Mission Scientist Report (by S.D. Eckermann)

IOP14, RF24

Mission Date: 15 July 2014
Takeoff Time: ~0647 UTC (1847 NZST)
Landing Time: ~1225 UTC (0025 NZST 16 July)
Duration: ~5.5 hours

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**Objective**: The objective of this flight was to observe deep propagating gravity waves over the Southern Ocean to the south-southwest of Christchurch, apparently associated with spontaneous emission of gravity waves from a strong polar tropospheric jet peaking at ~65°S with peak speeds in excess of 85 m s⁻¹ at 300 hPa (see Fig. 1).

**Forecast Guidance**: Fig. 1 shows that the polar jet was predicted to decelerate rapidly downstream of the region of largest peak winds and then to push strongly equatorward, with a thin streamer of enhanced jet-stream winds moving towards New Zealand, leading to strong gradients in 300 hPa wind speeds as a function of longitude just to the south of New Zealand. For several days in advance of this flight, the global forecast models predicted that this jet deceleration and deformation resulted in spontaneous emission of large-scale gravity waves in a characteristic bow-wave type response (see Fig. 2). Fig. 2 shows that the equatorward arm of this bow-like gravity-wave response at 200 hPa (the approximate flight altitude of the GV given a nominal FL400 cruise altitude) propagates rapidly eastward and southward from 0600 UTC to 1500 UTC, eventually reaching the southern edge of the South Island.

Figs. 3 and 4 show that the equatorward arm of these diverging bow-like gravity waves emitted from the polar jet propagates deep into the stratosphere to at least 1 hPa and probably higher, a result seen in forecasts from both the ECMWF IFS (Fig. 3) and the NIWA Met Office model (Fig. 4). Similar results to Figs. 3 and 4 shown for earlier and later times to 1200 UTC (not shown) reveal that these deep wave responses also propagate rapidly eastward and equatorward with the flow and thus appear to be definitively connected to the jet generation and evolution lower down and to the south. Forecasts winds and geopotentials at 1 hPa in Fig. 5 also show that these waves produce large oscillations in winds and temperatures, which should make these waves observable by both the MTP and the Rayleigh lidar on the Gulfstream V.

These Southern Ocean jet-generated gravity-wave cases are also scientifically interesting since the wave amplitudes in forecasts of some of these events studied earlier in the mission seemed to
be quite large at long forecast lead times and then became weaker as forecast lead times progressively shortened with successive 6 hourly update cycle. Fig. 6 shows some evidence for this too for the current event at 1 hPa, with the 60 hour forecast (Fig. 6a) showing strong waves but somewhat weaker waves in later forecasts over shorter forecast times. Several hypotheses have been advanced to explain this. This could mean that these forecast nonorographic gravity waves are spurious artifacts of the models, and have less time to grow as “errors” at shorter lead times. For example, all models suffer well-known cold-pole biases which lead them to generate excessively strong jets and thus, perhaps, excessive wave generation from these forecast jets. An alternative hypothesis is that these forecast waves are realistic, but that data assimilation and forecast initialization algorithms designed to restore balanced flow and eliminate spurious gravity-wave noise also suppress real geophysical wave emission from these jets. The larger amplitudes at longer lead times would then be consistent with forecast models regenerating these gradients and wave emission dynamics internally and then successively filling the deep forecast domain with these slowly propagating large-scale waves over longer forecast times, relative to shorter forecast lead times when initialization has removed these regions of imbalance and waves are only beginning to redevelop.

In summary, there is debate about whether these deep forecast jet-generated gravity waves are spurious or real, and if real, whether the wavelengths and amplitudes are accurate. If the latter holds, an additional question is whether these forecast wave properties are more accurate at smaller forecast lead times (when wave amplitudes are weaker) or at longer forecast times (when wave amplitudes are stronger). Our mission seeks verifying observations to test the above hypotheses and conjectures. If GV observations show these waves are real, this event would represent observations of a very interesting deep penetration of waves from an unstable polar tropopause jet that could motivate additional scientific modeling and research.

**Track design:** The planned flight track is summarized in Fig. 7, and the executed flight track is shown in Fig. 8 with the AIRS 2 hPa gravity wave imagery from the ~1230 UTC overpass overlayed, corresponding approximately to landing time. Figs. 7 and 8 show that the flight involved two westward segments designed to intercept these deep nonorographic gravity-wave packets at all altitudes (see Fig. 9), and to perhaps detect some eastward propagation of these wave trains during various repeated flight legs. Since lidars were critical observations for the science objectives, the entire flight was planned to operate at FL400. AIRS data in Fig. 8 suggest the flight strategy was successful in finding these waves.

**Dropsondes:** As shown in Figure 7, drops were planned at the eastward and westward edges of the flight segments through the waves so as to study the strong cross jet gradients that are forecast to occur at this time and appear to be implicated to some extent in the genesis of this wave event (see Fig. 1). COAMPS adjoint sensitivity (Fig. 10) also revealed regions of high sensitivity along segments of this flight track and so drops DP1, DP3 and DP6 were designed to sample these forecast sensitive regions of the flow. The strategy worked as planned in Fig. 7, with no fast falls and good data acquired at all altitudes.
**Instrument problems**: All instruments appeared to operate nominally. WIC had an early offset but seemed to behave again about an hour into the flight.

**Results**: The flight took off a little earlier than scheduled at ~0647 UTC. As shown in Figs. 6 and 9, nonorographic waves were also forecast to occur over the South Island and MTM indeed observed waves soon after takeoff, though the alignment of the phase fronts in the MTM cameras was not obviously consistent with the forecast guidance according to Dominique.

As we ferried to way point 1 (WP1) and then commenced to the first westward leg to WP2, we noted first a great deal of structure in flight level potential temperature (theta) and then a secular decrease in theta as we moved eastward, consistent with the strong lateral jet shear and forecast changes in tropopause height. Fig. 11 summarizes the time series for RF24 of aircraft latitude (top), and flight-level potential temperature (middle) and wind speed (bottom). During the WP1 ↔ WP2 transects (times ~0815 to 0945) and the WP3 ↔ WP4 transects (times ~1000 to 1130) we saw a secular decrease and then increase in potential temperatures from/to ~360 K to/from ~340K, associated with the forecast change in tropopause heights associated with traversal across this intruding polar jet structure (see Fig. 12). At the midpoint of this potential temperature variation the flight-level data also showed a region of highly structured potential temperature variability at ~0830 and ~0930 for WP1-WP2 and ~1015 and ~1115 for WP3-WP4, the latter looking more wavelike in theta. These small regions were also accompanied by some light turbulence, and by a sharp and sudden drop in wind speeds that returned to original levels about 15 minutes later.

These sudden wind drops and associated potential temperature variability in Fig. 11 are especially evident on WP3-WP4 and may be the flight-level evidence of the large-scale jet-generated wave we were seeking based on the 200 hPa forecast guidance in Fig. 2 (this needs to be checked as it could be nondivergent jet structure). As a back of the envelope calculation, the along-track wavelength $k$ of this feature in Fig. 11 is ~225 km and the horizontal velocity $u'$ is around ±15 m s$^{-1}$. If we assume (but cannot prove) that this feature is a divergent gravity-wave feature, then the divergence amplitude from the data in Fig. 10, $ku'$ is around ±4 $10^{-4}$ s$^{-1}$, which would be a large wave signature but in the range of some values seen in, for example, Fig. 4.

During the flight we inspected the MTP profiles coming from the instrument and saw large vertical oscillations in temperature above these regions as well, with amplitudes of 5K or more and a vertical wavelength of ~5 km. These MTP profile data were not available for analysis on the ground at the time of writing this report but merit further inspection. Another fascinating feature is that these structured periods in the flight level data occurred near drop points DP1, DP3 and DP6 in Fig. 7 which corresponded exactly to the forecast regions of sensitivity in COAMPS in Fig. 10, consistent with the idea that these regions of jet wave generation are unstable and rapidly growing.
Over these wavelike regions in WP3-WP4 the AMTM and Na lidar also observed bursts of small-scale wave activity above, with the Na lidar seeing a lot of this all along this flight leg (see Fig 16).

The dropsonde data shown in Fig. 13 reveal two striking aspects of the flow: first a strong lateral gradient in the vector wind profile from strong southerlies at the eastern way points (WP1 and WP3) transitioning to stronger westerly flow at the western way points WP2 and WP4, and also a strong change in tropopause height between these two regions as noted earlier in Fig. 11.

Gravity wave radiance anomalies extracted from the AIRS overpass at ~1413 UTC (about 90 minutes after landing) are plotted in Fig. 14 and show a large-amplitude large-scale wave along the RF24 flight track that is observed strongly at all altitudes, from 100 hPa all the way up to 2 hPa.

It is not clear yet at this very early stage of the data analysis (less than 12 hours after the flight completed) whether the mesospheric instruments on the Gulfstream V saw any evidence that this deep large-scale jet-generated gravity wave reached mesospheric altitudes (though significant amounts of small-scale wave activity was seen as mentioned earlier). Figure 15 shows preliminary temperature retrievals from the AMTM zenith camera along specific RF24 flight legs, which seem to show some evidence for long horizontal scale wave banding. Likewise, Na lidar signals in Figure 16 also appear to show some evidence of large-scale sloping structures that could be consistent with this large-scale wave propagating even higher to ~90 km altitude.

We should also note that spectacular Aurora Australis displays were observed visually and using the pilot’s night vision goggles near WP3, as well as evidence for extensive polar stratospheric clouds (we speculate) in the night vision goggles to the south.
Figure 1: +21 hour ECMWF IFS forecasts (valid at 0900 UTC 15 July) of wind speeds (see color bar to right) at (from left to right) 500 hPa, 300 hPa and 200 hPa. Note the strong polar jet south of 60°S peaking near 70 m s⁻¹ at 500 hPa and 200 hPa and at near 85 m s⁻¹ at 300 hPa.

Figure 2: ECMWF forecasts of 200 hPa divergence at (a) 0600 UTC, (b) 0900 UTC, (c) 1200 UTC and (d) 1500 UTC on 15 July 2014.
Figure 3: ECMWF +60 hour forecasts (valid at 1200 UTC on 15 July 2014) of divergences at (a) 100 hPa, (b) 10 hPa, (c) 1 hPa, (d) 250 hPa, (e) 200 hPa, and (f) 150 hPa, showing the deep vertical propagation of the equatorward arm of the bow-like gravity waves radiates from the polar jet.
Figure 4: NIWA Met Office N768L70 +24 hour forecasts of divergence, valid at 1200 UTC on 15 July 2014, at (a) 10 hPa, (b) 5 hPa, (c) 200 hPa, and (d) 100 hPa.
Figure 5: ECMWF IFS +24 hour forecast (valid at 1200 UTC on 15 July 2014) of wind speeds (color scale) and geopotential heights (contour lines) at 1 hPa.
Figure 6: 1hPa ECMWF divergences valid at 1200 UTC on 15 July 2014 based on a series of earlier initialized forecasts: (a) +60 hour, (b) +48 hour, (c) +36 hour, (d) +24 hour, (e) +12 hour, and (f) +0 hour (analysis).
Figure 7: Planned RF24 flight track for the Gulfstream V (aqua), planned way points (WP, white), and planned dropsonde points (DP, green).
Figure 8: Executed RF24 flight track for the Gulfstream V (yellow, red curves), with 2 hPa AIRS gravity wave imagery from ~1413 UTC on 15 July (about 90 minutes after landing). Aqua circles show location of the 7 drop sondes. Winds along the flight track are also depicted.

Figure 9: ECMWF +24 hour forecasts of divergence (valid at 1200 UTC on 15 July 2014) at 6 pressure levels from 200 hPa (flight level) to 1 hPa, with the planned flight track in Fig. 6 superimposed as the aqua curve, revealing that forecast waves at all levels are intercepted.
Figure 10: COAMPS +24 hour sensitivity for total energy over South Island, valid here at 0600 UTC on 15 July 2014.
Figure 11: Time series during the flight of (top) latitude (deg.), (middle) potential temperature (theta, K), and (bottom) wind speed (m s\(^{-1}\)). The various way point numbers from Fig. 6 are marked in red.
Figure 12: Forecast tropopause heights at 1200 UTC.
Figure 13: Dropsonde skew-T plots corresponding to dropsondes DP1-DP7. Note the strong lateral shear in the wind profiles and the variation in tropopause heights between WP1 and WP2 and between WP3 and WP4.
Figure 14: AIRS gravity-wave-induced brightness temperature anomalies at 8 levels ranging from 100 hPa to 2 hPa, from the ~1230 UTC overpass at about the landing time for RF24.
Figure 15: Temperatures at 87 km from various RF24 flight legs as retrieved from the AMTM zenith camera (image credit: Dominique Pautet).

Figure 16: Na lidar return counts for the last 2.5 hours of RF24, showing some evidence of tilted large-scale wave signals.