Detecting Gravity Waves in the Stratosphere using High Altitude Balloon GPS Data

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Introduction

What is a gravity wave? Gravity waves are buoyancy driven oscillations which occur throughout the atmosphere. Waves transport and deposit energy, making them an important driver of atmospheric dynamics.

Sources of gravity waves include:

- interaction of wind and obstacles such as mountains
- convection (time-varying thermal forcing)
- wave-wave interactions

Better gravity wave climatologies are needed to fully understand their role in energy transport and weather.

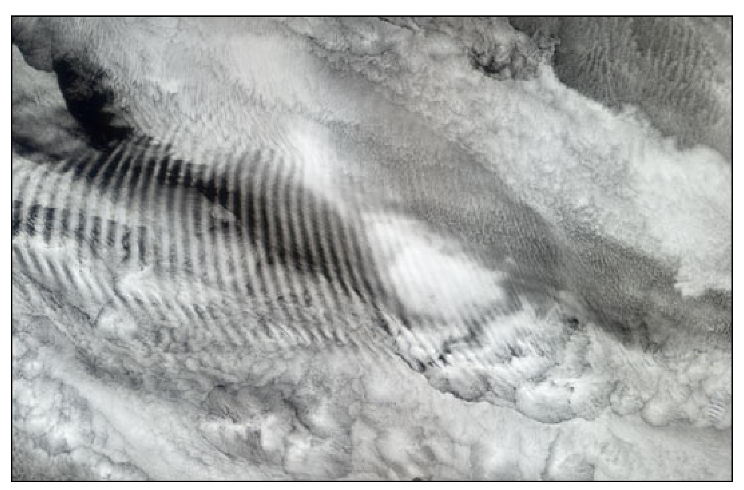

Fig. 1: Gravity wave ripples in stratocumulus clouds over the Indian Ocean. [NASA, 2004].

Fluid dynamics and waves. The Navier-Stokes equations (NSE) govern atmospheric dynamics, and gravity waves must be a solution to these equations.

$$\frac{du}{dt} - fv + \frac{1}{\rho}\frac{\partial p}{\partial x} = 0$$
$$\frac{dv}{dt} - fu + \frac{1}{\rho}\frac{\partial p}{\partial y} = 0$$
$$\frac{dw}{dt} + \frac{1}{\rho}\frac{\partial p}{\partial z} + g = 0$$
$$\frac{1}{\rho} + \frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} + \frac{\partial w}{\partial z} = 0$$

We assume that the gravity wave is a solution of the form

$$q(x,y,z,t) = q_0(z) + Qe^{i(kx+ly+mz-\omega t)}$$

where $q = (u, v, w, p, \rho)$. The two dimensional case can be visualized:

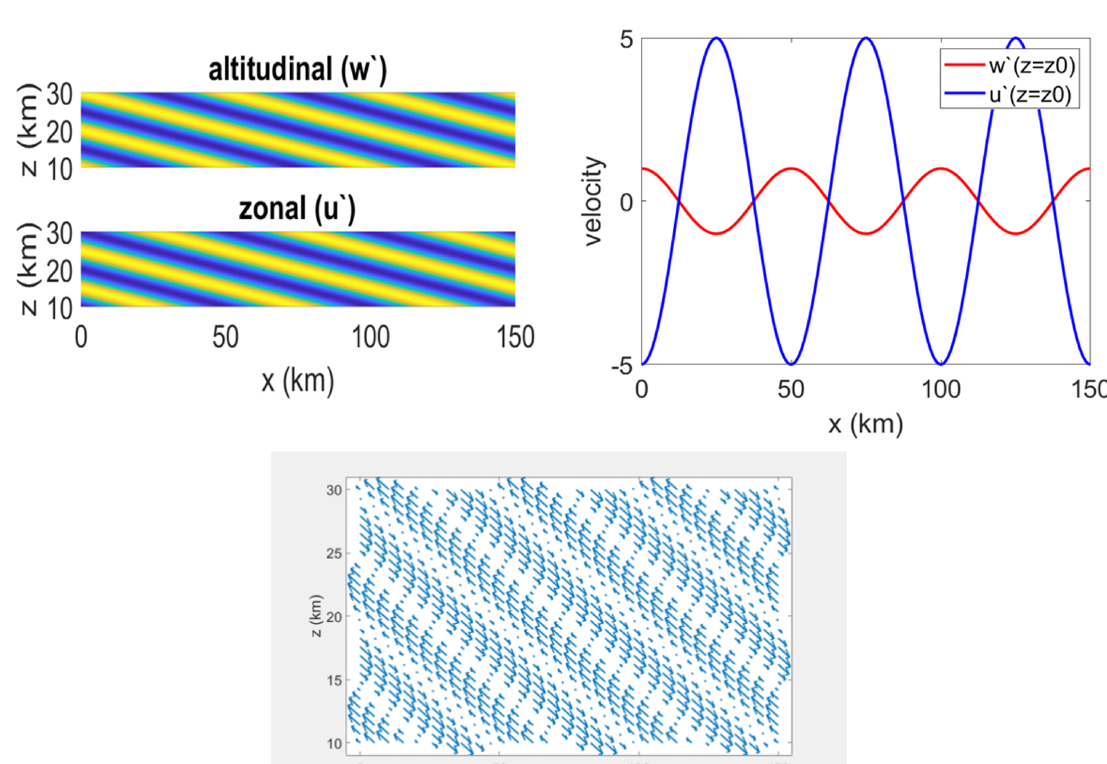

Fig. 2: Velocity fields for a 2D planar gravity wave.

Methods

Balloon flights. As part of MSGC's BOREALIS high altitude ballooning 2022 summer internship, several high altitude balloons were launched over central Montana in the months June-August. In this poster, data from a June 9th, 2022 zero-pressure balloon flight is analyzed.

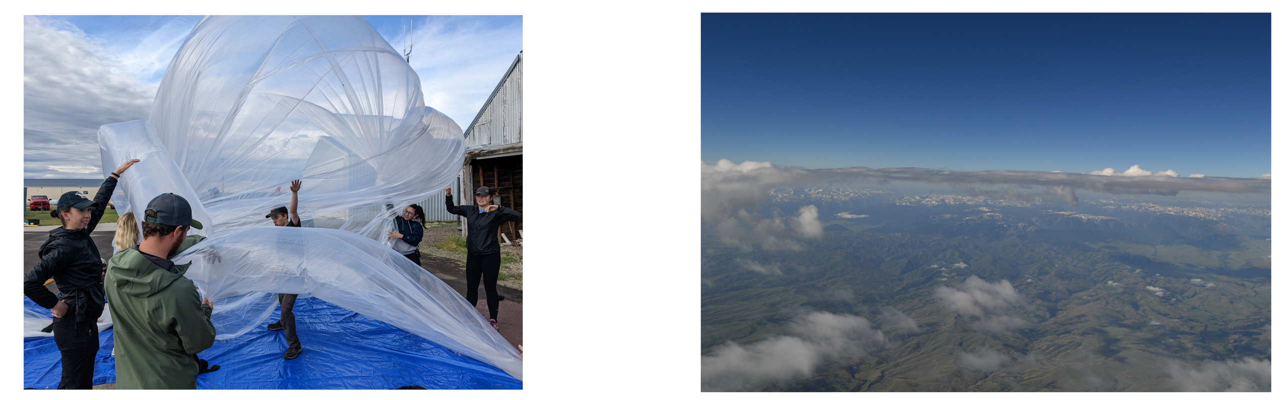

Fig. 3: Zero-pressure balloon and photograph over central Montana, 20,000 ft.

Filtering the velocity data. Precision GPS data and atmospheric parameters were recorded for each balloon flight. Gravity wave signals are difficult to see in the raw data due to high frequency noise like payload oscillations and low frequency trends like wind variation with altitude. Fourier analysis was applied to filter the data and identify dominant wavelengths.

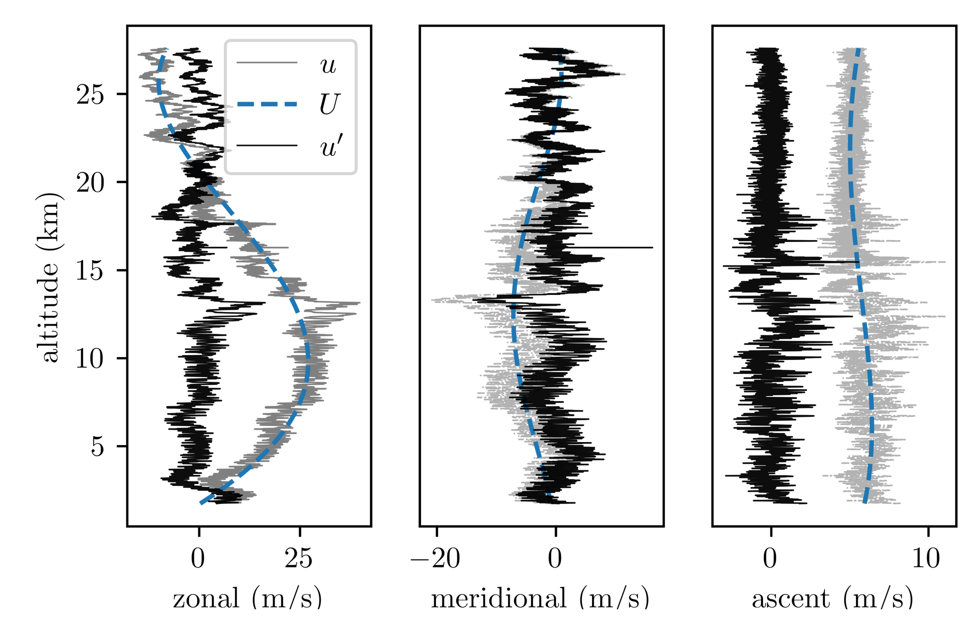

Fig. 4: Balloon ascent velocity data, fitted polynomial, and extracted perturbations.

The hodograph method. Substituting the linear solution assumption into the NSE yields the *polarization relation* [Nappo, 2013].

$$v' = -i\frac{f}{\Omega}u'$$

Since u' and v' are both sinusoidal, this predicts that the velocity perturbations trace out an ellipse with respect to altitude.

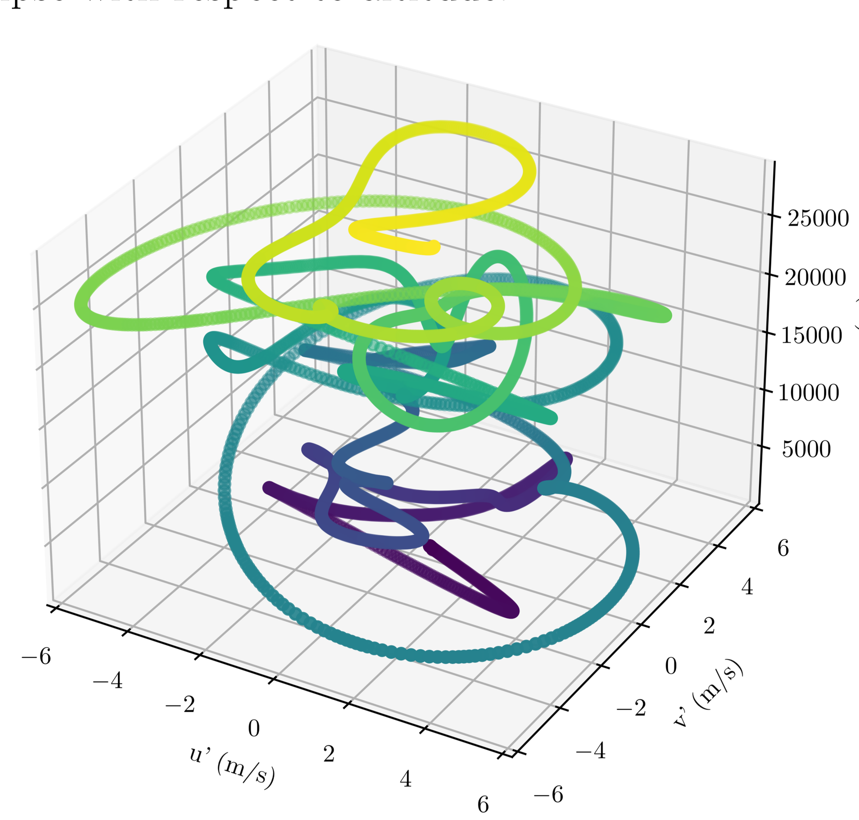

Fig. 5: Horizontal velocity perturbation versus altitude.

Results

Fourier analysis. Spectral power plots were generated for each of the perturbation velocities. Consistent vertical wavelength peaks are seen around 1-3 km and 5-6 km. The dominant vertical wavelength is calculated as $\lambda_z = 5.91$ km [Gong, 2010].

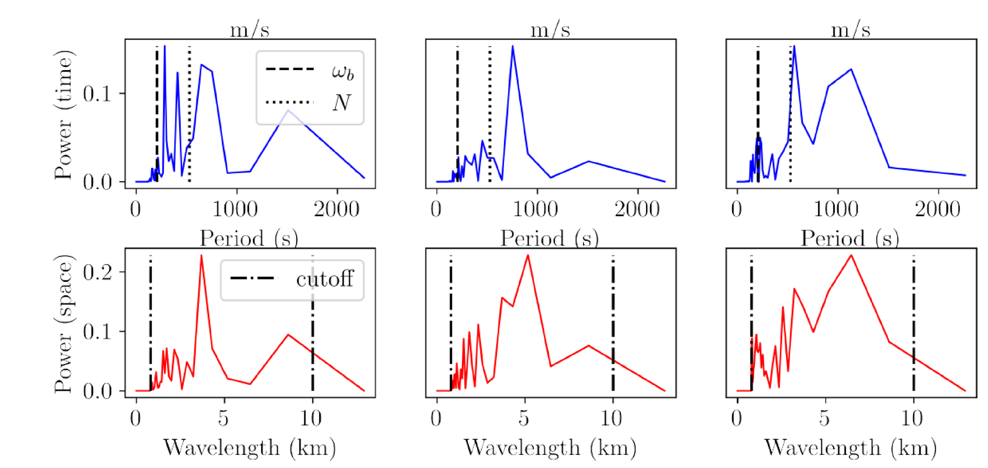

Fig. 6: Velocity perturbation versus altitude.

Hodograph analysis and candidate gravity waves. The horizontal velocity perturbation scatterplot (Figure 5) was examined for ellipsoidal patterns occurring over 1-3 and 5-6 km. Several candidate waves were identified.

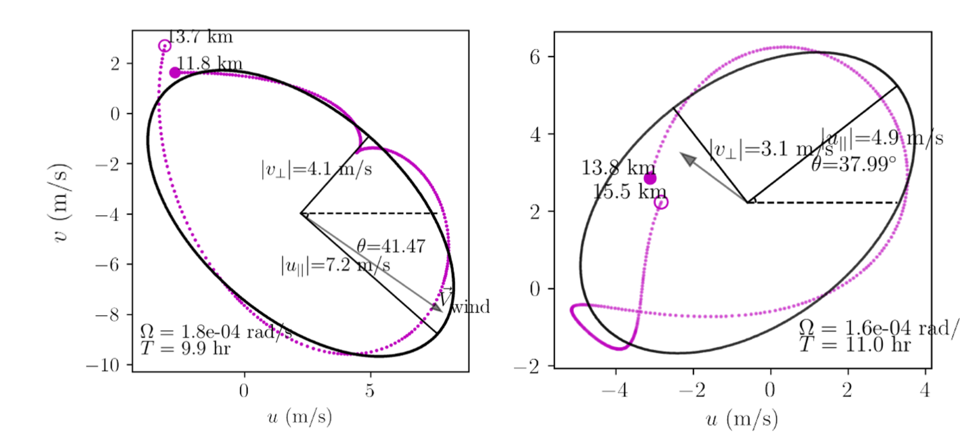

Fig. 7: Potential gravity waves at 12.75 and 14.6 km with intrinsic periods of 9.9 and 11 hours.

A high resolution camera on the balloon payload string captured cloud ripples at approximately 12.3 km.

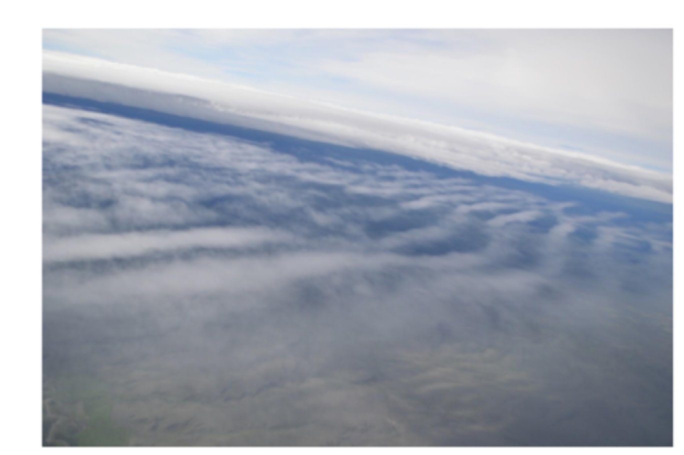

Fig. 8: Cloud ripples observed by an onboard DSLR camera.

Conclusions

- Potential gravity waves were identified using GPS data from high altitude balloon flights over central Montana.
- Ellipsoidal patterns in the horizontal velocity perturbation seem to match linear wave theory predictions.
- Cloud ripples indicative of wave behavior were observed near the ellipse altitudes.

References.

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