Global studies of stratospheric gravity wave activity using COSMIC GPS-RO

Simon Alexander¹, Toshitaka Tsuda², Andrew Klekociuk¹, Yoshio Kawatani³, and Masaaki Takahasi⁴

¹Australian Antarctic Division, Hobart, Australia
²Research Institute for Sustainable Humanosphere (RISH), Kyoto University, Japan
³Japan Agency for Marine-Earth Science and Technology (JAMSTEC), Yokohama, Japan
⁴Center for Climate System Research (CCSR), University of Tokyo, Japan
Outline

• Temperature profiles from GPS RO are used to study the behavior of atmospheric gravity waves (GW) in the stratosphere.

• Data analysis procedure of GW energy (Ep: potential energy)
  CHAMP: from May 2001 to December 2005
  COSMIC: from July 2006 –

• Generation of GW’s due to convection in the tropics and their interaction with background mean winds (QBO).

• Distribution of Ep in the Antarctic and Arctic regions
  Geostrophic adjustment of polar night jet
  Orographic effects
  Doppler shifting
Comparison of temperature profiles between COSMIC GPS RO and radiosonde at Kuching, Malaysia.

Temperature profiles around the cold point tropopause, 26 Dec 2006
- COSMIC GPS RO (Green) (4.1N, 110.4E, 11:32UTC)
- Radiosonde at Bintulu, Malaysia (Orange) (3.1N, 113.0E, 11:34UTC)
- HIRDLS (Blue,-solid) (3.4N, 118.6E, 16:38UTC)
- SABER (Blue-dotted) (3.8N, 108.6E, 10:39UTC)
- AQUA-AIRS (Red) (3.9N, 115.3E, 17:55UTC)
A global distribution of gravity wave energy

- The GPS RO data having a very good height resolution provides a unique opportunity to study a global morphology of atmospheric gravity waves in the stratosphere.
- CHAMP and COSMIC GPS RO data are used to derive the potential energy (PE) from gravity waves in an appropriate vertical wavelengths bands (1-7, 15 km) and to study longitudinal and latitudinal variations.

Atmospheric Gravity Wave Energy ($E_p$) in the Stratosphere by Using CHAMP and COSMIC GPS RO Temperature ($T$) data

Wave potential energy, $E_p=1/2(g/N)^2(T'/T_0)^2$

$g$; acceleration of gravity, $N$; Brunt-Vaisala frequency, $T'$; temperature perturbation, $T_0$; background temperature

Grid cell size (variable)
- CHAMP: 20° (lon) x 10°(lat) x 1-3 months
- COSMIC
  - Tropics 20°(lon)x5°(lat)x7 days, stepped forward by one day
  - Polar regions 30°-180°x (lon) x 5°(lat) x 5 days (constant grid cell area)
(1) Obtain all available GPS RO data in individual cells, and calculate the mean $T$ profile, then apply a low-pass filter with a cutoff at 7 or 15km. Then, the mean $T$ profile ($T_0$) is determined.

(2) Calculate $T' = T - T_0$ for individual GPS RO profiles, and apply FFT along altitude, then, extract the fluctuating components ($T'$) with vertical wave lengths of 2-7 km or 2-15 km. Finally, $E_p$ is determined by integrating the spectral density.
Generation, Propagation and Dissipation of Atmospheric Waves in the Equatorial Region

**Dissipation**
The waves dissipate through various instability processes, and deposit the momentum to the background winds, playing a key role to maintain the dynamical structure of the equatorial middle atmosphere.

**Propagation**
The atmospheric waves grow the amplitudes during upward propagation in the middle atmosphere (15-100 km). Energy and momentum are transported both horizontally and vertically by these waves.

**Generation**
Active convection in the tropics generates various atmospheric waves (equatorial Kelvin wave, atmospheric tide, gravity waves, etc).

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Active convection in the tropics generates various atmospheric waves (equatorial Kelvin wave, atmospheric tide, gravity waves, etc).
In the northern winter months (Dec/Jan/Feb), intense cloud convections are located over Indonesia and western Pacific, which actively generates atmospheric gravity waves as well as Kelvin wave-like disturbances in the equatorial region.
Jun-Jul-Aug, 2001

Sep-Oct-Nov, 2001

Dec, 2001 – Jan-Feb, 2002

CHAMP

Ep
Stratospheric
gravity wave energy

OLR
Cloud top height

TRMM
-PR
Convec
tive rain rate
Year-to-year variations of wave energy (Ep), OLR and convective rain rate in Dec/Jan/Feb in 2001-2005

OLR, TRMM-PR, TRMM-Storm Height, Ep

CHAMP

Black: Ep (0-10 J/kg), Blue: OLR (300-150K), Blue: Rain rate (0-0.25 mm)
Ep with CHAMP/GPS RO in 2001–2005 19–26 km
Season-height section of zonal mean PE at 25.5S-2.5N from Sep 2006 to Apr 2008

**COSMIC**

**LEFT:**
- Grid size: $20^\circ \times 5^\circ \times 7$ days,
- 7km high-passed perturbations from individual profiles, and get PE by integrating vertically over 7km, stepping up by 1km and forward by 1 day.
- Mainly meso-scale GWs with minor MRGW and higher speed KW contributions.

**RIGHT**
- Grid size: $20^\circ \times 5^\circ \times$ one month
- Height independent (1km) data by assuming that all wave phases are represented at that particular height
- Slower speed KWs but still mainly consists of GWs

• QBO westward shear initially, then eastward shear after mid-2007.
• QBO removes gravity waves, especially close to the 0 m/s phase line.

White contours: NCEP zonal mean zonal wind, units m/s, east/westward; solid dashed

(b) In each year residual of $Ep$ from global average in (a) is calculated, then, they are averaged for 5 years.

Results in (a) indicate a climatological pattern of the temperature disturbances in the stratosphere, including Kelvin waves, GW, etc. While, (b) shows regional wave activity, esp. GW is dominant GW energy seems to be larger over the Asian monsoon region, Indonesia-western Pacific by convection, and Southern America (Andes) due to orographic waves.
SUMMARY

1. GPS radio occultation (RO) temperature profiles, having a very good height resolution comparable to a radiosonde, are used to study meso-scale temperature perturbations in the stratosphere. We calculate potential energy (PE) from gravity waves with vertical wavelengths less than 7 km, and to study longitudinal and latitudinal variabilities in cells of size $20^\circ \times 5^\circ$ and $10^\circ \times 5^\circ$ for 7-day and seasonal averaging, respectively.

2. PE in the Northern Hemisphere during 2006/07 winter
   * Large PE at 17–23 km is mostly associated with the sub-tropical jet and shows significant longitudinal variability. Some contribution to total PE from local orographic sources may occur above the Canadian Rockies, Scandinavia and northern Japan.
   * Many of the waves are likely to have low ground-based phase speeds, as observed by filtering around the 0–10 m/s background zonal wind.
   * COSMIC results are compared with a T106L60 AGCM, confirming sub-tropical jet related generation, upward propagation and low phase speeds of the observed gravity waves.

3. Variations of PE in the tropics vs longitude, height and season
   * In the tropics vertically propagating convectively generated gravity waves interact with the background mean flow.
   * PE enhancements around the descending 0 m/s QBO eastward shear phase line are observed.
- N-H mid-latitude sub-tropical jet has maximum eastward winds at 10 km and 35N.
- Large PE above the jet core are distributed upward/poleward along the u contour lines.
- These waves seem to have small ground based phase velocities, and are critically filtered out by the westward wind shear. (Note: large decrease between 10 m/s and 0 m/s lines.)
- Large PE extends up to the edge of the polar stratospheric jet.
COSMIC PE at 140E during 12 – 18 Dec 2006

- Strong winter time sub-tropical jet
- Large PE from mid-troposphere up to polar night jet

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

- PE from waves with periods 6hr – 1 month, $\lambda_z < 7$km, $380 < \lambda_x < 40,000$km
- Note different colour scale
- Vectors show meridional and vertical energy fluxes due to $\lambda_z < 7$km

- The polar night jet itself generates gravity waves which propagate upward and downward, as evident in (b) by the downward flux vectors on the polar side of the jet above 20 hPa.
- Another consistency between the COSMIC and AGCM data is relatively low values of UTLS potential energy at 20N, which is a region that also corresponds to weaker energy flux.
PE & Zonal Wind, 24/02/2007, Lon:100.0
PE & Zonal Wind, 25/02/2007, Lon:100.0
PE & Zonal Wind, 26/02/2007, Lon:100.0

km

hPa

Latitude

12/16
Earlier studies of gravity waves (GW) in Antarctic region

- By using routine radiosonde data at Antarctic bases, GW energy is found to be large in October-November. [Yoshiki and Sato., 2000]
- The intensity of background mean winds (polar night jet) seem to be related to a generation mechanism of GW.
- GW energy was enhanced when the polar night jet approached over the station during its dissipating phase in spring. [Yoshiki et al., 2004]
- Rantnam et al. [2004] reported enhancement of GW at around the polar vortex during the major stratospheric sudden warming in 2002 by using CHAMP GPS RO data.

Seasonal variation of the mean square of temperature fluctuations averaged at 15-20km at the Antarctic stations [Yoshiki and Sato, 2000].
Rapid decay of Polar Vortex in September to October in Antarctica is associated with large enhancement of wave energy (Ep).
Horizontal distribution of Ep (12-33km), Geopotential height (250-7hPa) and Horizontal winds (250-7hPa) in September and October 2003

September 2003

Ep [J/kg]
12-33km

Geopotential Height [km]
250-7hPa

October 2003

V [m/s]
250-7hPa
Wave Energy (monthly mean rms $T'$) is closely related with E-P flux divergence (DF) in both Antarctic and Arctic regions.

In Antarctic during the vortex decay in spring (September-October) GW activity is considerably enhanced.

While in Arctic region, vortex decay does not effectively emit GW, but SSW (sudden stratospheric warming) events are closely related to GW energy increase.
Distribution of COSMIC GPS RO data around Antarctica in 5 days on 1-5 September 2006 (Left) and 27 September – 1 October 2006
Wave activity enhancements were also found around the edge of the polar vortex, which was attributed to reduced critical level filtering and Doppler shifting. Additional wave sources, such as geostrophic adjustment or shear associated with the jet, were not necessary to explain this enhancement.

Analysis with CHAMP GPS-RO and balloon soundings suggest that wave enhancement outside the Antarctic continent is related to structure of the polar vortex. Esp., large Ep was found near the edge of the vortex. (e.g., Yoshiki and Sato, 2000; Ratnam et al., 2004)
Longitude variation of Ep in 2003, averaged over 60-90S, Baumgaertner and McDonald (2007)

Topography is an important source of gravity waves in the two regions. The relation is less pronounced at 23-27 km probably due to the filtering effects.

Yoshiki and Sato (2000) reported that the gravity wave activity at 15-20km over Syowa has a weak correlation with tropospheric winds, so, they suggested stratospheric sources for wave generation.
Numerical model results for orographic generation of gravity waves

Orographic waves are generated near west coast of RASS sea

S. Watanabe et al., JGR, 2006

(a) Antarctic Region  (b) Arctic Region

Cell size for data analysis

Time resolution: 5 days
Cell size;
Latitude extent is 5°
Longitude binning is 30° at 40-50° latitudes, and it is increased poleward to maintain a nearly constant grid cell area.

Wave activity in the shaded regions is studied further.
(a) The Antarctic region: the Patagonian Andes, the Antarctic Peninsula, the Trans-Antarctic Mountains and the Southern Ocean regions shaded.
(b) The Arctic region: Scandinavia, southern Greenland, the Ural mountains and the North Pacific Ocean regions shaded.
May-December 2007 in **Antarctica** at 500 K (about 19-20 km)

During winds decreased from 60 m/s to 40 m/s in late-Sep to Oct (spring), large wave variance is observed inside the vortex boundary with symmetric distribution.

October-May 2006/7 for the **Arctic** vortex at 500 K

Enhancement of Ep does not occur during the vortex decay phase. But, large Ep in early Jan, Feb and March coincides with SSW (sudden stratospheric warming).

Contour: Ep, White line: 5-day smoothed UKMO zonal mean zonal winds (m/s, eastward solid), Yellow line: vortex edge (thick) and vortex boundary region (between the thin yellow lines).
Region of increased $Ep$ descends in concert with decreasing winds (from 80 to 40 m/s) and a descend of a region of increased stability.

At 71°S (outside of the vortex), the behavior of $Ep$ is similar, but with smaller magnitude. $Ep$ is 1.5 times larger at 61°S (inside the vortex boundary) than at 71°S.

At 800 K, $Ep$ exceeds 2.5 $K^2$ for certain short intervals in early July, mid September and early October, which is likely due to orographic source.
Stereographic map of wave variance during August-September-October at 500 K and 1,000 K in Antarctica

Large Ep (2.0-2.5 K²) is seen lee of the Andes.

During the vortex breakdown from Sep to Oct, Ep is enhanced in the strongest wind zone (40 m/s).

Large Ep on the coastline near the Trans-Antarctic mountains.

Orographic effects are dominant at 1,000 K. Esp. in Drake passage and in the lee of the Antarctic Penninsula.

Monthly median of wave variance calculated from the original 5-day determinations. White lines: the monthly mean zonal wind (m/s, solid eastward)
Short-term wave variability in Antarctica

Intermittent peaks of $E_p$ occur with 5-10 day duration, with larger values over Andes and Antarctic Peninsula than the Trans-Antarctic mountains. Orographic waves are not continuously generated, but they depend on the mean wind conditions.
Characteristics of Gravity Waves in the Polar Regions

- GW activity likely depends on a combination of orographic waves, Doppler shifting of tropospheric source waves and some in situ stratospheric wave generation.
- Antarctic vortex in 2007 shows enhanced Ep distributed about the vortex edge, which is mainly confined within the vortex boundary region between the 400 K and 600 K isentropes, with values approximately double those outside the vortex.
- The 2006/2007 Arctic vortex structure does not show the same increase of Ep at 400 K–600 K in the vortex boundary region as that observed in the Antarctic. Effects of SSW is more significant in the Arctic region.
- Wave activity in both hemispheres in the lower stratosphere (400 K–450 K) is directly related to the location of the vortex.
- The October average shows 3.0K² at 500K in the lee of the Andes and 1.0–1.5 K² away from mountainous regions within the vortex boundary region.
- Significant orographic wave events occur in the lee of the Andes and Antarctic Peninsula.
- Overall, the monthly spring median value of 6.0–7.0 K² at 1000 K above the Andes and Antarctic Peninsula is approximately double that over regions with similar wind speeds but less or no topography.
- Orographic waves last less than a week, resulting in short term fivefold increases of Ep above both Northern and Southern Hemisphere mountainous regions.
SUMMARY

• Temperature profiles obtained from GPS-RO are used to analyse the behaviour of atmospheric gravity wave (GW).
  ✓ COSMIC GPS-RO data have resulted in a more detailed understanding of global and regional scale GW activity on shorter time intervals in the lower stratosphere than previously possible.
  ✓ Specifically, the data allow the resolution of waves with vertical wavelengths of about 2–7 and 15 km on time scales of 5-7 days.

• In the tropics,
  ✓ We have studied convectively generated GW, and found hemispheric and regional scale changes in wave energy which are related to the convective source as well as background wind (QBO) conditions.

• In the polar regions,
  ✓ We have determined the latitudinal extent of enhanced gravity wave activity around the stratospheric vortex edge.
  ✓ We revealed the symmetric presence of increased gravity wave activity near the vortex edge around the 500K isentrope during Antarctic springtime decay.
  ✓ Most of the wave energy observed above various mountainous regions in the polar and sub-polar regions can be attributed to the presence of orographically generated waves.
CHAMP


COSMIC


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- Wave activity in both hemispheres in the lower stratosphere (400 K–450 K) is directly related to the location of the vortex.
- The October average shows 3.0K$^2$ at 500K in the lee of the Andes and 1.0–1.5 K$^2$ away from mountainous regions within the vortex boundary region.
- Significant orographic wave events occur in the lee of the Andes and Antarctic Peninsula, based on relatively low wind rotation angles from the surface to 400 K.
- Overall, the monthly spring median value of 6.0–7.0 K$^2$ at 1000 K above the Andes and Antarctic Peninsula is approximately double that over regions with similar wind speeds but less or no topography.
- Orographic waves last less than a week, resulting in short term fivefold increases of Ep above both Northern and Southern Hemisphere mountainous regions.
- Increases in Ep above the Southern Ocean during October 2007 coincides with strong wind speeds, which are conducive to Doppler shifting of tropospheric
Figure 2. Structure of the Antarctic vortex during austral spring 2007. Missing $\sigma^2$ regions are marked white. (a) $\sigma^2$ at 500 K (color), 5-day smoothed UKMO zonal mean zonal winds (white, eastward solid, units m s$^{-1}$), vortex edge (thick yellow line) and vortex boundary region (between the thin yellow lines). (b) Same but at 800 K. (c) $\sigma^2$ (color) at equivalent latitude 61°S. UKMO zonal mean zonal winds (white lines, units m s$^{-1}$) and COSMIC zonal mean Brunt-Väisälä frequency (yellow lines, units 10$^{-2}$ rad$^{-1}$ s$^{-2}$) are smoothed by 5 days. (d) Same but at 71°S.
Figure 3. Same as Figure 2 but for the Arctic vortex during the boreal winter of 2006/2007.
Figure 4. Contour plot of the median gravity wave variance relative to the vortex edge during (a) July, August, and September 2007 for the Antarctic vortex, and (b) January, February, and March 2007 for the Arctic vortex. Thick black lines indicate 1 K², 2 K², and 3 K². The zonal winds relative to the vortex edge are shown by the white lines for the same periods (units of m s⁻¹, solid lines eastward). The vertical gradient of zonal wind above 500 K is marked by the yellow dashed lines (units m s⁻¹ 100 K⁻¹, solid lines positive upward). Positive distances along the abscissa indicate the northward direction.
Figure 5. Gravity wave $\sigma^2$ in the Southern Hemisphere spring 2007 at (a) 400 K and (b) 450 K and the Northern Hemisphere winter of 2006/2007 at (c) 400 K and (d) 450 K. The 5-day smoothed UKMO zonal mean zonal winds (white, eastward solid, units in m s$^{-1}$), vortex edge (thick yellow line), and vortex boundary region (between the thin yellow lines) are also marked. Times of missing $\sigma^2$ are marked white.
Figure 8. Monthly median $\sigma^2$ during boreal winter 2006/2007 formed from the original 5-day calculations. Contours as per Figure 6. (a) December 2006 500 K isentrope, (b) December 2006 at 1000 K, (c) January 2007 at 590 K, (d) January 2007 at 1000 K, (e) February 2007 at 590 K, (f) February 2007 at 1000 K. Missing data regions are marked white.
Figure 9. COSMIC $\sigma^2$ at 500 K (thick solid line), 800 K (dashed line), and 1000 K (thin solid line) with scale to the left; and near-surface wind speed (dotted line, scale to the right), during the boreal winter 2006/2007 above (a) Scandinavia, (b) Southern Greenland, (c) the Ural mountains, and (d) the North Pacific Ocean. The averaged wind rotation angle $\psi$ is shown directly beneath the first three panels (solid line, scale to the left, in degrees) along with the direction toward which the surface wind travels (dotted line, scale to the right, in degrees).