# Validating mountain-wave updraft speeds predictions from the High-Resolution, Rapid-Refresh (HRRR) numerical weather prediction (NWP) model

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***Abstract:*** The United States has developed the HRRR NWP model and made the predictions available, free-of-charge, at *rapidrefresh.noaa.gov/hrrr/*. The model is sufficiently high-resolution to predict mountain waves. The waves appear in the 'max updraft' maps as linear and quasi-linear regions. In this study, glider flight recorder data from eastern US wave flights are compared with these regions. The regions, indeed, contained mountain waves. A number of the flights achieved the 5-km Diamond Altitude climb. The predicted updraft speeds were consistent with the updraft speeds calculated from the flight recorder data.

***Keywords:*** Mountain wave predictions, numerical weather prediction models, HRRR model validation

## Introduction

Climbs to achieve the altitude requirement for FAI soaring badges are often made in mountain waves. Thus, forecasts of these conditions are essential. The first report in the OSTIV literature about detecting and forecasting their occurrence is described in [1]. Since that report, there has been tremendous progress. Probably the most up-to-date system is described in [2] and a remarkable wave flight using the system is described in [3]. In the winter of 2016, I was asked by northeast US wave pilot Timothy Chow to help interpret the HRRR NWP model 'max updraft' forecasts. The forecasts depicted linear updraft regions resembling waves in mountainous regions. Thus, I compared his flight recorder data, and that of other northeast US wave pilots, with the corresponding HRRR model forecasts as follows.

## Methods

The locations of the high-points of wave flights and the maximum rate-of-climb to those points were determined from glider flight records (*.igc files). Then, those locations were identified on the 'max updraft' prediction charts (*.png files) and the magnitude of the updrafts were recorded. The measured and predicted updraft values were compared. Eight recent eastern US wave flights were investigated.

On 20160204 (Flight 1), Timothy Chow made a wave flight in the Green Mountains of Vermont. The high-point of the flight was determined from his *.igc file *(www.onlinecontest.org/olc-2.0/gliding/flightinfo.html?dsId=4835311*). In SeeYou (*www.naviter.com/products/seeyou*), the barogram trace was animated to the high-point and the time, altitude and latitude/longitude at that point were recorded.

The high-point was located on the corresponding HRRR model 'max updraft' *.png file using the image analysis software ArcSoft (*www.arcsoft.com*):

1. The file was expanded to extract x, y values of unique ground-points. Latitude and longitude values for the points were determined using the *skyvector.com* aeronautical chart.
2. An x-y grid with superimposed latitude and longitude values of the ground-points was constructed. The pixel corresponding to the latitude and longitude of the high point was determined by interpolation and recorded.
3. The Red Green Blue (RGB) values of the pixel were compared to the RGB values of the updraft speed scale. The closest match was defined as the predicted updraft speed; for the Chow flight the speed was 0 - 0.5 m/s. The predicted updraft was recorded (see the table).
4. The pixel in the *.png file that corresponded to the high point was colored red.
5. The pixel in the *.png file that corresponded to the summit upwind of Chow's high-point was colored green. Similarly, the pixels corresponding to locations of mountain summits where the other wave flights reported here were made were colored green: Mt. Washington in the White Mountains of NH, Sugarbush Peak in the Green Mountains of VT and Slide Mountain in the Catskill Mountains of NY.

The high-point for Chow's flight and the mountain summits are illustrated in Figure 1 (left).

The HRRR model atmospheric profiles for the location, date and time of the high-points were retrieved from *ready.arl.noaa.gov/READYamet.php*. The atmospheric conditions were determined from the profiles. The profile for Figure 1 (left) is given in Figure 1 (right). The '+1h' profile was the closest in the archive to the desired initialization profile (0h) which was not available in the archive.

The maximum climb rate achieved in the region of the wave at which the high-point was reached was determined from the *.igc file as illustrated for Flight 1 in the Table: 'Time' is the time the maximum rate-of-climb was achieved (steepest barogram slope) in the region of wave that led to the high-point, 'Altitude' is the altitude at the steepest slope, '+ alt' is the altitude at the top of the steepest slope, '– alt' is the altitude at the bottom of the steepest slope, 'del t' is the interval to climb from below to above the altitude with steepest slope, 'Climb rate' is equal to the difference between +alt and -alt divided by del t, 'Sink rate' is from the glider's polar, 'Measured' is the climb rate plus the sink speed, 'Predicted' is the HRRR model updraft prediction.

**Table**
**Measured and predicted updraft speeds**

| Flight | Date | Time | Altitude | + alt | t | - alt | t | del t | Climb rate | Sink-rate | Measured | Predicted |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | UTC | m AMSL | m AMSL | hhmmss | m AMSL | hhmmss | s | m/s | m/s | m/s | m/s |
| 1 | 20160204 | 165844 | 2520 | 3020 | 170204 | 2020 | 165548 | 376 | 2.7 | 0.9 | 3.6 | 0.5 |
| 2 | 20160206 | 185700 | 4274 | 4522 | 185940 | 4094 | 185340 | 360 | 1.2 | 0.7 | 1.9 | 0.75 |
| 3 | 20161010 | 163629 | 4250 | 4750 | 164054 | 3750 | 163150 | 536 | 1.9 | 0.6 | 2.4 | 2.3 |
| 4 | 20161014 | 193614 | 3500 | 3750 | 194102 | 3250 | 193118 | 584 | 0.9 | 0.5 | 1.3 | 0.75 |
| 5 | 20171117 | 180901 | 3000 | 3250 | 181259 | 2750 | 180450 | 469 | 1.1 | 0.6 | 1.7 | 1.8 |
| 6 | 20171126 | 153712 | 3500 | 3750 | 154010 | 3250 | 153438 | 332 | 1.5 | 0.6 | 2.1 | 3.8 |
| 7 | 20180127 | 154536 | 4500 | 4750 | 154848 | 4250 | 154243 | 366 | 1.4 | 0.8 | 2.1 | 2.25 |
| 8 | 20180205 | 143000 | 3250 | 3500 | 143158 | 3000 | 142812 | 226 | 2.2 | 0.8 | 3.0 | 3.8 |
| | AVERAGE | | | | | | | | 1.6 | | 2.3 | 2.0 |

The climb rate was adjusted to account for the headwind as follows. From the PIK-20D polar (Chow's aircraft), the minimum sink rate is 0.58 m/s at 40 knots (73 km/h). Using a indicated airspeed (IAS) - to - true airspeed (TAS) calculator (*indoavis.co.id/main/tas.html*) and atmospheric conditions from Figure 1 (right), the IAS was 68 knots (124 km/h) for Chow to remain stationary in the wave and the TAS was 69 knots (126 km/h). The sink rate of the ship in still-air at 126 kph from the polar is 0.9 m/s. So, the measured maximum updraft was 2.7 + 0.9 m/s = 3.6 m/s. The value was recorded (see the Table).

Seven additional flights were analyzed: Timothy Chow's 20160206 flight (Flight 2) in the Sugarbush wave, Paul Villinski's 20161010 flight (Flight 3) and Roy Bourgeois's 20161014 flight (Flight 4) in the Mt. Washington wave and Daniel Sazhin's 20171117, 20171126, 20180127 and 20180205 flights (Flights 5 – 8) in the Slide Mountain wave (all flight logs were found at *www.onlinecontest.org*). The high-points and profiles for the Villinski and 20171117 Sazhin flights are given in Figures 2 and 3 (the results from the remaining flights are in [4]). The updraft values for all the flights are listed in the Table.

## Results

It can be seen from Figure 1 (left) that Chow's high-point pixel was 4240 m AMSL (altitude gain 2597 m, Silver Badge) in a linear updraft region just downwind of Okemo Peak. The maximum predicted updraft speed for that pixel was 0 - 0.5 m/s and the maximum climb rate was 3.6 m/s passing through 2520 m AMSL (Table). This altitude corresponds to approximately the 750 mb level where, from Figure 1 (right), the winds were from 205 degrees-true at 68 knots.

It can be seen from Figure 2 (left), that Villinski's high-point pixel was 6412 m AMSL in a quasi-linear updraft region just downwind of Mt. Washington (altitude gain 4818 m, Gold Badge). The maximum predicted updraft speed for that pixel was 2 – 2.5 m/s and the maximum climb rate was 2.4 m/s passing through 4250 m AMSL (Table). This altitude corresponds to approximately the 600 mb level where, from Figure 2 (right), the winds were from 360 degrees-true at 45 knots.
It can be seen from Figure 3 (left), that Shazin's high-point pixel was 5435 m AMSL in a linear updraft region just downwind of the SW-NE oriented ridge of Slide Mt. (altitude gain 5095 m, Diamond Badge). The maximum predicted updraft for that pixel corresponded to 1.5 - 2 m/s and the maximum climb rate was 1.7 m/s passing through 3000 m AMSL (Table). The 3000 m altitude corresponds to approximately the 700 mb level where, from Figure 3 (right), the winds were from 350 degrees-true at 40 knots. Reference [3] details this extraordinary flight.

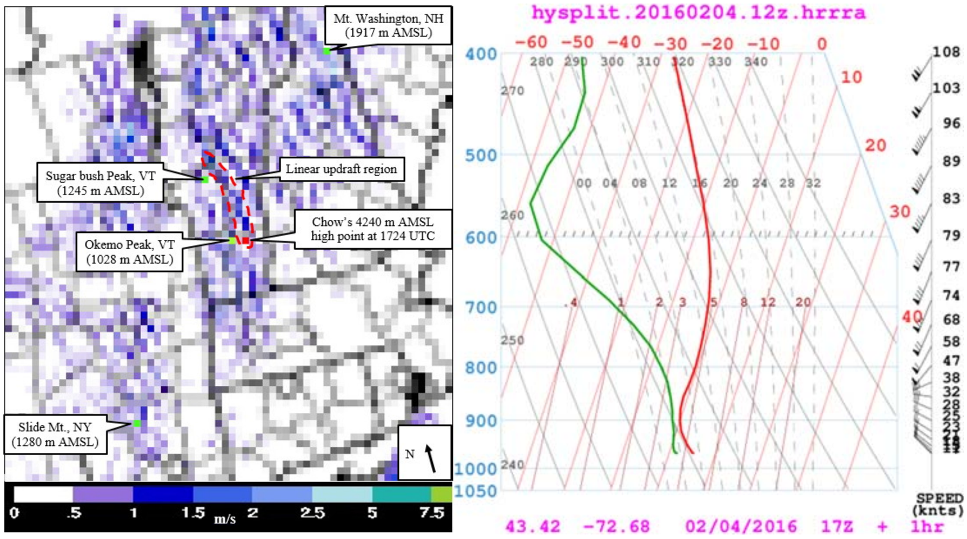


**Figure 1: Left, 20160204, HRRR model 7h forecast valid at 1700UTC (1200LT) for the maximum updraft speed (m/s) surface to 100 mb over the previous hour. Labeled is the high-point of Tim Chow's flight (red pixel), the linear updraft region (dashed red line) and the location of mountains (green pixels) that produced the wave flights described herein. Right, the atmospheric profile for the location, date and time of the high-point.**

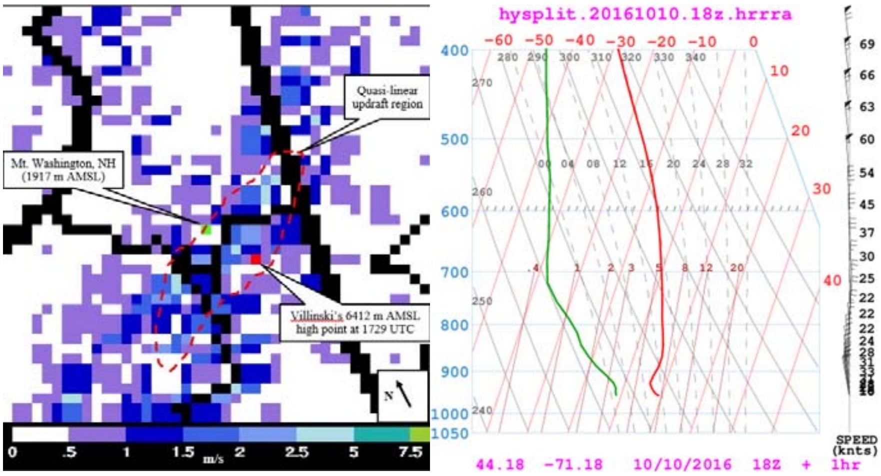


**Figure 2: Left, 20161010, HRRR model 6h forecast valid at 1800UTC (1300LT) for the maximum updraft speed (m/s) surface to 100 mb over the previous hour. Labeled is the high-point of Paul Villinski's flight (red pixel), the quasi-linear updraft region (dashed red line) and the location of the mountain summit (green pixel) on the ridge that triggered the wave. Right, the atmospheric profile for the location, date and time of the high-point.**

## Discussion

The HRRR model is a real-time, 3-km resolution, hourly-updated, cloud-resolving, convection-allowing model, initialized by 3-km grids with 3-km radar assimilation. The model covers the contiguous US. The model predicts hourly for an 18h period the major meteorological parameters. Hence, predictions made in the evening should be useful for next-morning flight decisions.

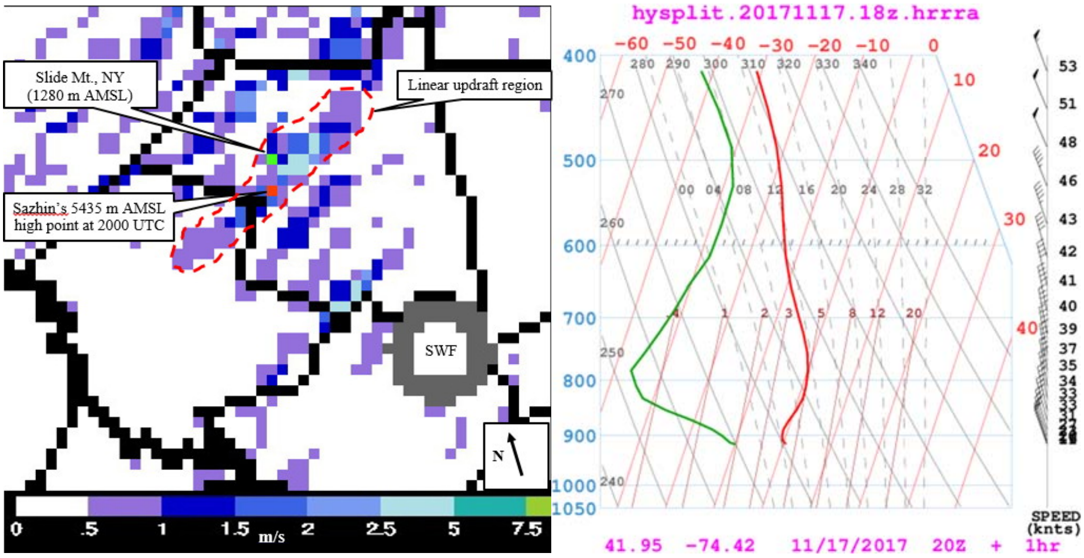


**Figure 3: Left, 20171117, HRRR model 10h forecast valid at 2000UTC (1500LT) for the maximum updraft speed (m/s) surface to 100 mb over the previous hour. Labeled is the high-point of Daniel Sazhin's flight (red pixel), the linear updraft region (dashed red line), the location of the mountain summit (green pixel) on the ridge that triggered the wave and Steward Field (SWF). Right, the atmospheric profile for the location, date and time of the high-point.**

Of the eight flights, five of the high-points were in linear updraft regions (Figures. 1 and 3, the remainder are in [4]) while three were in quasi-linear regions (Figure 2, the remainder are in [4]). These coincidences prove the predicted updraft regions, indeed, were mountain waves.

On 9 February 2016, I e-mailed a HRRR model developer, Dr. John Brown of the NOAA-ESRL in Boulder CO, and asked how to interpret the 'maximum updraft/downdraft' predictions. Here is his helpful response: "*In the case of mountain waves, the vertical velocity in vertically propagating mountain waves is fairly well represented, but trapped lee waves in general will not be well described because these waves are typically too small in horizontal wavelength to be well represented by a model with 3km grid spacing*." Brown's statement is supported by the results in the Table. The average of the measured updraft speeds was 2.3 m/s and the average of the predicted updraft speeds was 2.0 m/s. But, there is no correlation between the individual speeds. When higher resolution predictions are available, the correlation should improve. Nevertheless, the HRRR model 'max updraft' predictions are consistent with the measurements. Hence, the prediction can be used to estimate whether a wave will be 'weak' or 'strong'.

## Conclusions

The freely available HRRR NWP model predictions (*rapidrefresh.noaa.gov/hrrr/*) of 'max updraft' have been shown to identify regions and strengths of mountain waves. Hourly predictions are available for an 18-hour period. Hence, predictions of the location and strengths of mountain waves made in the evening should be useful for next-morning flight decisions.

## References

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