Spatial structures of stratospheric gravity waves derived from COSMIC GPS occultation data

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GPS Radio Occultation (RO)

- GPS signals are received by low-earth-orbiting satellites
  → refractivity profiles → Temperature
    (&humidity in lower-to-mid troposphere)

Global distribution of potential energy of stratospheric GWs
COSMIC / FORMOSAT-3

- by UCAR(US) & NSPO(Taiwan)
- Launch: Apr 2006
- 6 LEO satellites (recv 2 ways)
  → substantial increase of RO measurements (~2500 per day)
S. Alexander et al 2008

GW energy averaged between 130E-150E
23-28 Dec 2006 using COSMIC data
Purpose of this study

• To study spatial structures of gravity waves using multiple GPS RO profiles nearby
  – Earlier studies: profile-base

• Merit: Good vertical resolution (1km or better)
• Demerit: Horizontal resolution/sampling lower than conventional instruments (e.g. AIRS)
On the average, COSMIC sampling is still too sparse (1 per 500km*500km*1day) → Examine satellite orbits

- Launched by a single rocket (inclination 72°)
- Alt. raised 1 per ~2 months (500km → 800km)

Liou et al (2007)
LEO orbits relative to the stars (ECI coordinate)

3 LEOs still on one orbit after 1 year since launch
→ High data acquisition rate around the orbit
We focus on the neighborhood of the orbit having multiple satellites

Coordinate transformation

- $p$: along the satellite track
- $q$: perp to $p$
Tangent points are found to be frequently organized in linear shapes.

Occultation points by 4 satellites on the same orbit in Dec 2006.
Strategy

• Extract groups of data points organized linearly → Obtain vertical cross sections
  – Snapshots within ~ 1 hours → Good to analyze short-lived disturbances with high vertical resolution

Dataset used

• COSMIC Level 2 by UCAR (dry temperature)
Heuristic Line Clustering

- Algorithm

1. Initial pairs: nearest neighbors (distance $\leq dr$, and $\geq$ a threshold)

2. Find points in a rectangle like this:

3. If found, add & extend the rectangle like this: (back to 2)
Extracted lines

\[ dr = dw = 600 \text{ km} \]
\[ dr = 1000 \text{ km} \]
\[ dw = 600 \text{ km} \]

- Dense in mid to high latitudes (Rarely crossing the equator)
- Hemispheric, preferred longitudes moving eastward slowly, with wave number=2
Now in stratospheric sudden warming near the polar vortex edge
near the polar vortex edge
Amplitudes at 28km using lines with lengths 1500 ~ 3000 km

(a) Amplitude (cutoff 10km)

(b) Amplitude (horiz.dev & cutoff 10km)

(c) Amplitude (cutoff 5km)

(d) Amplitude (horiz.dev & cutoff 5km)
Preusse 2006

Features of GW amplitudes in $T$
(cutoff: 10 km)

- SH / Summer: positively skewed PDF
- EQ: mean PDF
- NH / Winter: positively skewed PDF
S. Alexander et al 2008 (again)

GW energy averaged between 130E-150E
23-28 Dec 2006 using COSMIC data
Alexander et al 2008

GW energy averaged at 40N using COSMIC data
(a) 29 Nov-5 Dec 2006  (b) 24-30 Dec 2006
Winter NH cases

(a) Line 86 & NCEP SLP
(b) High pass < 10.0km

(c) Line 171 & NCEP SLP
(d) High pass < 10.0km

(e) Line 148 & NCEP SLP
(f) High pass < 10.0km

(g) Line 415 & NCEP SLP
(h) High pass < 10.0km
$T$ amp (25km) vs $U$ shear (10 – 70hPa)  40-65N
$T$ amp (25km) vs $V$ (30hPa)  40-65N
$T$ amp (25km) vs $V$ shear (10 – 70hPa) 40-65N
GW propag directions and mean winds

**Zonal propagation**
- Westerly shear survives both directions.
- Easterly shear survives e’ward GW.

**Meridional propagation**
- Northerly wind & shear doesn’t reach mid latitudes.
- Southerly wind & shear reaches mid latitudes.
**Summary**

- **Snapshot “lines” were extracted from COSMIC RO data**
  - Found: GPS RO events are frequently form lines (esp. mid-high latitudes)
  - Longitudinally concentrated, which moves eastward
- **Vertical cross sections → Spatial structures of GWs**
  - In many cases, horizontal structures indicating GWs are identified over multiple RO events
  - Statistics → GWs of $5 < \lambda_z < 10$ km tend to have relatively large $\lambda_H$ in the equatorial region & SH.
  - GW in NH (winter) mid-to-high lat
    - Propagation: zonally both Eward&Wward, meridionally northward
    - Source: mainly in subtropics
    - GW amp correlated negatively with U shear and positively with V wind; Critical-level filtering for zonal amp fluctuation
Gridding by triangulation  (2006/12/01 4LEOs $\Delta p_{\text{max}}=\Delta q_{\text{max}}= 0.1 \text{ rad} / 2\pi$) 

Work done by Y. Azuma, Horinouchi, and Tsuda
Polar case

Horizontal x-sec
z=30km
(2000 km x 2000 km)

x-z sec
(dev. from horiz. mean)

z high pass
(< 5km)

Horizontal mean

y-z sec
(dev. from horiz. mean)

z high pass
(< 5km)
Sample transformation results (Nov 16, 2006 leo:1,3,4,6)

day:2006.320  leo ids:1346
Strong winter time subtropical jet

Large PE from mid-troposphere up to PNJ

AGCM PE 140E, 1 – 7 Jan
(similar wind conditions to COSMIC)

PE from waves with periods 6hr – 1 month, $\lambda_z < 7km$, $380 < \lambda_x < 40,000km$

Note different colour scale

Vectors show meridional and vertical energy fluxes due to $\lambda_z < 7km$

Most mid-lat stratospheric PE due to the jet (upward vectors)

by Alexander and Tsuda
予備スライド
Delaunay triangulation

Allow no other point in the outer circles of all triangles
N.H. Stratosphere of the period

- 3 major sudden warmings
Vertical high-pass filtering

- Based on FFT
- Padding & Extending to avoid leak from cyclic discontinuity

Data up to 40 km; Graphics up to 35 km

Constant extrapolation for missing (esp. low alt)

Linear interpolation to avoid discontinuity in cyclic treatment (Result QUITE DIFFERENT without it)
座標変換

・衛星進行方向($p$とする)とそれに直交する方向($q$)に軸を取る。
  - 通常のswathデータ同様
  - ただし、軌道情報がなくても、掩蔽点の位置だけから求まるよう工夫（＊：衛星が複数なので、軌道パラメタも一意でない。
    利点：解析的。軌道データがない場合でも適用できる）。

$$
\sin q = \sin \phi \cos \theta - \sin \lambda' \cos \phi \sin \theta \\
\cos p = \frac{\sin \lambda' \cos \phi}{\sqrt{1 - \sin 2q}} \\
\sin p = \frac{\sin \lambda' \cos \phi \cos \theta + \sin \phi \sin \theta}{\sqrt{1 - \sin 2q}}
$$

ここで

$$
\lambda' = \lambda - \lambda_0 - \alpha \omega^{-1} p
$$

$p$について再帰的なのので、反復法。

$\lambda_0$も $p \cos q$ をゼロに近づける反復より求める。