Aircraft Measurements and Numerical Simulations of Gravity Waves in the Extratropical UTLS Region during the START08 Field Campaign

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Outline:

• Importance of Mesoscale Gravity Waves in A Jet-Front System

• Flight Track Design in Research Flight 02 (RF-02) of START08 field experiment for jet-front gravity waves

• Spectral Analysis and Wavelet Analysis of Aircraft Measurement

• Phase and Amplitude Relation of Linear Theory in Wavelet-Filtered Observational Data

• Comparison with High-Resolution Mesoscale Model

• Sensitivity Experiment for the Generation Mechanism of Jet-Front Gravity Waves in RF-02
Importance of Mesoscale Gravity Waves:

• Energy and Momentum Transfer (Eliassen and Palm 1960)

• Initiation and Organization of Convection (Zhang et al. 2001)

• Generation and Modulation of Atmospheric Turbulence (Shapiro 1981)

• Impacts on the General Circulation and Thermal Structure of the Atmosphere (Holton et al. 1995)
Generation of Baroclinic Jet-Front Gravity Wave

Simulated Long-lived Vertically Propagating Mesoscale Gravity Waves Originating from the Exit Region of the Upper-Tropospheric Jet Streak (Zhang 2004)
Stratosphere-Troposphere Analyses of Regional Transport Experiment 2008

Goals:
Targeting Major Transport Pathways in the Ex-UTLS

1. Extratropical UT/LS Survey (including cirrus clouds)
2. Stratospheric Intrusion (Tropopause Fold)
3. Tropospheric Intrusion
4. Convective Influence
5. Gravity Waves (RF 02)

HIAPER Flight Tracks (18 flights; Phase I: April 18-May 16; Phase II: June 16-27)
Flight Track of RF-02 in START08

1.67-km WRF simulations at 1800 UTC 04/22/2008 (1600 MDT 04/21/2008)

- Grey Shaded Area: 9-km Wind Speed (m/s)
- Blue/Red Contour: 12.5-km Divergence (pos/neg)
- Black Contour: 9-km Pressure
- Vector: 9-km Wind Field (m/s)
Spectral Analysis of Aircraft Measurements: Southbound Leg Along Jet

Power Spectra for Southbound Leg Along Jet. Color Lines Show the 5%, 50%, and 95% confidence levels.

- Significant Waves with Wavelength from 10 to 300 km
- Power Peaks at 10 km in Vertical Motion – Also Seen in T-REX Project (Ronald et al. 2008)
Wavelet Analysis of Aircraft Measurements: Southbound Leg Along Jet

Wavelet Analysis for Southbound Leg Along Jet. Shaded Area represent significant level over 95%

- Significant Localized Variations of Wave Signal
- Mesoscale Gravity Wave in Along-Track V
- Possible Wave-Wave Interaction
- Physical Reliability of 10-km Wave in W
Phase Relation in Aircraft Measurements: Southbound Leg Along Jet

- **Momentum Equation**: 
  - U & P

- **Thermodynamic Equation**: 
  - Theta & W

- **Energy Flux**: 
  - W & P

- **Momentum Flux**: 
  - U & W

**Remarkable Localized Quadrature Variance** From 4 km to 64 km in Thermodynamic Equation

**Mesoscale Gravity Wave** with Wavelength of 128 km in Momentum Equation

**Similarity and Inconsistency** in Phase Relation Analysis – Possible Reason?
Amplitude Relation in Aircraft Measurements: Southbound Leg Along Jet

**Linear Theory**

\[
\begin{align*}
\left( \frac{\partial}{\partial t} + \overline{U} \frac{\partial}{\partial x} \right) u' &= -\frac{1}{\rho} \frac{\partial p'}{\partial x} \\
\left( \frac{\partial}{\partial t} + \overline{U} \frac{\partial}{\partial x} \right) \theta + w' \frac{\partial \bar{\theta}}{\partial z} &= 0
\end{align*}
\]

\[
\Rightarrow w' = \frac{p' \theta' k}{u' \rho \frac{\partial \bar{\theta}}{\partial z}}
\]

Based on the wave solution form of momentum equation and thermodynamic equation, the theoretical/predicted vertical motion perturbation can be derived as the abovementioned formula.
Comparison with High-Resolution Mesoscale Model: Wavelet Analysis

- **Spatial Series**
- **Wavelet Analysis: Observation**
- **Wavelet Analysis: 1.67-km WRF**

- Similarity Between Aircraft Data and Cloud-Resolving Simulation in Mesoscale Gravity Wave
- Significant Disagreement in The Small-Scale Component of Vertical Velocity
Comparison with High-Resolution Mesoscale Model: Phase Relation

Similarity Between Observation And Simulation

- 128-km Along-Track-Propagating Mesoscale Gravity Wave (Momentum Equation)
- Waves From Small Scale to Mesoscale Gravity Wave (Thermodynamic Equation)
- 128-km Downward-Propagating Wave in Momentum (Momentum Flux)
Numerical Sensitivity Exp for Jet-Front Gravity Waves during RF-02

- Similarity Between Full-Physics EXP and Dry Run over the Rockies, due to dry environment
- Weakened Wave Signal Across Surface Front in Dry Run
- In dry flat-topography Exp, the jet-front gravity waves are generated more slowly
Numerical Sensitivity Exp for Jet-Front Gravity Waves during RF-02

*Cross sections (A-B): Tropopause (1.5 PVU), GWs (+,-divergence) and Convections (dbz)*

- **Dry dynamic (balance adjustment) may dominate over the Rockies**
- **Convections only changed the lower-level structures, but not for the gravity waves propagating over the tropopause.**
- **Similar features were found for the gravity waves in flat-topo Exp, but at higher level. It is said that the changes of background flow may have impacts on the critical level of them.**
Concluding Remarks

- Long-Track G5 Flight Successfully Captured Mesoscale Gravity Waves.

- Spurious wave signal in vertical motion with wavelength about 10 km, which maybe related to 30-60s aircraft autopilot intrinsic period.

- The observed mesoscale gravity wave activities are simulated reasonably well by a high-resolution mesoscale model but not 1-to-1 match of individual waves.

- Sensitivity experiments show that convection mainly changes lower-level structures, while topography may result in the change of background flow.