National Aeronautics and Space Administration

FY23 Topic Areas Research and Technology Development (TRTD)

Origin of Titan's Superrotation, and OSSE for Titan Sub-mm Instrument Development

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Strategic Focus Area: Planetary Atmospheres

Objectives:

The objectives of this effort were to (1) Identify the dominant atmospheric wave modes driving and maintaining Titan's superrotation, (2) Create a point design for a JPL orbital submillimeter spectrometer for use at Titan to measure vertical profiles of winds, temperature, and trace gases in the atmosphere, and (3) Evaluate the efficacy of the sub-mm point design in measuring the quantities in Obj. 2 and for detecting waves and their impacts in Titan's atmosphere via our OSSE methodology.

Background:

Planetary-scale waves have been thought to drive and maintain superrotation on slow-rotating planets like Titan and Venus (e.g., [1]). Newman et al. [2] performed numerical simulations and found that the waves generated by barotropic instabilities were responsible for the accelerations of stratospheric superrotation via wave absorptions near critical layers. Subsequently there were studies that showed that the Rossby-Kelvin instabilities could also drive the equatorial superrotation on Titan [3-4]. The detailed wave properties and how they interact with zonal flow were not thoroughly investigated by [2]. Thus, we perform additional analysis of TitanWRF model results to identify the dominant wave types and how wave-mean interaction drives stratospheric superrotation via both of these jet-driving mechanisms.

Approach and Results:

To understand the waves driving superrotation, we performed a set of analysis of TitanWRF simulation results, focusing on the wave-wave and wave-mean interactions as well as the generation of the planetary waves that are responsible for jet acceleration/deceleration during the two strongest angular momentum (AM) transfer events, $L_s = 261°$ and $L_s = 191°$ events (Figures 1, 2). Similar to [2] and recent studies by [4], we find that the dominant wave modes that contribute eddy momentum to the zonal flow are low-order zonal wave modes with wavenumber 1 being the most prominent feature.

In parallel, we used the TitanWRF output, with a simulated spacecraft orbit, to sample the atmosphere as an instrument would (Fig. 3). The next step is to apply sub-mm instrument noise on that to create a synthetic retrieved dataset. We will compare that to the TitanWRF output and perform analogous wave analysis to evaluate how well we can pick up the signatures of these AM transfer events from a sub-mm sounder in orbit.

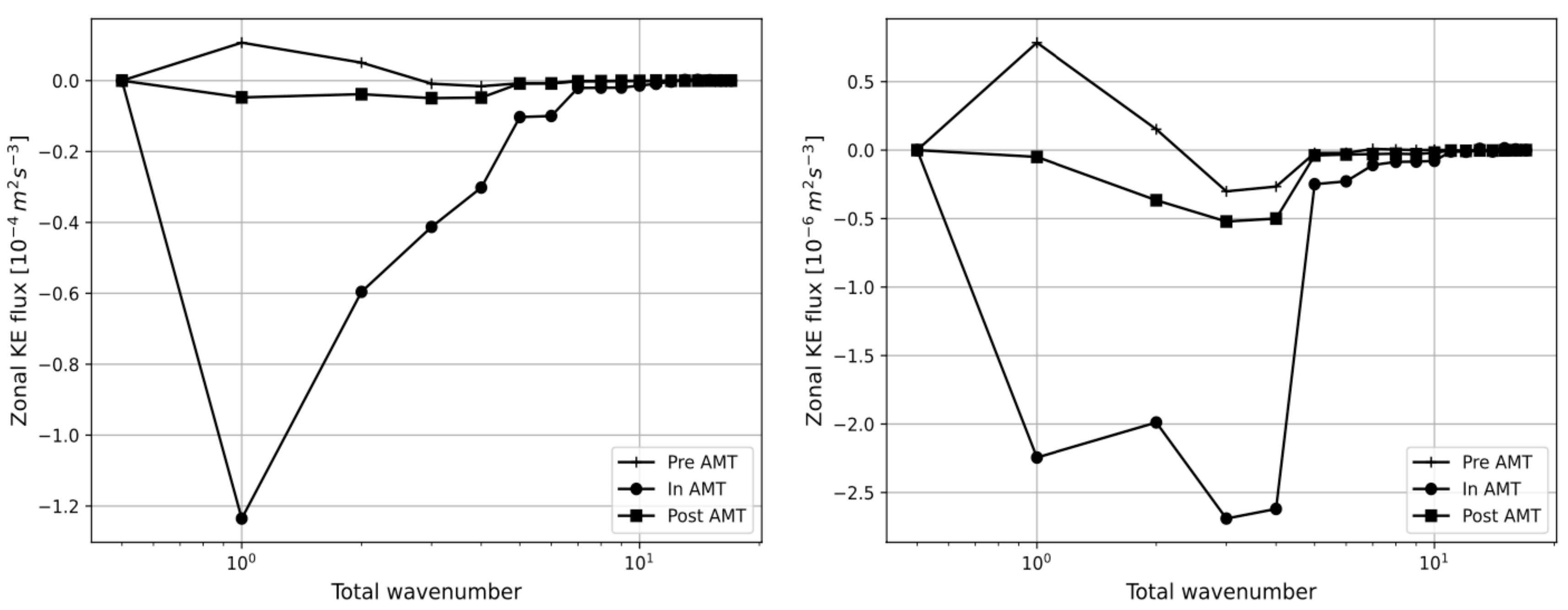

Figure 1: Spherical harmonics analysis shows that, during both angular momentum transfer events, the zonal flow gains energy from eddies with zonal wavenumbers ranging from 1-5. These waves are primarily Kelvin waves, but there is a signature of other waves including Rossby waves and inertia gravity waves (seen by comparing the power spectral density distribution in wave frequency-wavenumber space and the theoretical dispersion relations of various equatorial wave modes).

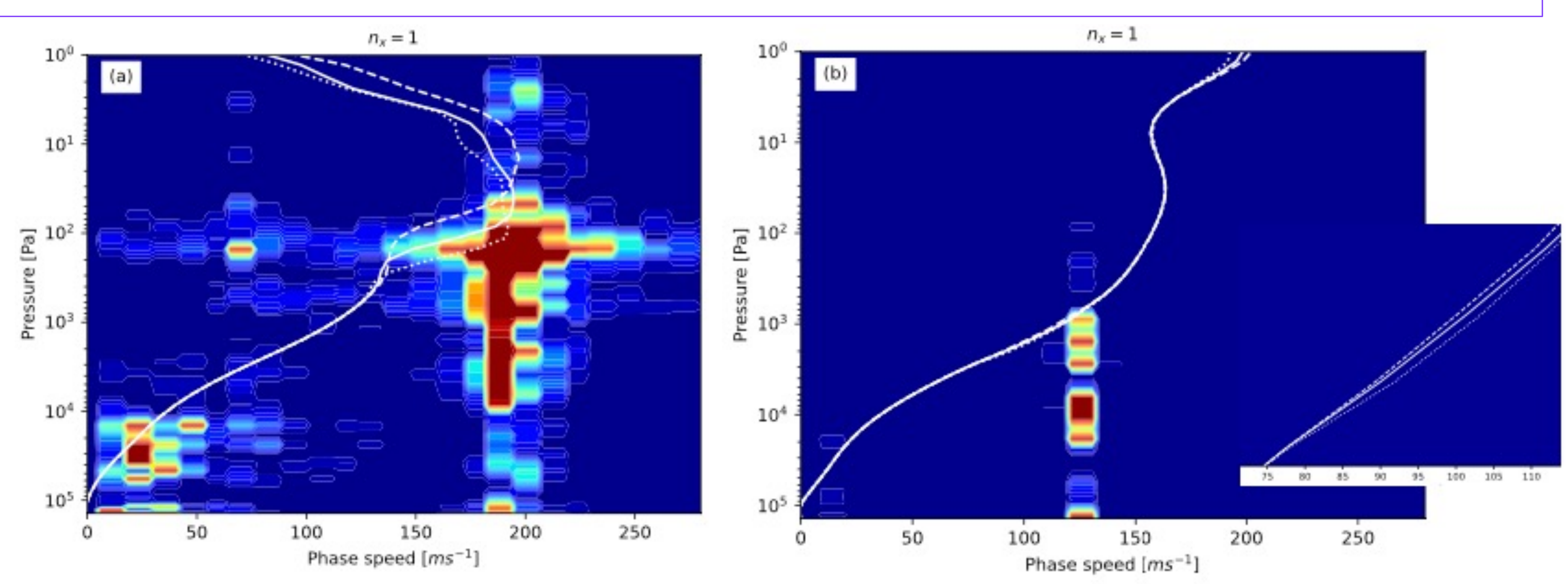

Figure 2: There are two mechanisms driving equatorial superrotation. (1) acceleration of equatorial zonal flow due to absorption of vertically propagating Kelvin waves at the critical layers where the wave phase speed and the background wind speed become comparable, allowing angular momentum to transfer from the wave to the mean flow. This occurs in the region above 200 Pa for $L_s = 261°$ and near 1000 Pa for $L_s = 191°$. (2) convergence of eddy momentum flux, from eddies produced by Rossby-Kelvin instabilities, lead to acceleration of the equatorial zonal flow. This occurs in the region between ~ 3000 Pa and 1000 Pa for $L_s = 191°$, which corresponds to a Froude number between 1 and 1.5 (indicating a resonance condition between Rossby and Kelvin waves that destabilizes waves and produces eddies).

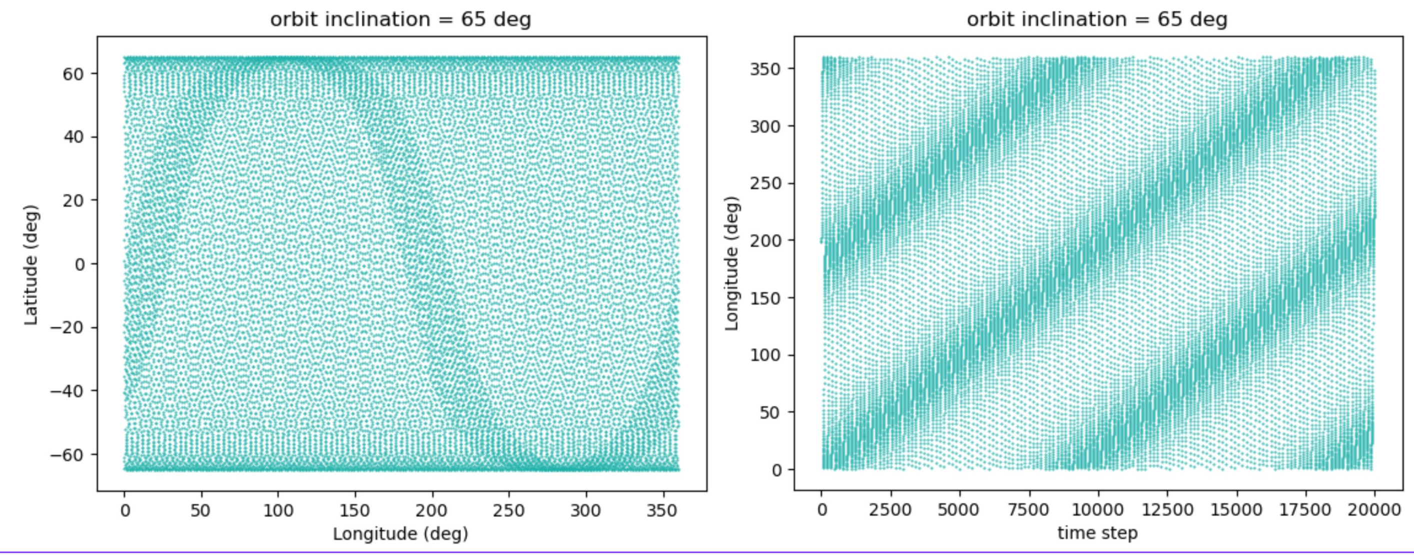

Figure 3: Tangent Points of 20,000 samplings, 75 seconds apart, showing example coverage. (17.36 days total). This assumes the spacecraft is in an inclined orbit of 65 degrees. The orbital period for sampling is synchronous to Titan's rotation rate (sidereal): 15.945 days.

Significance: Understanding the theoretical signatures in the atmosphere (temperature, waves, and winds) that are linked to superrotation is necessary to develop methods and instrumentation to test if the hypotheses are correct and provide measurement requirements for future observations. JPL has developed sub-mm sounding instrumentation as a product line and a Titan Orbiter is proposed for a future New Frontiers mission. Thus, understanding the ability of JPL's instrumentation to address future high-priority science goals is needed.

National Aeronautics and Space Administration

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Clearance Number: CL#00-0000
Poster Number: RPC#

Publications:

Yuan Lian et al. "The Role of Planetary-Scale Waves on the Stratospheric Superrotation in Titan's Atmosphere". Manuscript to be submitted to *Icarus* or *JGR Planet* (2023).

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References:

[1] Iga, S.-I. and Matsuda, Y., 2005. [2] Newman, C. E. *et al.*, 2011. [3] Wang, P., and J. L. Mitchell, 2014. [4] Lewis, N. T. *et al.*, 2023.