




Example 5: GW-Tide Interaction

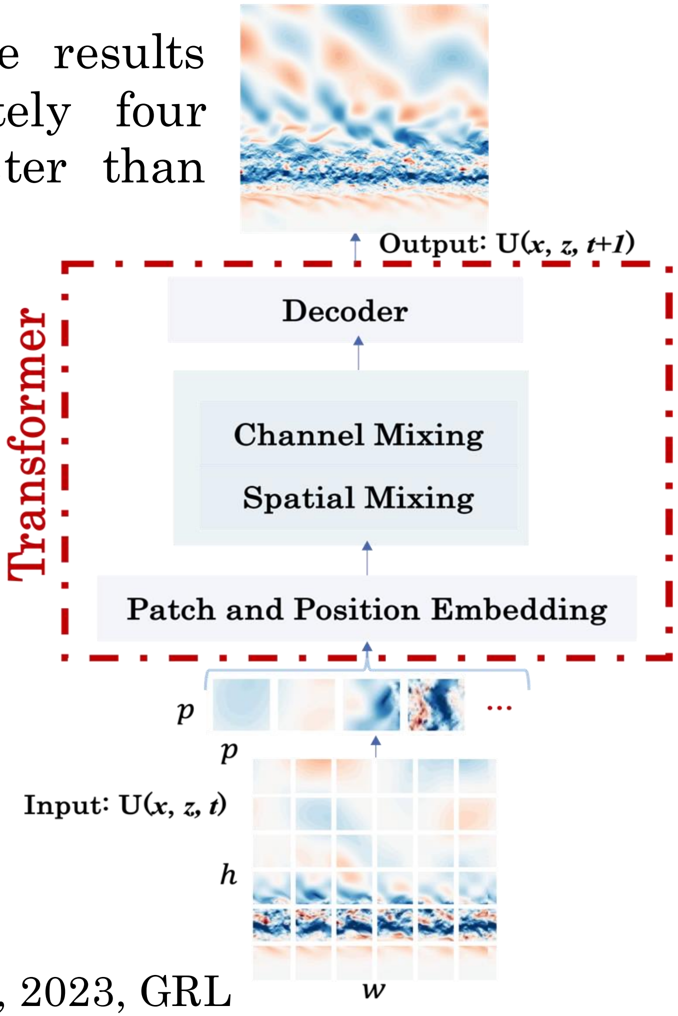
- Tidal winds can modulate GW by capturing their energy and inducing bore dynamics.
- Tides cause the GW energy to oscillate in a tidal cycle, In turn, GWs can enhance tidal amplitude.
- There is an approximately 90-degree phase difference between the tides and GW energy. The GW is more easily captured when wind shear is large, occurring where the wind speed is zero and located between the tidal peaks



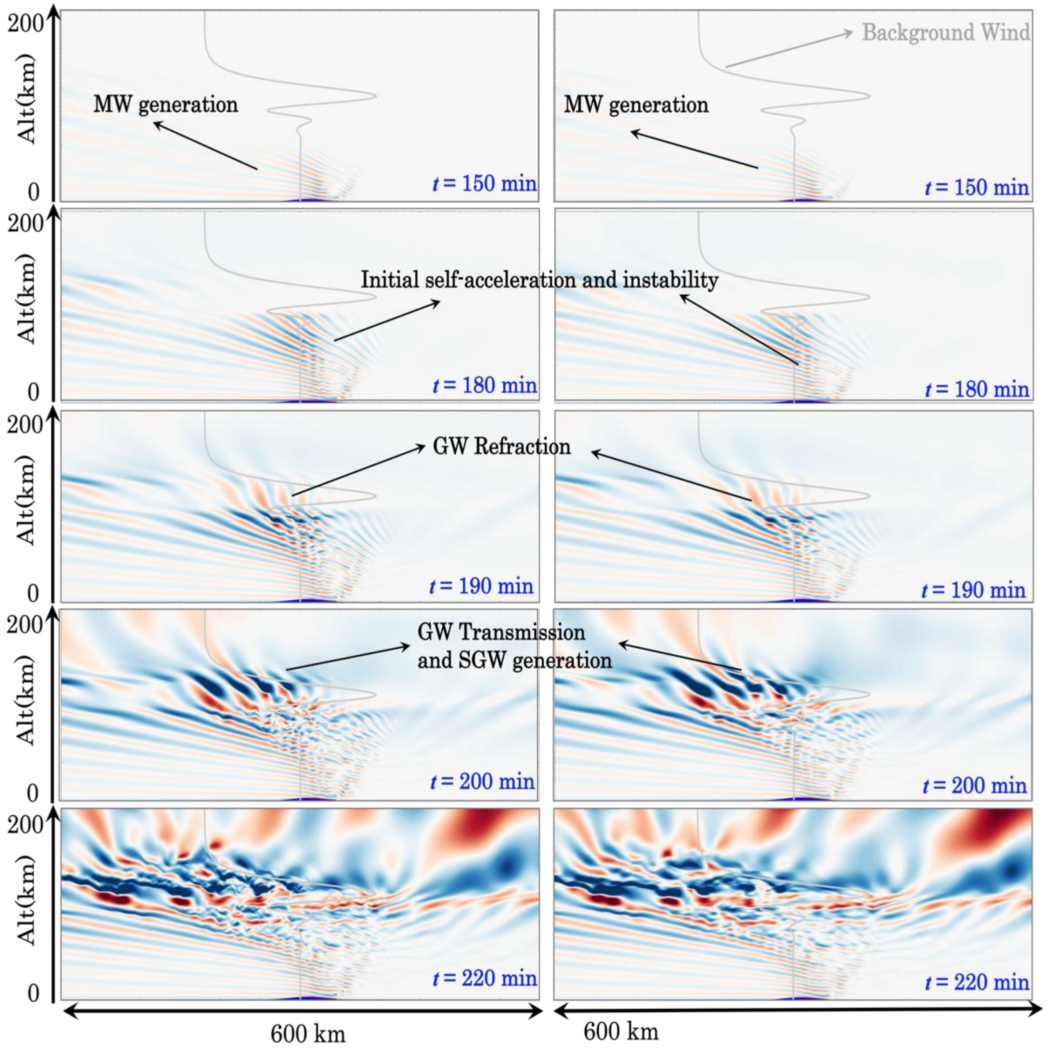


Example 6: From CGCAM to CAM-NET

- The well-trained CAM-NET demonstrates excellent modeling skill in capturing GW generation and breaking.
- CAM-NET achieves these results with speeds approximately four orders of magnitude faster than CGCAM



CGCAM	CAM-NET
~40 mins (36 CPU cores)	~0.5s (1 A100 GPU)



Dong et al., 2023, GRL

Conclusions

- CCGAM is a highly parallelized and optimized compressible atmospheric simulation code. It has been used for studying GW self-acceleration, wave breaking, SGW generation, KHI, wave-wave interactions, among others.
- GW self-acceleration and breaking can be SGW sources.
- Tracer variables can serve as indicators for GW breaking and SGW generation. An important benefit of such modeling to be the ability to infer local GW forcing.
- KHI can cascade energy upward to GWs and downward to turbulence, significantly impacting atmospheric mixing processes.
- Tides can modulate GWs, causing the GW energy to oscillate in a tidal cycle. In turn, GWs can enhance tidal amplitude.
- A well-trained machine learning GW model could serve as an efficient alternative for GW parameterization schemes in GCMs.