Rossby wave propagation into the stratosphere: The role of zonal phase speed

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Introduction

Upward propagating planetary-scale Rossby waves are the dominant cause of day-to-day variability in the extratropical winter stratosphere. Anomalous wave forcing can lead to strong disruptions of the stratospheric flow, so-called Sudden Stratospheric Warming (SSW) events, which in turn affect tropospheric variability [e.g. *Baldwin and Dunkerton*, 2001] and predictability [e.g. *Domeisen et al.*, 2015; *Karpechko et al.*, 2017]. While theory predicts that the zonal phase speed of a tropospheric wave forcing affects wave propagation into the stratosphere, its relevance for SSW events has so far not been considered.

Theory (1D) and Observations

There exists a limited range of zonal background wind speed u_0 for which upward propagation of waves is possible [*Charney & Drazin,* 1961] . This is also observed in the real atmosphere (Fig. 1). The majority of the planetary-scale waves are stationary in the troposphere. According to theory, waves with an eastward phase speed *c* are able to propagate into stronger winds. **Indeed, the spectral density maximum moves towards eastward phase speeds for all wave numbers for the stronger winds of the stratosphere**, while the long tail for wave-1 towards westward phase speeds persists with height.

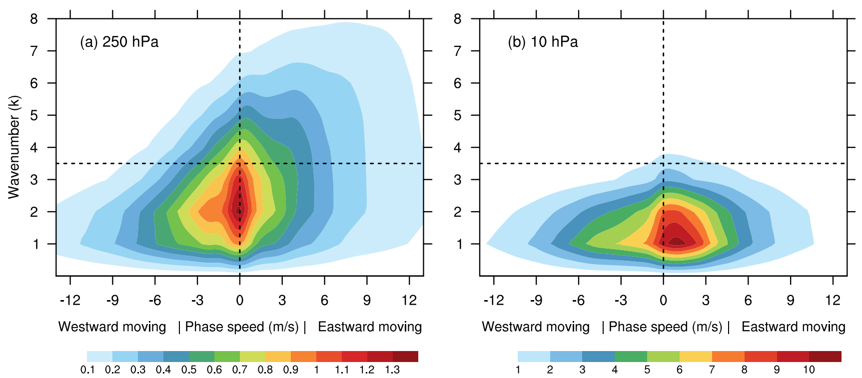

Figure 1. Hayashi spectra (density power of geopotential height) for the observed range of phase speeds [m/s] (relative to the ground) vs zonal wave number k averaged over 30-75N. Units are $m^2/\Delta c$, where Δc=0.33m/s is the phase speed interval.

Wave propagation in 2D

In a 2D wave propagation model (*Harnik, 2001; Harnik & Lindzen, 2001*), an **increase in upward propagation is observed for eastward phase speeds and a decrease for westward phase speeds (Fig. 2). The effect is considerably stronger for wave-2**: A phase speed of 5 m/s yields an increase in the upward EP flux for wave-2 by more than 50% with respect to *c* = 0.

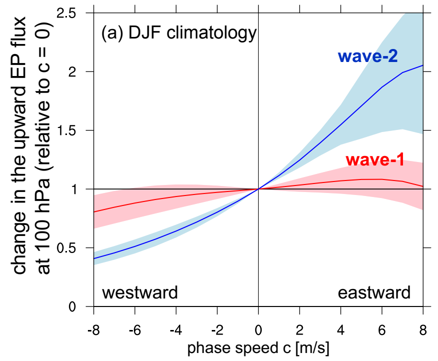

Figure 2. The relative change in the vertical EP flux component at 100hPa, as computed from the wave diagnostic, for a finite phase speed of the forcing relative to a stationary forcing (*c* = 0).

Wave propagation in 3D

The above results lead to the notion that during periods of strong upward wave propagation, e.g. before SSW events, waves with eastward phase speed may dominate, as they are more likely to propagate into the stratosphere. Indeed, **ahead of split SSW events, phase speed in the lower stratosphere (100hPa) increases significantly for both wave numbers** (Fig. 3), consistent with the dominant precursor role that wave-1 often plays ahead of split events in preconditioning the mean flow [*Bancalá et al.*, 2012; *Watt-Meyer & Kushner*, 2015b]. Ahead of displacement events, strong eastward phase speeds of wave-2 occur much less frequently, as expected, while wave-1 does not exhibit a significant phase speed signal. For wave-1, changes in wave amplitude play a much more important role.

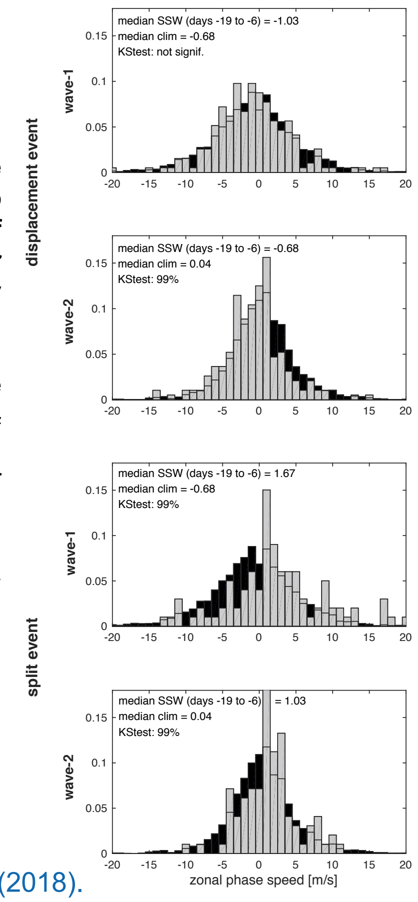

Figure 3. Phase speed [m/s] at 100hPa for daily values for days -19 to -6 before a SSW event (gray) and for the Nov-Mar climatology (black) from JRA re-analysis data (*Kobayashi et al.,* 2015). Significant differences from a two-sample Kolmogorov-Smirnov test are indicated. All distributions are normalized.

Case study: The SSW event on 24 January 2009

The 2009 SSW event was the strongest split event on record in terms of the observed heat flux [*Ayarzagüena et al.*, 2011]. The eastward acceleration of the wave may have increased propagation for wave-2 ahead of the event, contributing to the record heat flux injection into the stratosphere. The tendency towards smaller phase speeds just before the event is reminiscent of resonance behavior.

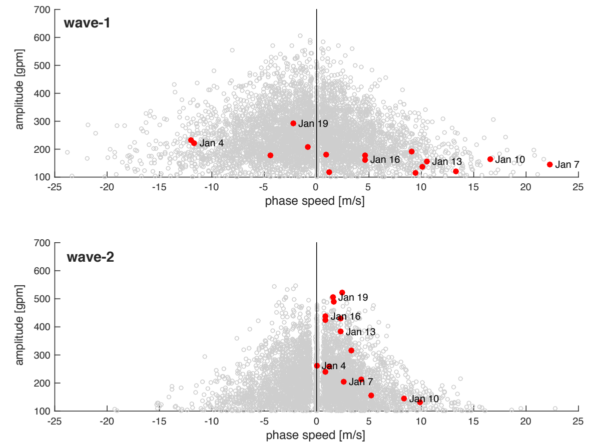

Figure 4. Daily zonal phase speed [m/s] vs wave amplitude [gpm] for Nov - Mar 1958-2013 (gray) and for days -20 to -5 before the 2009 SSW event (red) at 100hPa.

Conclusion

- **Upward wave flux increases with increasing eastward phase speed**, and decreases with increasing westward phase speed of the forcing. The effect is stronger for wave-2 compared to wave-1 for the Northern Hemisphere.
- **Split SSW events tend to be preceded by anomalously eastward zonal phase speeds.** Zonal phase speed may indeed explain part of the increased wave flux observed during the preconditioning of SSW events, as e.g. for the record 2009 SSW event.
- The effects observed for the 2009 SSW event may be linked to **resonant wave excitation** [*Geisler*, 1974; *Tung & Lindzen*, 1979b,a; *Plumb*, 1981; *Esler & Scott*, 2005; *Esler & Matthewman*, 2011]. The exceptional eastward phase speed and amplitude of wave-2 may have facilitated upward wave propagation before the event, thereby nudging the stratosphere towards resonance [*Matthewman & Esler,* 2011; *Albers & Birner,* 2014]. The decreasing phase speed shortly before the event is suggestive of resonant behavior, possibly caused by an assimilation in phase speed between a stationary wave and a free mode, in line with the mechanism for resonant self-tuning [*Plumb*, 1981].
- **Zonal phase speed of a wave has to be considered along with the duration and amplitude of a wave forcing when evaluating precursors to stratospheric variability.**

For more detailed information: Domeisen, D. I. V., Martius, O., & Jiménez-Esteve, B. (2018). Rossby Wave Propagation into the Northern Hemisphere Stratosphere: The Role of Zonal Phase Speed. Geophysical Research Letters. http://doi.org/10.1002/2017GL076886

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