Introduction

- 28 Jul case excellent for studying transient wave forcing
- Unfortunately occurred after end of IOPs...so no flight data
- During examination of WRF simulations, we found some interesting features...
WRF Model Setup

> Real configuration
  > WRF 3.8
  > Δx = Δy = 18, 6, 2 km
  > 108 vertical levels
  > Model top ~ 0.5 hPa
Introduction

- Waves oriented at an angle to the topography
- Persist for ~15 hr
Possibility #1

- Waves are due to the lee-side ridges and valleys
“No Lee Ridges”

- Not due to lee side ridges
- Waves are more apparent
- So what is the cause?

Vertical Velocity (z = 15 km)
Possibility #1
Possibility #1

> Waves are due to the lee-side ridges and valleys
Possibility #1

> Waves are due to the lee-side ridges and valleys ❌
Possibility #2

> Waves are due to the lee-side ridges and valleys

> Waves are trailing waves à la Jiang et. al. (2013)
Lateral Shear

Jiang et. al (2013) demonstrate the formation of transverse waves in the presence of large lateral shear.

Meridional CS of Zonal Wind

Jiang et. al. (2013)
Jiang et al. (2013) demonstrate the formation of transverse waves in the presence of large lateral shear. Of the negative lateral shear of the westerlies (i.e., $\frac{\partial U}{\partial y}$, $\partial U/\partial y$), and the zonal wavenumber becomes slightly smaller, presumably from (6), because of accumulating effects of wind gradients in the zonal direction. In general, shorter waves (i.e., $l < 300$ km) propagate faster in the vertical with little southward bending. This is especially true for the packets with $l < 50$, whose ray paths are nearly vertical. Longer waves (i.e., $l > 400$ and 600 km) propagate upward more slowly. The slow upward propagation allows for a greater accumulation of lateral wavenumber refraction via (7), which in turn allows wave groups to propagate farther south in the stratosphere and mesosphere, via (3). It is noteworthy that, even for $l < 50$, the rays of longer waves (i.e., $l > 600$ km or longer) exhibit substantially more southward refraction associated with the increase of the meridional wavenumber along each ray and slower vertical group velocity. In summary, the ray path calculation suggests that the northwest–southeast-oriented waves over Drake Passage are likely one branch of the diverging three-dimensional "ship" waves from Patagonia (Smith 1980), while the other branch is largely absorbed by critical levels to the north of Patagonia. The southward transfer of wave momentum flux is enhanced by lateral wave refraction associated with the strong meridional shear of zonal winds aloft. The stratospheric momentum flux maximum right above the Patagonian peaks is associated with relatively short waves (i.e., $l < 300$ km or shorter). The wavelength dependence of the southward ray group propagation is consistent with the observed and simulated increase of wave lengths aloft with distance away from the wave source (i.e., Patagonia). Finally, we briefly discuss the sensitivity of the ray path corresponding to $k_0 = l_0 = \frac{2\pi}{400}$ km generated by flow over Patagonia to the Coriolis parameter, buoyancy frequency, vertical wind shear, and meridional winds. Although the spatial variation of the buoyancy frequency and Coriolis parameter appears in (3)–(8), their impact on wave refraction is rather insignificant over the parameters examined here (Fig. 14). This is consistent with Dunkerton (1984), who calculated ray paths of IGWs with an analytical zonal jet profile similar to the mean profile shown in Fig. 11b. According to (3), the squared ratio of the Coriolis parameter and the wave intrinsic frequency, $f_v^2/v_2$, provides a useful measure of the importance of the Coriolis parameter in wave refraction. We can define a wave Rossby number squared, $R_w^2 = v_f^2/f_2^2$, which reduces to $F_{IGW}$.
Lateral Shear

Horizontal Wind Vectors and Speed (North ↑)

Meridional CS of Zonal Wind

Just one problem…

We don’t have much lateral shear (North ↑)

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Horizontal Wind Profile

(z = 10 km) Horizontal Wind Vectors and Wind Speed (z = 15 km)
Possibility #2
Possibility #2

- Waves are due to the lee-side ridges and valleys ✗
- Waves are trailing waves à la Jiang et. al. (2014)
Possibility #2

- Waves are due to the lee-side ridges and valleys
- Waves are trailing waves à la Jiang et. al. (2014)
Possibility #3

> Waves are due to the lee-side ridges and valleys
> Waves are trailing waves à la Jiang et. al. (2014)
> Waves are one half of a ship wave pattern, with the other half destroyed by a directional critical level à la Doyle and Jiang (2006)
Vertical Wind Profile

Directional Critical Level?
Directional Critical Level?

Doyle and Jiang (2006)

Vertical Velocity (z = 15 km)
WRF Idealized Configuration

**Idealized Static Stability**

[Graph showing Brunt-Väisälä Frequency vs Geopotential Height]

**Real & Idealized Wind Profiles**

[Graph showing Wind Velocity vs Geopotential Height with different profiles for real and idealized conditions]
Idealized Terrain Configuration

> Five peaks on top of an isolated ridge
Ship Waves

No Directional Shear  Directional Shear

(z = 15 km, t = 3 hr)
Ship Waves

> Problem:
>  > Waves are transient
>  > Disappear almost completely by 10 hr

(z = 15 km, t = 10 hr)
Possibility #3
Possibility #3

> Waves are due to the lee-side ridges and valleys
> Waves are trailing waves à la Jiang et. al. (2014)
> Waves are one half of a ship wave pattern, with the other half destroyed by a directional critical level à la Doyle and Jiang (2006)
Possibility #3

- Waves are due to the lee-side ridges and valleys
- Waves are trailing waves à la Jiang et. al. (2014)
- Waves are one half of a ship wave pattern, with the other half destroyed by a directional critical level à la Doyle and Jiang (2006)
Possibility #4

- Waves are due to the lee-side ridges and valleys
- Waves are trailing waves à la Jiang et. al. (2014)
- Waves are one half of a ship wave pattern, with the other half destroyed by a directional critical level à la Doyle and Jiang (2006)
- Horizontal variations in the wind field are important to the formation of the waves (through some as yet unexplained mechanism)
Horizontally Heterogeneous Winds

Horizontal Wind Vectors and Speed (North ↑)

Cross Section Points

Geopotential Height (km)

Wind Speed (m/s)

A
B

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Horizontally Heterogeneous Winds

(z = 3 km)  t: 8.5 hr

(z = 15 km)  t: 8.5 hr
Horizontally Heterogeneous Winds

- We get the waves!
- Wind is essentially steady and non-divergent
- Therefore, something about the inhomogeneities in this wind field helps generate the waves

![Vertical Velocity](z = 15 \text{ km}, \ t = 10 \text{ hr})
Some Notes...

- These waves are fairly low (~15 km)
- They appear in regions of little lateral shear
- Previous dynamical explanations require:
  - Either directional critical levels...
  - ...or...
  - Large lateral shear
- Neither of which are present in this case
A Long Time Ago, On A Level Down Down Low

- Low-level trapped waves oriented SW-NE appear in the real simulations
- However, here the transverse waves also appear
- Is wave interference present?
- Are the SW-NE waves trapped, while the N-S waves can propagate?

(z = 3 km, t = 1.5 hr)
A Long Time Ago, On A Level Down Down Down Low

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- However, here the transverse waves also appear
- Is wave interference present?
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Vertical Velocity

(z = 3 km, t = 1.5 hr)
Conclusions

- Horizontal inhomogeneities appear to be important
- However, none of the existing dynamical explanations are particularly well suited to explain this