Full gravity-wave characteristics inferred from long-duration balloon flights in the tropics and over Antarctica

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http://www.tinyurl.com/strateole
Outline

• Motivations
• Superpressure balloons and balloon flights
• Techniques to retrieve gravity-wave characteristics
• Wave characteristics
  • In the southern hemisphere polar region
  • In the tropics
• Conclusions
Motivations

- Gravity waves contribute to the driving of middle-atmosphere large-scale circulations
  - Brewer-Dobson circulations in the extratropics
  - QBO and SAO in the tropics
- Gravity waves remain subgrid-scale processes in climate models
  - Their forcing of the background flow needs to be parameterized in those models
    - Source, propagation, breaking
- Gravity-wave observations can provide constraints to GWD parameterizations
  - Increase our confidence in climate projections
Superpressure stratospheric balloons

- (first order) Fly on constant-density surfaces in the lower stratosphere (~ 19 km/60 hPa)
  - Flight duration ~ 2-3 months
- Measurements of $\vec{X}(t)$, $P_T(t)$, $T(t)$
- Balloons are advected by the wind
  - $u$, $v$ are deduced from successive balloon positions
  - Measurements provide intrinsic periods/frequencies ($\hat{\omega}$) of wave disturbances
Balloon flights

- Pre-Concordiasi (Tropics)
  - 3 flights
  - Feb. – May 2010

- Concordiasi (South Pole)
  - 19 flights
Balloon flights

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Energy spectrum with balloon obs.

GPS measurements performed every minute during the 2010 flights => Long-duration balloons can resolve the whole spectrum of atmospheric waves.
Retrievals of gravity-wave characteristics (1)

- Wavelet decomposition of observed timeseries → \((t, \hat{\omega})\) space
- Working out linear GW polarization relations, and assuming perfect isopycnic balloon...
  - Momentum flux
    \[
    \text{Im}(\bar{\rho} \ddot{u}_\parallel^*) = -\bar{\rho} H \frac{N^2}{\hat{\omega}} \text{Re}(\ddot{u}_\parallel^* \ddot{w})
    \]
  - Phase speed
    \[
    \delta = \frac{1}{\bar{\rho} \hat{\delta}_-} \frac{\text{Re}(\bar{\rho} \ddot{u}_\parallel^*)}{\ddot{u}_\parallel}
    \]
  - Phase speed, where
    \[
    P_T' = P' + \zeta' \frac{\partial P}{\partial z}
    \]
  - Vertical wave number
    \[
    m = -\bar{\rho}^2 \hat{\delta}_- \left( \frac{N^2 - \hat{\omega}^2}{\hat{\omega}} \right) \frac{\text{Re}(\ddot{u}_\parallel^* \ddot{w})}{\bar{\rho}^2}
    \]
- Horizontal wave number through the GW polarization relation
- Ground-based frequency/phase speed through Doppler-shift equation
Retrievals of gravity-wave characteristics (2)

- But the balloons are not perfectly isopycnic...
- We looked at the response of superpressure balloons to gravity-wave disturbances (Vincent & Hertzog, AMT, 2014)

![Graph showing balloon neutral oscillation period, Brunt-Vaisala period, and isopycnic limit.](image)
Retrievals of gravity-wave characteristics (3)

- Tests based on (random) choice of GW characteristics, synthetic timeseries of balloon observations (including observation noise), and retrieval analysis

\[ u' \parallel w' \quad \hat{c}_h \quad \theta \]

\[ 2\pi/\hat{\omega} \quad 2\pi/\hat{\omega} \quad 2\pi/\hat{\omega} \]

\[ 2f < \hat{\omega} < \frac{N}{2} \]

Vincent and Hertzog (2014)
Gravity-wave momentum fluxes

Absolute momentum fluxes

\[ \overline{\rho u' w'} \]

Campaign mean: 8.8 mPa

Largest values over Peninsula and Transantarctic mountains (maximum: 180 mPa)

Lowest values over the Plateau

Ring of 8-10 mPa fluxes at 60°S over the ocean

Absolute momentum fluxes (Concordiasi 2010)
Zonal-mean momentum fluxes exhibit a secondary peak at 55°S, which seems to be associated with non-orographic gravity waves in the balloon data: Jet/front waves in the SH storm track.
Zonal and meridional momentum fluxes

Zonal momentum fluxes are negative almost everywhere
Campaign mean: -1.2 mPa

Insignificant bias on meridional momentum fluxes
Campaign mean: 0.1 mPa
Polar flights indicates a predominance of westward-propagating waves in the LS

Waves with zero ground-based phase speeds are associated with westward fluxes, i.e. mountain waves
Phase-speed momentum-flux spectrum

Polar flights indicate the predominance of westward-propagating waves in the LS.

Waves with small ground-based phase speeds are associated with westward fluxes, i.e. mountain waves.
Phase-speed momentum-flux spectrum

Polar flights indicate the predominance of westward-propagating waves in the LS.

Waves with small ground-based phase speeds are associated with westward fluxes, i.e., mountain waves.

Tropical flights do not show any preferential direction of propagation (isotropic sources + balloons experienced both QBO phases).

Mountain waves
Concordiasi

Pre-Concordiasi
1D phase-speed spectrum

Concordiasi flights

Most of the flux associated with $|c| < 50$ m/s
Ground-based phase-speed spectrum narrower than the intrinsic phase-speed spectrum
1D phase-speed spectrum

Pre-Concordiasi flights

Intrinsic phase speed

\( \sigma_{\hat{c}_x} \sim 20 \text{m/s} \)

Ground-based phase speed

\( \sigma_{\hat{c}_y} \sim 20 \text{m/s} \)

Phase-speed spectrum in the tropics are more symmetric than over the Pole

Isotropy of convective source and wind filtering
\((m, \hat{\omega})\) 2D spectra

Momentum fluxes almost separable in \(m\) and \(\hat{\omega}\)

Largest fluxes associated with 3-10 km

(Kinetic-) energy associated with mostly long-period waves

Mountain waves show up at \(\lambda_z = 3\) km, \(\hat{T} = 1-4\) hr

Corresponding to \(\lambda_h = 100-200\) km
(\(m, \hat{\omega}\) 2D spectra)

Momentum fluxes almost separable in \(m\) and \(\hat{\omega}\).
Largest fluxes associated with 3-10 km.

(Kinetic-) energy associated with mostly long-period waves.

Mountain waves show up at \(\lambda_z=3\) km, \(\hat{T}=1-4\) hr.
Corresponding to \(\lambda_h=30-150\) km.
(m, \hat{\omega}) 2D spectra

Momentum fluxes almost separable in m and \hat{\omega}.
Largest fluxes associated with 3-10 km
(Kinetic-) energy associated with mostly long-period waves

Mountain waves show up at \lambda_z=3 \text{ km}, \hat{T} = 1-4 \text{ hr}

Equatorial 2D spectra much like the polar ones, but extend to lower intrinsic frequencies (and we did not explore the even longer-period waves)

Balloon’s artifact
(k_h, m) 2D spectra

Waves with small horizontal scales (down to 10 km) contribute more to the momentum fluxes than to the kinetic energy.
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Kinetic-energy dominated by long-horizontal, long-period waves in the tropics

Momentum flux spectrum broader (shallower spectral slopes)
PDF/Intermittency

Concordiasi absolute momentum fluxes ($\rho<u',\rho'w'>$)

Concordiasi

Pre-Concordiasi

Occurrence frequency

(mPa)
PDF/Intermittency

Concordiasi absolute momentum fluxes ($\rho<u',w'>$)

Concordiasi
Pre-Concordiasi
Peninsula
PDF/Intermittency

Concordiasi absolute momentum fluxes \( \langle \rho u''/w' \rangle \)

Concordiasi
Pre-Concordiasi
Peninsula
Southern ocean

Occurrence frequency

(mPa)
PDF/Intermittency

Concordiasi absolute momentum fluxes ($\rho<u''/w'>$)

- Concordiasi
- Pre-Concordiasi
- Peninsula
- Southern ocean
- Plateau

Occurrence frequency vs. (mPa)
Contribution of the 10% largest wave events to the total flux
Pre-Concordiasi: 32%
Southern Ocean: 32%
Plateau: 37%
Concordiasi: 49%
Peninsula: 84%
Conclusions

- Long-duration balloons provide a unique description of the whole gravity-wave field in the lower stratosphere
  - Quantitative assessment of momentum fluxes in the lower stratosphere
    - Peninsula mountain wave hotspot
    - Importance of non-orographic GW on the zonal-mean MF at 50-60°S
  - Insights into phase-speed spectrum and horizontal/vertical wavelengths
  - Highlight gravity-wave intermittency
- Strateole 2 (2018-2023) will study wave processes at global scale in the deep tropics
  - 45 balloon flights in total
  - Generation by convection
  - Forcing of the QBO/SAO
  - Transport through the CPT
  - Interaction with microphysics
Thank you for your attention!