FY24 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 – Objective 1:

Wave analysis was used to characterize dominant atmospheric waves modes that drive and maintain Titan's atmospheric superrotation (**Fig. 1 and Fig. 2**), using the Titan Weather Research and Forecasting (WRF) Global Circulation Model (GCM). Eddies generated by Rossby-Kelvin instabilities may be the major source of prograde angular momentum with possible contributions from absorption of vertically propagating equatorial Kelvin waves, like [7], but different from [6].

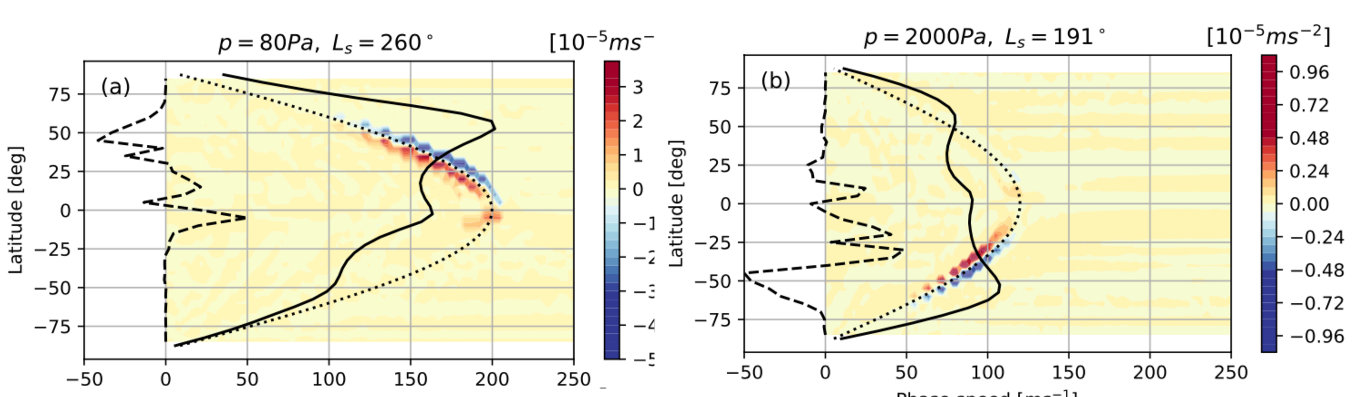

Figure 1: Convergence of horizontal eddy momentum (colored contours) and total zonal acceleration summed over all phase speeds (the dashed lines) near $\mathrm{L_s} = 260^\circ$ (a) and $\mathrm{L_s} = 191^\circ$ (b). The total zonal acceleration is scaled for better visibility. The solid lines are zonal mean zonal wind as references. The dotted lines are the constant angular velocity $c_0 \cos(\phi)$, where c_0 is the typical phase speed at equator and ϕ is the latitude. The east-westward acceleration correlates well with the intrinsic speed of the dominant wave mode (zonal wavenumber 1). This figure demonstrates the effect of Rossby-Kelvin instability on zonal jet acceleration.

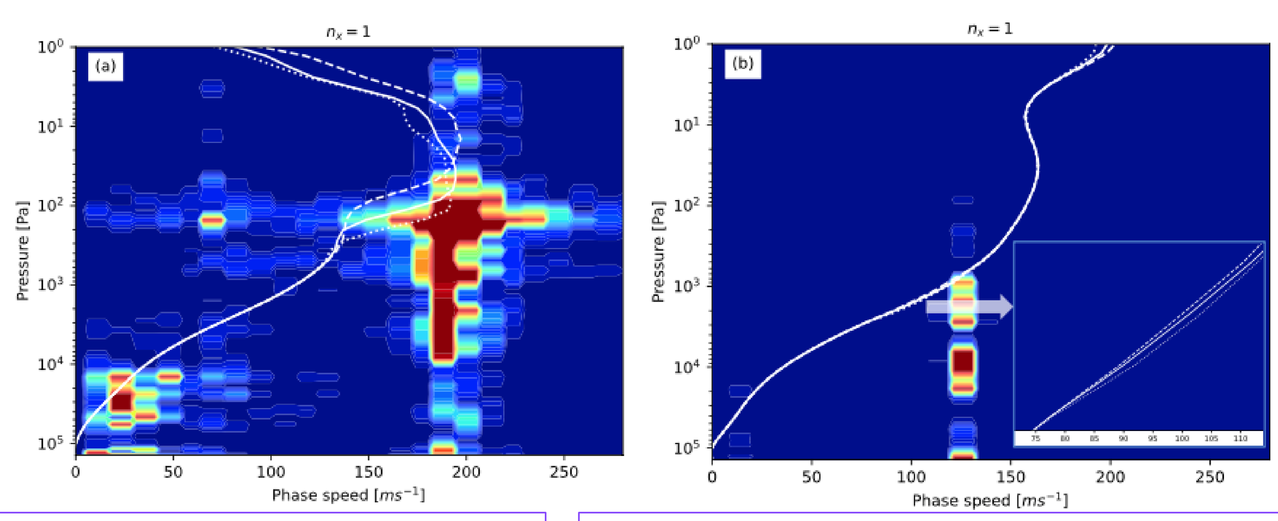

Figure 2: Two mechanisms drive superotation: (1) acceleration of equatorial zonal flow due to absorption of vertically propagating Kelvin waves at the critical layers where the wave phase speed and the background wind speed become comparable, allowing angular momentum to transfer from the wave to the mean flow. This occurs in the region above 200 Pa for $\mathrm{L_s} = 261^\circ$ and near 1000 Pa for $\mathrm{L_s} = 191^\circ$. (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 $\mathrm{L_s} = 191^\circ$.

Approach and Results – Objective 2:

We created a point design for a Titan orbital sub-mm spectrometer [8-9]. The 430-470 GHz frequency region offers the best sensitivity and the highest TRL instrument components. It would measure between 100-500 km altitude the line-of-sight winds, temperature, and composition: isotopologues of CO (CO, ^{13}CO, C^{18}O), HCN (H^{13}CN, HC^{15}N), and methane (CH_3D; **Fig 3**). Heritage: Aura MLS, MIRO, Herschel, cell phone industry. TRL 5/6.

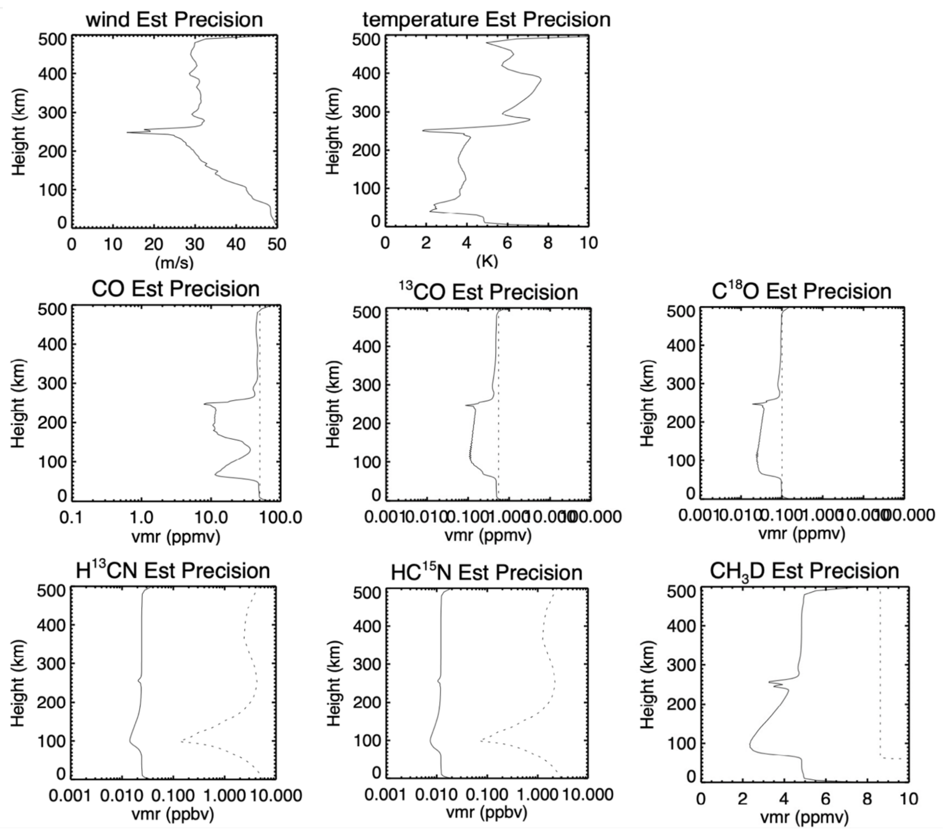

Figure 3: Estimated precision (solid lines; dotted lines are the assumed abundances) of temperature, wind, and composition of CO, HCN, and methane isotopologues for our point design submillimeter instrument.

Approach and Results – Objective 3:

Objective 3 analyses: A pseudo-OSSE process was developed to evaluate the efficacy of the sub-mm point design in measuring the key atmospheric quantities (T, wind, gases) in Titan's atmosphere. We created a synthetic dataset sampled as though from a spacecraft in orbit by a sub-mm (**Fig. 4**) and compared this to the original model (e.g., the Titan WRF GCM, the "truth"; **Fig. 5**). The two compare well.

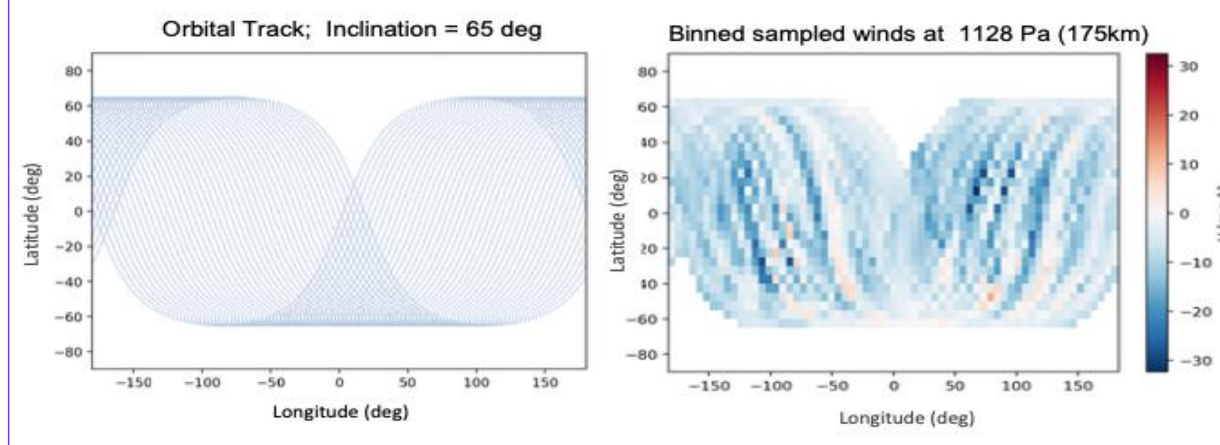

Figure 4: (Left) The assumed orbit of 65 deg inclination ground tracks. (Right) The sampled zonal winds assuming the orbit.

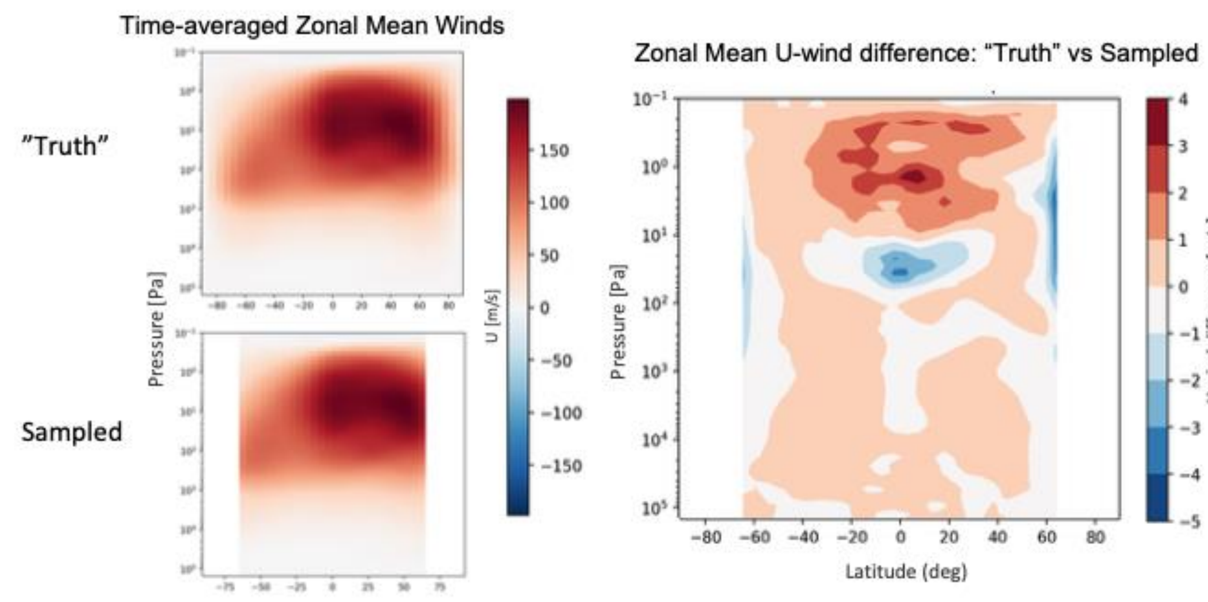

Figure 5: (Left, top) The time-averaged zonal mean winds from the Titan WRF GCM (e.g., "truth") and (left, bottom) the synthetic retrieval of the same quantity. (Right) The difference between the two figures on the left. The magnitude of the differences is < 5 m/s, or < 5%.

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.

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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 Planets*.

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References:

[1] Randel et al. (1991). [2] Dawson, A. (2016). [3] Zurita-Gotor et al. 2022. [4] Wang and Mitchell (2014). [5] Iga and Matsuda, 2005. [6] Newman et al. 2011. [7] Lewis et al. 2023. [8] Read et al. 2018. [9] Tamppari et al., 2024 (in revision)