Exploring the Influence of Density Contrast on Solar Near-Surface Shear

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Motivation

Helioseismic observations have revealed two boundary layers of shear in the solar convection zone (CZ), the dynamical origins of which have remained a mystery.

- In the **tachocline** at the base of the CZ, there is a sharp transition between differential rotation to solid-body rotation in the radiative zone.
- At the top of the CZ, there is a 35-Mm-thick **near-surface shear layer** (NSSL), in which the average rotation rate of the plasma at all latitudes slows by about 5% with increasing radius.

We have run 3D global hydrodynamic simulations of convection in a solar-like star with three different degrees of density contrast across the shell.

- We have determined the average torque balance in detail for each stratification.
- We show how the Coriolis-deflection of downflows produces near-surface shear.
- We discuss the likely mechanism that tends to wipe out shear at high latitudes in simulations, unlike in the real Sun.

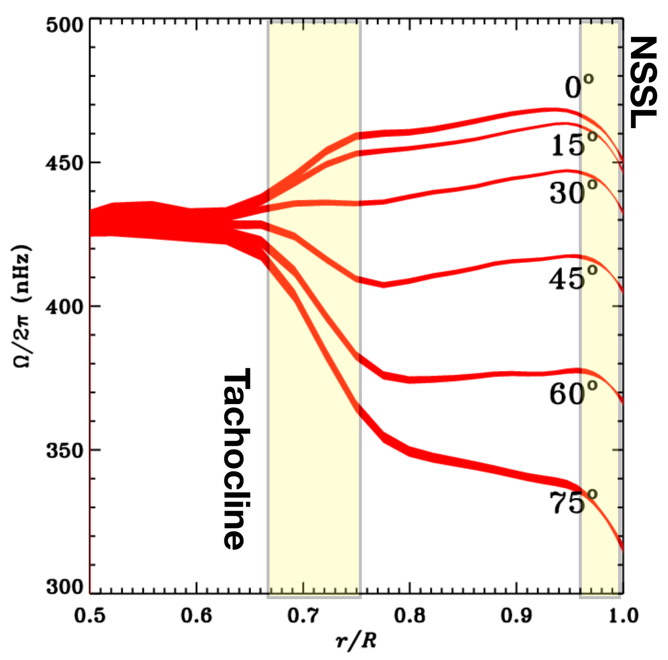

Figure 1: Rotation rate as a function of fractional solar radius, at selected latitudes. The two boundary layers at the top and bottom of the CZ are highlighted. Image from GONG.

Tilt of Busse columns

Each equatorial cross section of the Busse columns has a noticeable "prograde tilt:"

- Upflows tend to move prograde relative to the background flow.
- Downflows tend to move retrograde.
- Both upflows and downflows transport angular momentum outward, increasing the fluid rotation rate far from the rotation axis.
- The differential rotation is "solar-like:" the equator (far from the rotation axis) rotates faster than the poles (close to the rotation axis).

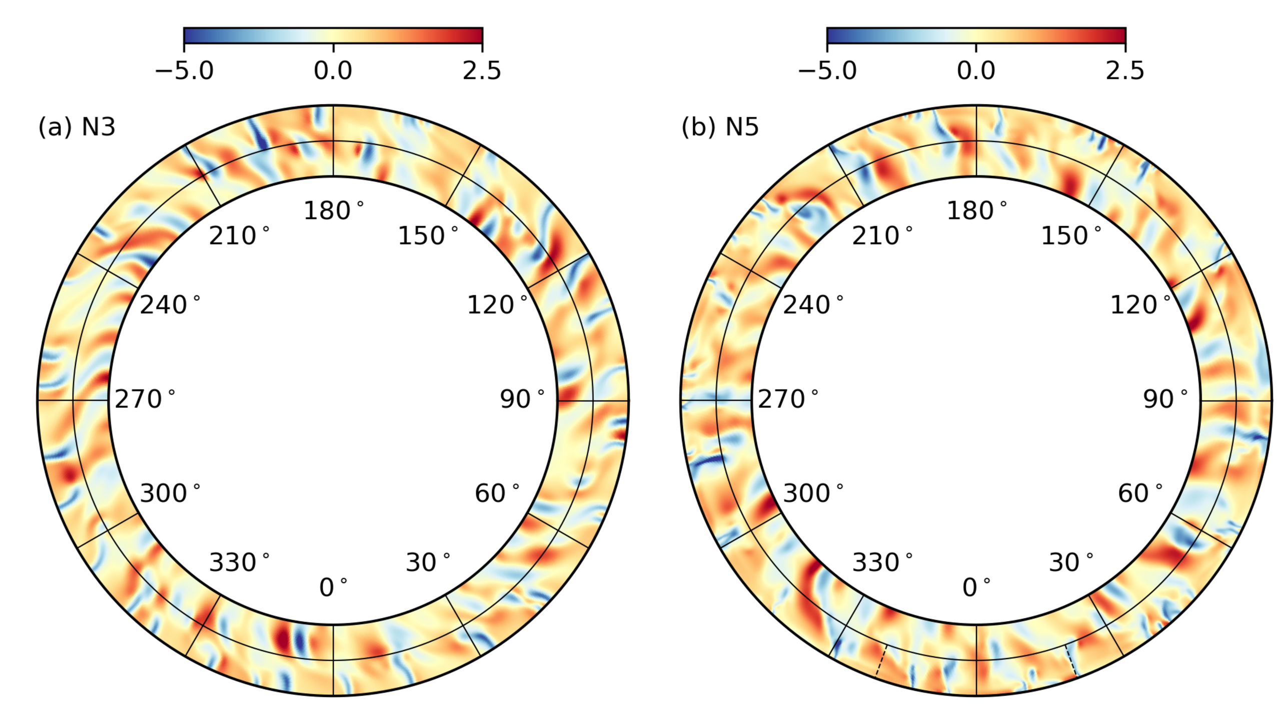

Figure 3: Equatorial slices of the radial velocity for cases N3 and N5. The velocity has been normalized by its rms value over the equatorial slice.

Torque balance

The steady-state differential rotation can be understood in terms of the time-averaged torque balance in the meridional plane. There are three torques that can operate: advection of angular momentum by the meridional circulation, turbulent advection of angular momentum (Reynolds stress) and viscous torque.

- At low latitudes, Reynolds stress is balanced by viscosity
- At high latitudes, Reynolds stress is balanced by meridional circulation.
- There is a thin layer of negative Reynolds stress torque near the outer boundary in case N5, not seen in case N3. It is coincident with the near-surface shear in case N5.

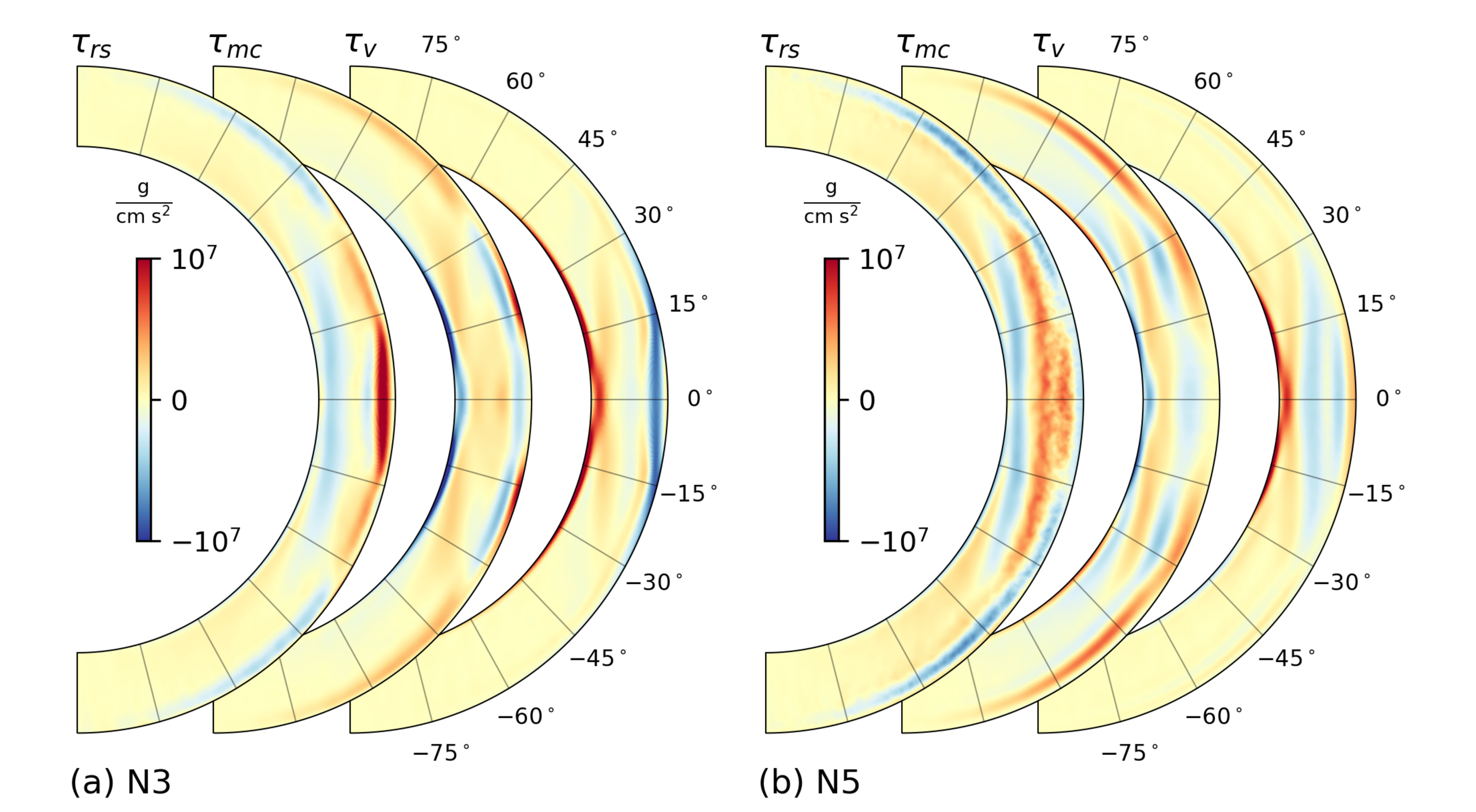

Figure 5: Temporally and zonally averaged torque balance in the meridional plane for cases N3 and N5. The subscripts "rs," "mc" and "v" denote torques due to the Reynolds stress, meridional circulation and viscosity, respectively.

Numerical experiment

We use the open-source software *Rayleigh* (Featherstone & Hindman 2015) to solve the equations of hydrodynamics in rotating spherical shells.

- All models rotate at three times the solar rate and have a solar luminosity driven through the shell via fixed internal heating.
- We explore three density contrasts across the layer: 20, 55 and 150, which we refer to by N3, N4 and N5, respectively.
- For case N3, flows are organized by rotation (at all depths) into columnar structures at low latitudes, which we call "Busse columns" (Busse 2002).
- For case N5, the flow structures near the outer surface are uninfluenced by the rotation and largely isotropic. Deeper down, where the convection is slow and large-scale, the Coriolis force organizes the flows into Busse columns.

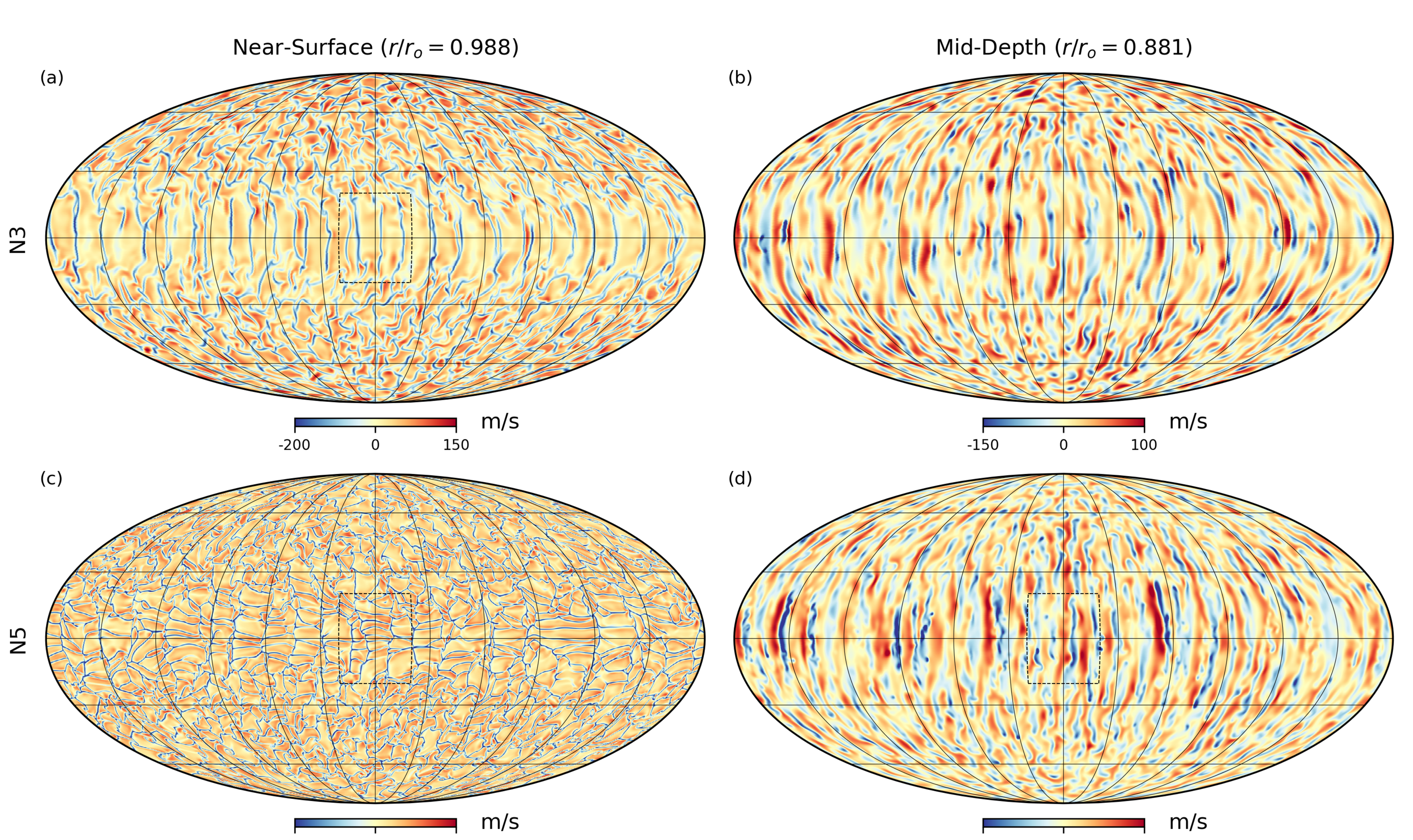

Figure 2: Spherical slices of the radial velocity profile for cases N3 and N5, taken near the outer surface and at mid-depth, shown in Mollweide projection. Positive radial velocity (red) is called "upflow," while negative radial velocity (blue) is called "downflow."

Differential rotation

- The average rotation rate in case N3 increases monotonically in both radius and latitude, consistent with the outward transport of angular momentum caused by the Busse columns.
- For case N5 (at low latitudes near the outer surface), the rotation rate decreases with radius by about 3%, comparable to the solar NSSL.
- At high latitudes for case N5, there are some signs of shear as well, although the overall reduction of rotation rate is only 0.5% (compare to Hotta et al. 2015).

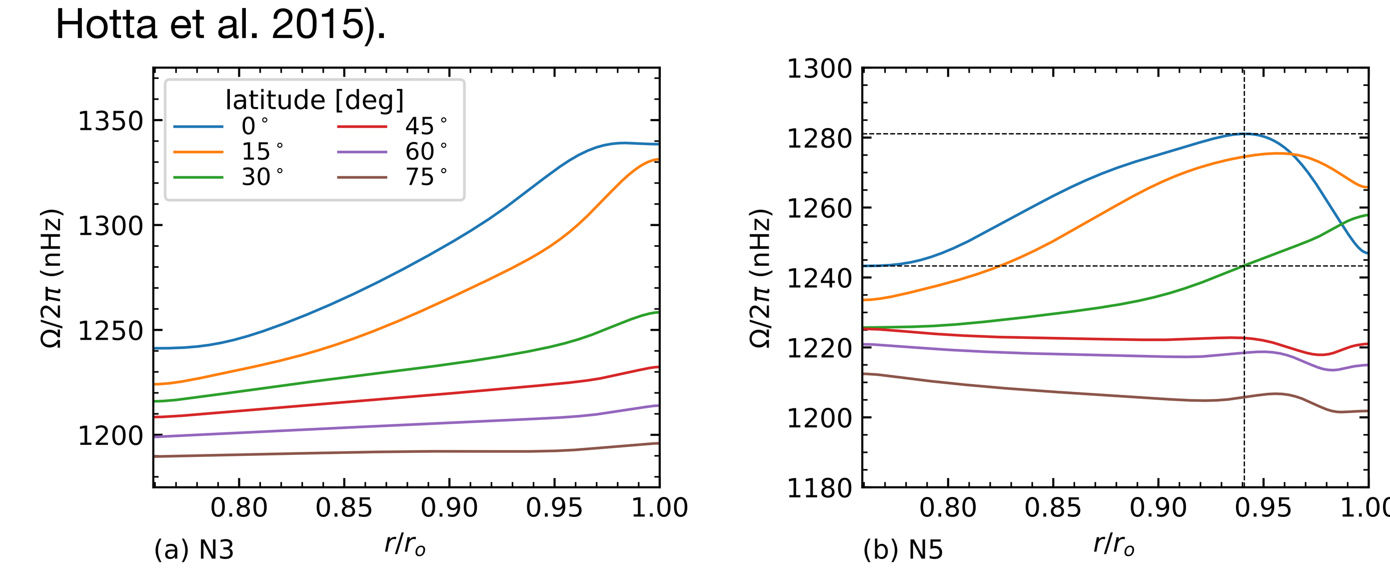

Figure 4: Radial profile of temporily and azimuthally averaged rotation rate at various latitudes for cases N3 (panel a) and N5 (panel b). Rotation rate is computed in the non-rotating lab frame.

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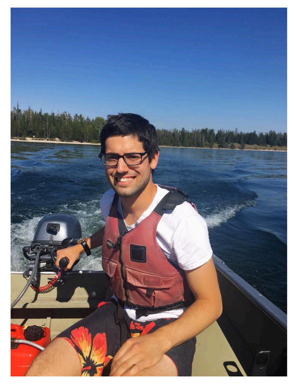
References:
- *Busse, F.H., 2002, APS Award Papers, 14, 4*
- *Featherstone, N.A. & Hindman, B.W, 2016, ApJ, 818, 32*
- *Hotta, H., Rempel, M. & Yokoyama, T., 2015, ApJ, 798, 51*



Discussion

A breakdown of the Reynolds stress torque due to upflows and downflows separately reveals that only the downflows cause negative Reynolds stress torque.

- In case N3 at low latitudes, both upflows and downflows have positive flux.
- In case N5 at low latitudes, the downflow flux is negative in the top half of the layer, most likely due to Coriolis deflection.
- At high latitudes (not shown), both upflows and downflows carry a negative angular momentum flux.
- The absence of near-surface shear at high latitudes is probably due to "back-reaction" from the meridional circulation, which tends to force the rotation rate to be constant on cylinders.
- In the real Sun, which has near-surface shear at *all* latitudes (low and high), there must be a mechanism to counteract the back-reaction of the meridional circulation. One candidate is a thermal wind, the presence of which we plan to explore in the future.

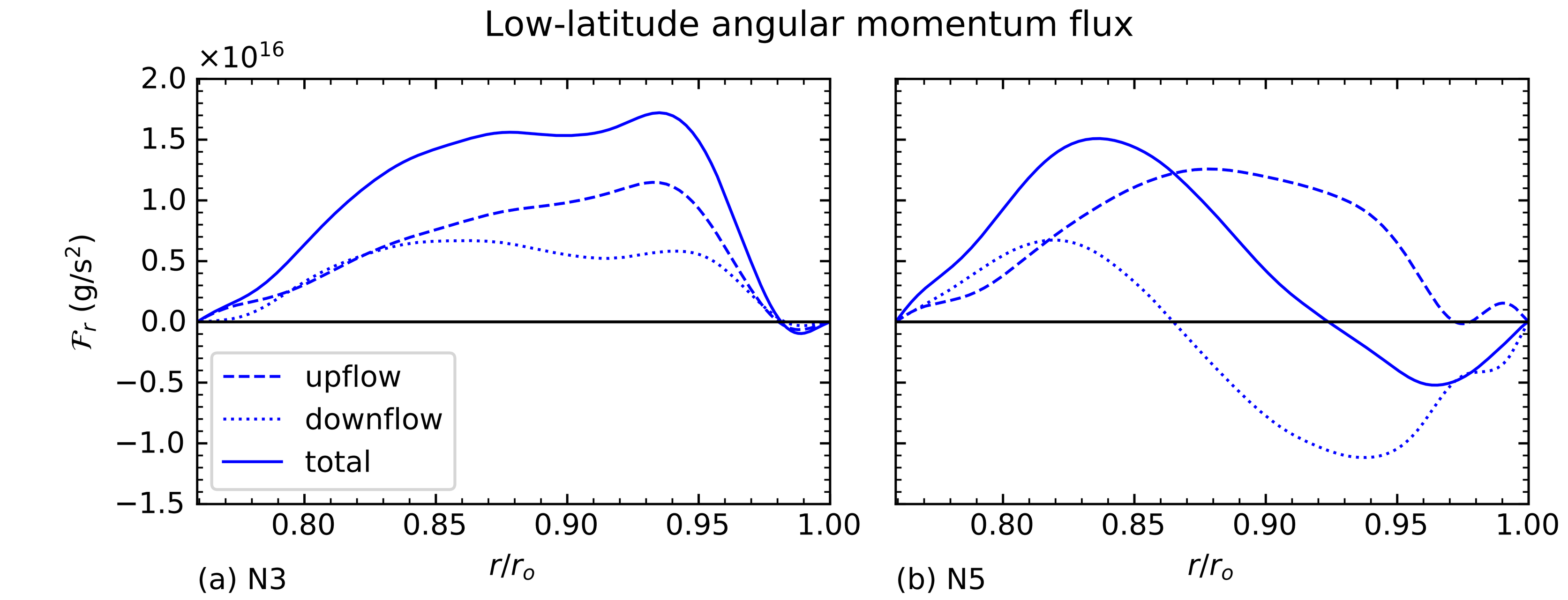


Figure 6: Reynolds stress angular momentum flux due to upflows and downflows separately, averaged over low latitudes for cases N3 and N5.