Characteristics of Atmospheric Waves in the Stratosphere Revealed by GPS Radio Occultation (RO) Temperature Data

Toshitaka Tsuda[1], Simon Alexander[2], Yoshio Kawatani[3], Masaaki Takahashi[4]

1) Research Institute for Sustainable Humanosphere, Kyoto University, 2) Australian Antarctic Division, Hobart, Tasmania, ... Glob... ...rsity of Tokyo

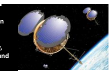
ABSTRACT

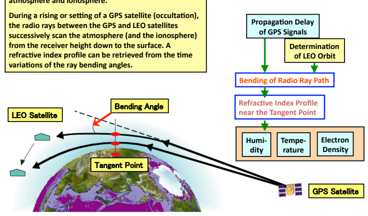
1. **GPS radio occultation (RO)** is an active limb-sounding satellite measurement, which provides an accurate temperature profile below about 40 km with a very good height resolution comparable to a radiosonde.
   * The GPS RO data is useful to study meso-scale temperature perturbations due to atmospheric waves. COSMIC GPS RO data are used to derive the potential energy (PE) from gravity waves with vertical wavelengths less than 7 km, and to study longitudinal and latitudinal variavirities in cells of size 20°x5° and 10°x5° for 7day 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.

1. Basic Concept of GPS Radio Occultation

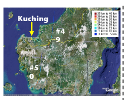
GPS Signals received on a low earth orbiting (LEO) satellite are used for an active limb sounding of the atmosphere and ionosphere.

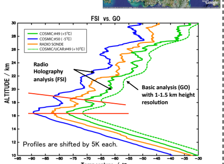
During a rising or setting of a GPS satellite (occultation), the radio rays between the GPS and LEO satellites successively scan the atmosphere (and the ionosphere) from the receiver height down to the surface. A refractive index profile can be retrieved from the time variations of the ray bending angles.



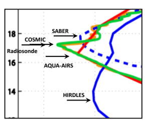


Comparison of temperature profiles between COSMIC GPS RO and radiosonde at Kuching, Malaysia.



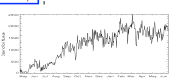


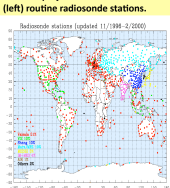
NOTE: Profiles with GO are used in this study.



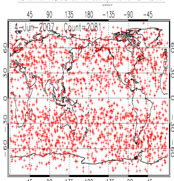
Temperature profiles around the cold point tropopause, 26 Dec 2006
- COSMIC GPS RO (Green) (4.1N, 110.4E, 11:32UTC)
- Radiosonde at Bintulu, Malaysia (Orange) (3.1N, 113.0E, 11:34UTC)
- HIRDLS (Blue,–solid) (3.4N, 118.6E, 16:38UTC)
  SABER (Blue–dotted) (3.8N, 108.6E, 10:39UTC)
- AQUA–AIRS (Red) (3.9N,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

Comparison of data points (temperature profiles) between (right) GPS RO with 6 satellites of the COSMIC project and (left) routine radiosonde stations.





Routine radiosonde stations (850 sites, 1-2 launches/day)



COSMIC GPS RO data on 4 June 2007, 2081 points

- **GPS radio occultation (RO) can measure temperature profiles with a good height resolution and accuracy, comparable to radiosondes.**
- **COSMIC GPS RO data provides a unique opportunity to study a global morphology of atmospheric gravity waves.**
- **We study distribution of gravity wave (potential) energy as a function of latitude, height, longitude and season by using COSMIC data.**
- **The results are compared with the NCEP mean winds, OLR and an atmospheric general circulation model (AGCM).**

COSMIC GPS RO temperature data are used to derive the 2006/07 winter mean stratospheric Northern Hemisphere potential energy (PE) from gravity waves with vertical wavelengths less than 7 km, and to study longitudinal and latitudinal variability in cells of size 20°x5°x7days and 10°x5°x1 month.

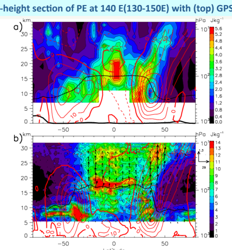
Wave potential energy, $PE=1/2(g/N)^2(T'/T_0)^2$

g; acceleration of gravity, N; Brunt-Vaisala frequency,

T'; temperature perturbation, T_0; background temperature

T106L60 AGCM: CCSR/NIES/FRCGC AGCM (Kawatani et al., 2005, GRL)
- Equatorial lon / lat interval of 1.125°
- Top boundary 1hPa, but maximum useable level 10hPa
- No GW drag parameterization
- GW behavior using 3-hourly data in January during westward shear phase of QBO

2-1 Latitude-height section of PE at 140 E(130-150E) with (top) GPS RO and (bottom) AGCM



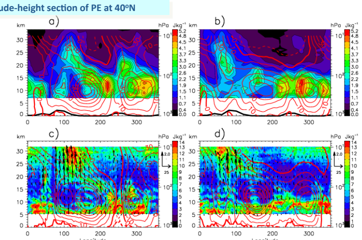
COSMIC PE on 12 – 18 Dec 2006
- NCEP 7-day averaged zonal winds (red line, solid/dashed; eastward/westward) shows strong winter time sub-tropical jet
- Large PE along the jet from mid-troposphere up to polar night jet

AGCM PE at 130-150E on 1–7 Jan; similar wind conditions to the results in (a)
- PE from waves with periods 6hr–1 month, λ_z < 7km, 380 < λ_x < 40,000km
- Note different colour scale
- Vectors show meridional and vertical energy fluxes due to λ_z < 7km

- 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 zonal winds 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.

- Large tropical PE above about 30 hPa are not detected by COSMIC, because the associated gravity waves seem to have short periods (and short λz).
- As with COSMIC, larger PE is located equatorward of the sub-tropical jet and is also distributed upward and poleward along the zonal wind contour lines.
- Large PE at 30–10 hPa at 40N are mostly due to gravity waves generated in the vicinity of the sub-tropical jet, propagating upward as indicated by the the vertical energy flux vectors.
- 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 results is relatively low values of UTLS potential energy at 20N, which is a region that also corresponds to weaker energy flux.

2-2 Longitude-height section of PE at 40°N

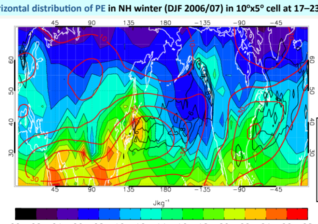


COSMIC (a) Nov 29–Dec 05 (b) Dec 24–30
- Planetary wave activity, calculated from the wave number spectra of NCEP geopotential height at 30 hPa and 40N, is strong throughout December 2006.
- Longitude-height contour plots of COSMIC PE at 40N in (a) and (b) show wave sources and interaction with the background mean wind.
- Large PE near the two jet maxima is seen in (a). PE decreases to be less than 1.2 J/kg around the 0 m/s stratospheric wind level.
- The 0 m/s level extends from 100E to 300E in late December in (b) and filters out nearly all of the wave energy entering the stratosphere.

AGCM (c) 1-7 Jan and (d) 22-27 Jan, similar zonal winds to (a) and (b), resp.
- PE from AGCM and COSMIC agree well. In (c) large PE occurs above the jet core.
- Upward wave flux appears in the region of eastward stratospheric winds, while PE is much smaller in the westward wind regions.

- Zonal variation of PE vs ground based horizontal phase velocity (not shown) reveals that most PE above 30 hPa are associated with eastward propagating waves and that these waves generally propagate westward in the background eastward winds with ground-based speeds of less than 10 m/s (O'Sullivan and Dunkerton, 1995; Kawatani et al., 2004).
- These waves reach their critical level thus the flux reduces substantially at 0–10 m/s wind line.
- Large energy fluxes are due to gravity waves generated around the jet. On the other hand, the relatively small PE in the westward stratospheric wind regions are due largely to westward propagating waves relative to the ground.

2-3 Horizontal distribution of PE in NH winter (DJF 2006/07) in 10°x5° cell at 17–23 km



Red contour: winter mean NCEP u (m/s) at 500–100 hPa.

Black contour: winter mean GPCP precipitation (mm/day):

- Mean wintertime PE exceeds 2.4 J/kg above the Himalayas and eastern China. A separate peak of 2.2–2.6 J/kg appears above Japan. The entire Asian mid-latitude region is located under a strong winter jet.
- A region of PE of up to 2.0 J/kg appears above the Eastern USA, similarly over a strong winter jet.
- For both the USA and East Asia, larger PE occurs over land than over sea, despite the larger oceanic precipitation.
- PE directly above the Canadian Rocky Mountains is 1.2–1.6 J/kg. This is in a low 500–100 hPa wind speed region, although significant precipitation occurs along the west Canadian coastline.

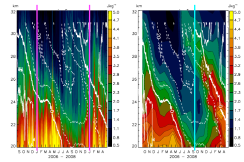
- MU radar revealed winter-time gravity wave generation around the sub-tropical jet which followed the seasonal variation of jet-stream intensity [Murayama et al., 1994]. Other results pointed to orographic sources [Sato, 1994; Ogino et al., 1999].
- The COSMIC and AGCM results suggest that more of the total Japanese Ep is due to the jet-stream than orography. But, mountain waves can contribute to some of PE above Canadian Rockies, Northern Japan, and Scandinavia.

SUMMARY (1/2)

- In northern hemisphere mid-latitude winter, gravity waves with λz < 7 km are studied using COSMIC GPS RO and compared with T106L60 AGCM results.
- The potential energy (PE) of these waves is mostly related to the sub-tropical jet stream with some regional scale contributions from orography.
- Strong wave filtering above the jet stream core results in decreases of PE around the 0–10 m/s zonal wind line, suggesting low ground-based phase speeds of these waves which interact with the background wind, an interpretation supported by an analysis of the AGCM results.
- Clear longitudinal dependence of PE is apparent, which mainly depends upon the sub-tropical jet location and subsequent stratospheric wave filtering.

- The 2006–2007 winter mean 17–23 km Ep is over 2.0 J/kg above the Himalayas, Japan and Eastern USA, co-incident with the strongest sub-tropical jet speeds. Wave generation above the Eastern United States may be partially related to active precipitation events as well as the jet.
- Local Ep maxima above the Canadian Rockies, Scandinavia and Japan are observed, suggesting that some of the total Ep in these regions is due to orographic waves, although it is not possible to separate orographic waves from other gravity wave sources in the COSMIC data because individual phase speeds are indeterminable.
- The peak above the Himalayas is only due to the sub-tropical jet because theoretically, orographic waves are unobservable at 17–23 km during this winter.

3-1 Season-height section of zonal mean PE at 25.S-2.5N from Sep 2006 to Apr 2008



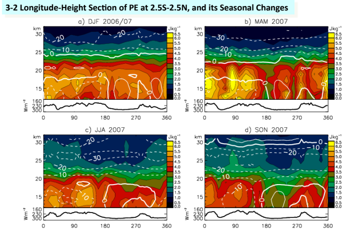
LEFT:
- Grid size: 20°x5°x7 days,
- 7km high-passed pertur-bations from individual profiles, and get PE by integrating vertically over 7km, stepping up by 1km and forward by 1 day.
- Mainly meso-scale GWs with minor MRGW and higher speed KW contributions.

RIGHT
- Grid size: 20°x5°x 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-1 phase line.

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

3-2 Longitude-Height Section of PE at 2.5S-2.5N, and its Seasonal Changes

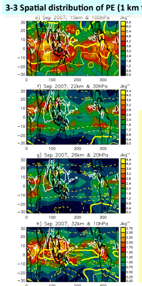


White contour: NCEP mean zonal winds (m/s), with westward wind shear initially, becoming eastward in the stratosphere after JJA

Black contour: OLR (W/m2)

- The seasonal structure of equatorial PE (in a grid cell at 2.5S-2.5N with 7km thickness) varies with height and longitude as well as the background mean winds.
- A clear relation between deep convective activity (low OLR) and large UTLS PE is observed. e.g, in MAM 2007 (b), PE exceeds 5.0 J/kg at 0–40E, 70–140E and around 300E, corresponding to low OLR values above Africa, Indonesia and South America respectively (Note: artificial increase of PE due to effects of sharp cold point tropopause at about 17 km altitude)
- Stratospheric PE above about 22 km are not affected by the cold-point tropopause problem. The seasonal mean PE in DJF(a) and MAM(b) at 30 km is fairly constant in longitude, probably because the background wind profile below 30 km filters out of most of the convective gravity waves.
- The JJA(c) and SON(d) PE at 30 km shows longitudinal differences, with larger PE above deep convection. Only westward propagating gravity waves in the Eastern Hemisphere are filtered out below 30 km. This leaves all of the eastward propagating components.

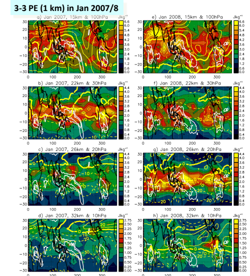
3-3 Spatial distribution of PE (1 km thick) in Sep 2007



- Yellow contours: monthly mean NCEP zonal wind (m/s), with east/west-ward by solid/dashed lines. QBO was westward throughout the lower stratosphere.
- White contours: monthly mean OLR at 200 & 220 W/m². Asian monsoon visible in the OLR

At 15km, just below the tropical tropopause, there is some relationship between PE and convection.
At 22km, local minimum in PE at equator, with off-equatorial symmetry noticed. Wave filtering below 22km will have removed slow cx < 0 waves
At 26km, a similar structure to that observed at 22km is apparent, with off-equatorial peaks visible around Africa and South America. Gravity waves with faster cx < 0 are removed between 22km and 26km
At 32km, the background wind is approaching 0 m s-1. Large PE is visible directly above deep convective activity. Gravity waves are beginning to encounter their critical level. (Group velocities also decrease close to critical levels, increasing the chance of observation.)

3-3 PE (1 km) in Jan 2007/8



PE in January 2007 and 2008 are shown for a comparison with the model results of Kawatani et al. (Poster A-00122).
Although the convective source distribution is similar for both months, the stratospheric PE is different due to the changes in the QBO structure (see panel 3-1).
In January 2007, the QBO is in its westward shear phase with the 0 m/s line at 24 km, while one year later, the QBO is in its eastward shear phase with the 0 m/s line at 25 km.

During January, the deep convective regions are centered south of the equator
- Larger PE is generally observed above the three deep convective regions at 22km in January 2007 (b) and 26 km in January 2008 (g), close to the 0m/s line, at which altitude most of the waves with low cx are filtered out.
- Due to lower level filtering, both of the 32 km altitude regions generally have low PE values compared with September 2007.

SUMMARY (2/2)

- Seasonal hemispheric differences in GW PE are observed, with larger values occurring around the tropopause above deep convective activity and also in the Eastern Hemisphere stratosphere during SON 2007 at which time the background winds are westward throughout the entire height region.
- Monthly averaged 1 km height independent PE show differences in potential energy depending upon the QBO phase and the location of convection. Large PE are visible directly above deep convection at altitudes which are close to the QBO 0 m/s phase line. This PE is probably primarily due to convectively generated gravity waves propagating nearly vertically.

Recent Publications on analysis of atmospheric waves with GPS RO data

CHAMP

Tsuda, T., M.V. Ratnam, T. Kozu, S. Mori, Characteristics of 10-day Kelvin Wave Observed with Radiosondes and CHAMP/GPS Occultation during the CPEA Campaign (April–May, 2004), *J. Meteorol. Soc. Japan, 84A, 277-293, 2006*

Ratnam, M.V., T. Tsuda, S. Mori, and T. Kozu, Modulation of tropopause temperature structure revealed by simultaneous radiosonde and CHAMP GPS measurements, *J. Meteorol. Soc. Japan, 84, 989-1003, 2006*

Hei, H., T. Tsuda, and T. Hirooka, Characteristics of atmospheric gravity wave activity in the polar regions revealed by GPS radio occultation data with CHAMP, *J. Geophys. Res., 113, D04107, doi:10.1029/2007JD008938.*

Tsuda, T., M.V. Ratnam, S.P. Alexander, T. Kozu, and Y. Takayabu, Temporal and Spatial Distributions of Atmospheric Wave Energy in the Equatorial Stratosphere Revealed by GPS Radio Occultation Temperature Data obtained with the CHAMP Satellite during 2001-2006, *Accepted, Earth, Planets and Space, 2008*

COSMIC

Alexander, S.P., T. Tsuda, and Y. Kawatani, COSMIC GPS Observations of Northern Hemisphere winter stratospheric gravity waves and comparisons with an atmospheric general circulation model, *Geophys. Res. Lett., 35, L10808, doi:10.1029/2008GL033174.*

Alexander, S.P., T. Tsuda, Y. Kawatani, and M. Takahashi, Global Distribution of Atmospheric Waves in the Equatorial Upper Troposphere and Lower Stratosphere: COSMIC Observations of Wave Mean Flow Interactions, *J. Geopyhs. Res., in press, 2008*

Kawatani, Y., M. Takahashi, K. Sato, S.P. Alexander, and T. Tsuda, Global distribution of atmospheric waves in the equatorial upper troposphere and lower stratosphere: AGCM simulation of sources and propagation, *J. Geopyhs. Res., in revision, 2008*