Deepwave GV flux measurements: methods and uncertainties

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DEEPWAVE GV statistics

• Location: New Zealand and surrounding ocean
• Observing period: SH Winter; June/July 2014
• Aircraft: NSF/NCAR GV (26 flights, 180 hours)
• Typical leg: length=350km, altitude= 12.1km
• GV Survey legs
  – Over New Zealand (97 legs; 49.1 hours)
  – Over Ocean (157 legs; 84.3 hours)
Types of analyses

1. Vertical displacement curves
2. Flux computations
3. Transience
4. Eliassen-Palm check (Bernoulli check)
5. Direction of horizontal EF
6. Pressure analysis for Energy Flux
7. Wavelet scale analysis
8. Reverse fluxes
9. Effect of leg length
RF04: 7 legs over Mt Aspiring
Vertical displacement (estimated)

Mountain to scale but offset vertically
RF05: 9 Legs over Mt Cook
Vertical displacement

Mountain to scale but offset vertically
RF08: 7 Legs over Mt Aspiring

Vertical displacement

![Graph showing vertical displacement over distance.](chart.png)
RF09: 6 legs over Mt Cook

Vertical displacement

Mountain to scale but offset vertically
RF012: 5 legs over Mt Aspiring
Vertical displacement

Large Flux Case
RF012: 5 legs over Mt Cook  
Vertical displacement
RF13: 6 Legs over Mt Aspiring
Vertical displacement
RF16: 7 Legs over Mt Aspiring

Vertical displacement

Large Flux Case
RF21: 9 Legs over Mt Cook
Vertical displacement
Flux calculations

The fluxes are computed from

• $MF_x = \bar{\rho} < u'w'>$  
• $MF_y = \bar{\rho} < v'w'>$  
• $EF_z = < P_{cg} w'>$  
• $EF_x = < P_{cg} u'>$  
• $EF_y = < P_{cg} v'>$  
• $EFzM = -(U*MF_x + V*MF_y)$
Zonal Momentum flux

MFx
Units: Pa
NZ legs only

RF# -->
RF12    RF16
Vertical Energy Flux
EFzCG
Units: W/m²
NZ Legs only

RF Number

RF12  RF16

RF Number -->
Momentum Flux
EFzM (from MF)
Units: W/m²
NZ Legs only

RF12
RF16

RF Number -->
Eliassen-Palm Check
EFzCG vs. EFzM
Units: W/m²
RF12: Alternating Mt Cook and Aspiring

Variable altitudes

EFz vs Leg #

RF12

Units: W/m²

d<50km
EFz vs Leg #
RF16
Units: W/m²
d<50km

Leg 5 is at z=13km
Yale WRF Long Run
SI Averaged EFz

SI Flights

SI Flights

Combination
Horizontal energy flux direction

• The horizontal energy flux (EFx, EFy) vectors should be acting against the mean flow.
Horizontal Energy Flux

EFxCG versus EFyCG
Units: W/m²

y = -0.8671x
R² = 0.292
Pressure analysis

- Error analysis for EF
- Correcting for aircraft altitude and the Coriolis force
- Redundant static pressure
Error estimates for \( \text{EFz}=\langle p'w' \rangle \):

- Assume a reference case with \( w'=1 \text{ m/s} \) and \( p'=10 \text{ Pa} \) so \( \text{EFz}=10 \text{ W/m}^2 \)

- A typical error in \( P_{\text{static}} \) is \( p'=0.1 \text{ hPa}=10 \text{ Pa} \)
  - (100% error in \( \text{EFz} \))

- A typical error in altitude is 1 meter, giving a pressure error of \( (0.31)(9.81)(1)=3 \text{ Pa} \)
  - (30% error in \( \text{EFz} \))

- A typical error in \( W \) is 0.2 m/s.
  - (20% error in \( \text{EFz} \))
Corrected pressure

- $P_{\text{static}}$ is fuselage static pressure corrected for airflow effects
- $P_{\text{cg}}$ is the static pressure, corrected for altitude fluctuation and the geostrophic pressure gradient

\[
P_{\text{corr}}(x) = P_{\text{static}}' + \bar{\rho}g(GGalt')
\]
\[
P_{\text{GOES}}(x) = \bar{\rho}2(0.0000727) \int_0^x \sin(\varphi) U_{CT} dx
\]
\[
P_{\text{cg}}(x) = P_{\text{corr}}(x) - P_{\text{GOES}}(x)
\]
RF04 Leg 11

Leg 11: Pcorr and Pgeos

\[ y = -0.3376x + 181.42 \]
\[ R^2 = 0.8959 \]
$y = 0.958x$

$R^2 = 0.9294$

Pcorr vs. Pgeos Slope
Ocean
Units: Pa/m
Instrument Redundancy

• In the Preliminary Deepwave data set, the only useful redundant measurement is static pressure (PSXC and PS_A).

• In the final data set, with the gust pod recalibrated, we hope to have an additional u,v,w,p data set and a new DGPS data set for two flights.
Redundant static pressure (RF04)
Uncertainty=10Pa
Vertical Energy flux:

two different pressure sensors (PSX and PS_A)

\[ y = 0.7703x + 0.0657 \]

\[ R^2 = 0.8859 \]

Compare EFzCG using PSX and PSA
Wavelet Scale Analysis of RF04; Leg 3 @z=12.2km

Flux-carrying Waves
Negative Energy Flux EFz

- A few legs with negative EFz are seen
- These fluxes still fall on the E-P line
- Mostly caused by downward wave beams over the east end of Mt Aspiring
Vertical Energy Flux
EFzCG
Units: W/m²
Full NZ Legs only
RF12 Leg 1: EFz ~ -3W/m²
Sensitivity to leg length

- Compute fluxes only for distance from mountain peak < d
- Compare d=50km and d=125km
- Maximum flux legs change with d
- Average flux values are less on the longer legs
Compare leg length $d=50$ vs $125\text{km}$

The relationship can be approximated by the linear equation:

\[ y = 0.5573x \]

with a coefficient of determination $R^2 = 0.475$. The scatter plot indicates a positive correlation between $EFz$ and $EFz$ values for distances $d < 125\text{km}$.
Conclusions I

• Energy and Momentum fluxes are very transient within flights. Strong wave days have the largest flux variance and reversed fluxes.
• Observed momentum and energy fluxes satisfy the Eliassen-Palm condition: $EF_z = EF_z M$.
• Energy fluxes are sensitive (e.g. +/-20%) to static pressure sensor error.
Conclusions II

• Horizontal energy flux direction is mostly NW-ward; upwind and perpendicular to the NZ terrain.

• Almost every case has vertical velocities dominated by short waves with wavelength from 8 to 12km. These waves carry little flux.

• Dominant flux-carrying waves have wavelength from 70 to 250km
Conclusions III

• Flux values are sensitive to leg length. Flux density is greatest near the mountain peaks. Average flux decreases with integration leg length.

• Aircraft flux measurements in Deepwave have uncertainties of 30% or larger due to:
  – Lack of redundant sensors (so far?)
  – Large Unsteadiness
  – Sensitivity to leg length
Yale Deepwave Priority Research

- Mountain wave transience
- Wave generation and the ABL
- Wave dissipation in the stratosphere
- Wave diagnostics from model output
- Flux error estimates, redundant measurements
- Trapped waves
- Moist processes; convection
- Downward propagating waves
The End
Conclusions IV

• South Island area is approximately 160,000km\(^2\), so EFz=10W/m\(^2\) gives 1.6 TeraWatts

• WRF and GV flux values are in rough agreement

• WRF-based deep cases on June 19-21
  - RF07: Not flown over NZ
  - RF08: Weak waves over Mt Aspiring
Vertical Energy Flux
EFzCG
Units: W/m²
Ocean Legs only

RF Number -->
Std(W)
Units: m/s
Oceans only)
Significant “Ocean” vertical velocity or fluxes

- RF02: Tasmania
- RF06: Tasmania
- RF07: NZ box pattern (Bad WIC)
- RF10: Trailing wave leg near NZ
- RF13: Trailing wave leg near NZ
- RF23: Macquarie and Auckland Islands
Outline

• Deepwave GV flight level data set
• Momentum and Energy Flux statistics
• Pressure corrections for energy flux
  – Error analysis
  – The constant P assumption
  – Coriolis correction
  – Redundant pressure sensor
• Trapped waves and dominant scales
• Downgoing waves
• Effect of leg length
• WRF comparison
• Ocean versus NZ legs
Types of flux measurements

• Momentum flux
  – Traditional mountain wave quantity
  – Impacts large scale flow
  – Need gust-probe wind field only
  – Constant with height in steady, linear, non-dissipative flow
  – (not wave specific)

• Energy flux
  – New diagnostic quantity
  – Better physical interpretation in unsteady flows
  – Wave specific
  – (needs static pressure)
Motivations for flux measurements

- Statistics for global models
- Compare with GW parametrizations
- Compare with hi-res models
- Compare with remote sensing wave data
- Examine the physics of GW
Internal data checks

• Vertical displacement
  – Vertical velocity
  – Potential temperature

• Pressure
  – Static P corrected for altitude and Coriolis force
  – Bernoulli equation using wind speed

• Energy flux (EP relationship)
  – \( \text{EFz} = \langle p'w' \rangle \)
  – \( \text{EFz2} = -U^*\text{MFx}-V^*\text{Mfy} \)

• Mean W over the sea

• EF and MF direction
WRF “Long Run”

Deep propagation
RF07 & 08

10W/m²

Integrated EFz [W]

May 24 Jun 01 Jun 10 Jun 20 Jul 01 Jul 10 Jul 20 Jul 31

30 km
12 km
4 km
Results of setting $P_{\text{static}}' = 0$

• One potentially reasonable assumption is to set the static pressure perturbation equal to zero. This is the assumption that the aircraft maintains itself on a constant pressure surface. However:

• This assumption leads to a large negative bias in the vertical energy flux $\text{EF}_z = <p'w'>$, because of a systematic negative correlation between $P_{\text{static}}$ and WIC. This is due to the aircraft altitude responding to vertical air motion.
RF04: Raw Pstatic vs WIC
CC~ -0.4

Aircraft leaves the constant pressure surface by +/- 0.2 hPa
Instrument Redundancy

• Momentum and Energy Fluxes require: u,v,w,p,z
• In the Preliminary Deepwave data set, the only useful redundant measurement is static pressure (PSXC and PS_A). For u,v,w,z we have only: UIC, VIC, WIC from the nose cone and GGALT from Omnistar.
• In the final data set, with the gust pod recalibrated, we hope to have an additional u,v,w,p data set
• It seems as if the Omnistar satellite DGPS will give z=+-20cm accuracy for altitude (z). For two flights, we will have redundancy from the ground station DGPS.
EFz vs Leg #
RF09
Units: W/ms
Mt Cook
d<50km

Legs 9 and 10 at z=13.5 km
Pcorr vs. Pgeos Slope
New Zealand
Units: Pa/m
$y = 0.8647x$
$R^2 = 0.7838$
Wavelet Analysis of RF05; Leg 3 @z=12.2km

Flux-carrying Waves
Wavelet Analysis of RF09; Leg 8 @z=12.2km

Flux-carrying Waves

RF09 Leg 8 W Power

RF09 Leg 8 PW CoSp

RF09 Leg 8 PU CoSp
RF16 Leg 4: EFz $\sim -4\text{W/m}^2$
Results of pressure redundancy test (PSX->PSA)

- Reduces EFz by 23%
- Degrades EP-check slightly
- Maintains qualitative checks
  - EFhor direction
  - Ranking flights by energy flux
- PSX is probably better than PSA