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THE USE OF SATELLITE WATER VAPOR IMAGERY AND MODEL DATA TO DIAGNOSE AND FORECAST TURBULENT MOUNTAIN WAVES

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1. Introduction

A technique for forecasting turbulent mountain waves was investigated using MODIS and GOES-12 water vapor (6.7um) imagery combined with hourly analyses from the RUC model. The limited domain of the Colorado and New Mexico mountains was chosen as the study site. Upon examining MODIS water vapor imagery daily from January 2004 through October 2004 within this domain, it was found that wave signatures related to orography were present approximately 18% of the time.

To determine the probability of turbulence occurring in the waves seen in the imagery, pilot reports were examined for correlation. Approximately 90% of the severely turbulent days had wave signatures in the water vapor imagery during the time period of the reports. The wave signatures on these turbulent days appear different in the imagery from the signatures on the days that were less turbulent. The turbulent days exhibited complex wave patterns with apparent interference and crossing wave fronts that extended downwind for a significant distance. The days that were less turbulent showed wave signatures that were much simpler with wave patterns that were linear in orientation and shape. The next step in the research process was to quantify the difference in the turbulent wave patterns versus the non-turbulent wave patterns as seen in the water vapor imagery. This paper will give brief discussion of the methods, data and results to date.

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2. Methods

Once it was determined that mountain waves, or lee waves, create recognizable signatures in satellite imagery in the water vapor channel (Fritz, 1964, Ellrod, 1986), a study was begun that would investigate these signatures. The first step was to develop some sort of climatology of waves as seen in the satellite water vapor imagery. All Aqua and Terra MODIS overpasses from January to October 2004 over Colorado and New Mexico were analyzed for lee wave patterns. Approximately 18% of the days analyzed displayed lee wave patterns of varying intensity and extent. The imagery was available for quick analysis of snapshots on the MODIS Direct Broadcast website maintained by the Space Science and Engineering Center (SSEC) at the University of Wisconsin-Madison. The data was ordered from the Earth Observing System Data Gateway online for further study upon determining that a particular MODIS scan contained lee wave signatures. When the climatology was completed, a data set of turbulence reports was needed to validate the dangerous nature of the lee waves seen in the imagery.

Bob Sharman at the National Center for Atmospheric Research (NCAR) provided all archived pilot reports for the entire duration of the study. The reports were run through simple algorithms to determine if turbulence was any more likely to have occurred on the days when lee wave signatures were present in the satellite imagery than days with no apparent lee wave signatures. After examining the results, it was found that turbulence was more likely on days with lee wave signatures. More notably, approximately 90% of the days with the most reports of moderate to severe turbulence were concurrent with lee waves in the imagery in the same geographic regions.

Upon the discovery of a statistically viable relationship between lee wave signatures in satellite water vapor imagery and turbulence reports, the next logical step was to determine the possibility of using satellite imagery to nowcast and forecast turbulent lee wave events.

Prior research has suggested that certain atmospheric conditions are more likely to produce lee waves than others (Fritz, 1964, Nichols, 1973). Studies have shown that moderate to high values of speed shear in the vertical, i.e. an increase in wind speed with height, in the flow over mountain ranges is one important factor. It is also important that the flow be nearly uni-directional across the mountain range and that the flow be within about 30° of the normal to the range. The other factor that is central for lee wave formation is atmospheric stability. It has been shown that waves are much more likely to form if the atmosphere is generally stable throughout, and it is even more likely when there is a layer of strong stability or an inversion near the level of the top of the mountain range.

Given these conditions, it was thought that the inclusion of model output data could aid in determining if lee waves were likely to occur over a certain area at a specific time. Lee waves, by nature, are in the small to medium size scale, meaning that they rarely extend for more than hundreds of kilometers in any direction in the horizontal. They are also dynamic over relatively short periods of time. The atmospheric conditions that are conducive to their formation can change in a matter of tens of minutes. Lee waves can also change direction, intensity, wavelength, etc. without much notice. Due to the constraints on the necessary spatial and temporal resolution, the RUC model was used to analyze the appropriate fields.

A brief version of a case study done on one of the more turbulent days will be presented below. On 06 March 2004, there were more pilot reports of turbulence than any other day in March, or any day in the first half of 2004 for that matter, over the Colorado area. Furthermore, a significant number of the reports were of moderate to severe turbulence to full size passenger jets run by major airline companies.

3. Data

The data used in the study include pilot reports, archived RUC model output, soundings from radiosondes, GOES-12 data, and MODIS data. All MODIS scans were run through a destriping algorithm written by Liam Gumley of the Space Science and Engineering Center in Madison, WI. This maximized the clarity of the images and the ability to use the images for visual interpretation of features.

Figure 1 shows a graph of pilot reports of turbulence in the month of March over the entire state of Colorado. As noted above, March 6 was a particularly active day for turbulence in the area.

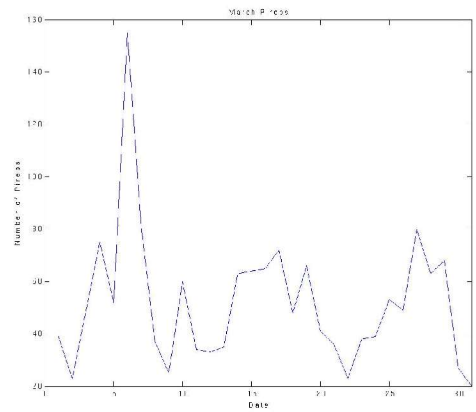

Figure 1: Total number of turbulence reports in March 2004 plotted by date.

The numbers of severe turbulence reports during the month of March 2004 are shown in Figure 2.

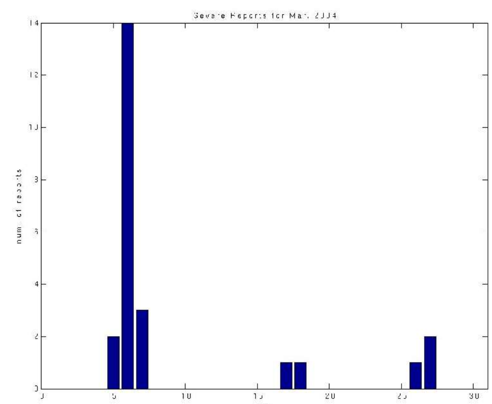

Figure 2: Severe turbulence reports in March 2004 plotted by date.

Figure 2 clearly shows that 06 March 2004 was by far the most severely turbulent day of that month. The next step was to examine the water vapor imagery for all MODIS overpasses on 06 March 2004 to determine if lee wave signatures were present and to what extent. Figure 3 shows an Aqua MODIS channel 27 (water vapor channel) scan over Colorado at 1950Z on 06 March 2004. Figure 4 shows the channel 1 (visible-red) scan at the same time and location. The lack of wave signatures illustrates that even though the waves were clearly present in the water vapor imagery, they would not have been detectable in the visible, and therefore, probably not by the eyes of pilots in the area. The disparity in the images has implications for avoidance of the turbulent lee waves.

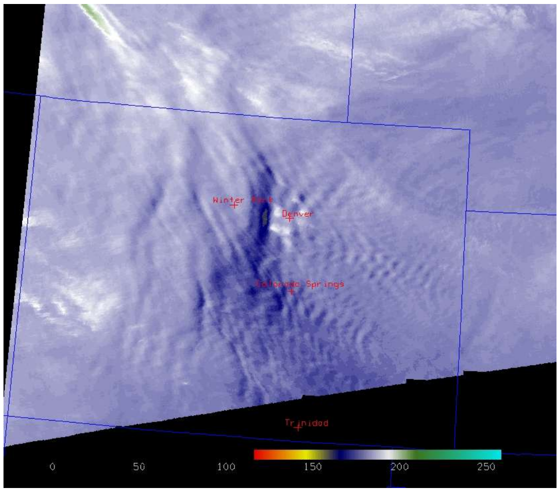

Figure 3: Aqua MODIS channel 27 at 1950Z on 06 March 2004 over Colorado.

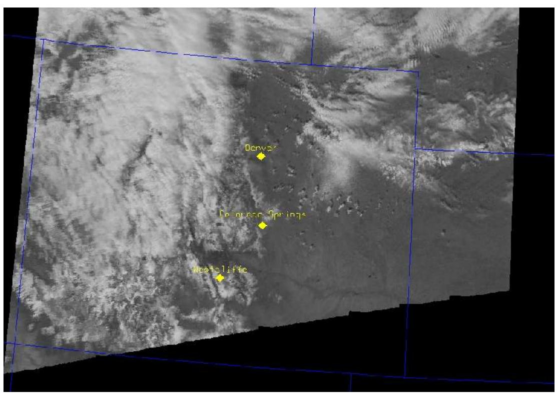

Figure 4: Aqua MODIS channel 1 scan at 1950Z on 06 March 2004 over Colorado.

The next set of data obtained was the archived RUC model output for the time the waves were seen in the imagery. The archived model output was obtained through the NOMADS data access web interface maintained by the National Climatic Data Center (NCDC). The model output was analyzed using Unidata's Integrated Data Viewer, or IDV. Figure 5 shows a cross section of the zonal winds through the atmosphere above Colorado at 1900Z on 06 March 2004. The cross section was taken along the 39th parallel from 114° W to 102° W. The display clearly shows that the cross-mountain winds were increasing steadily with height, thus satisfying the speed shear requirement for lee wave formation.

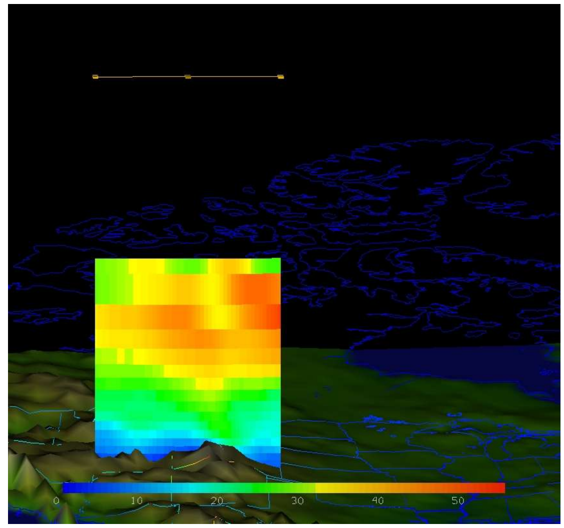

Figure 5: RUC model output of zonal winds over Colorado at 1900Z on 06 March 2004 in IDV.

The second parameter of interest from the model output was atmospheric stability; however, at the time of print, the NOMADS site did not have the appropriate variables for this problem. Instead, soundings from radiosondes around the lee wave area were used to determine the level of stability at the time the lee waves were seen. Figure 6 shows the sounding from Denver, Colorado at 1200Z on 06 March 2004. The winds do indeed increase with height without much change in direction, verifying the model output. As for the stability, there is an inversion from the surface (near 825mb) to about 800mb. From 800mb up to the tropopause, the atmosphere is unconditionally stable. There is a more stable layer between 650mb and 575mb, which is very near the height of the ridge and the waves at around 5000m. Therefore, both the wind and stability criteria for lee waves appear to have been met on March 6.

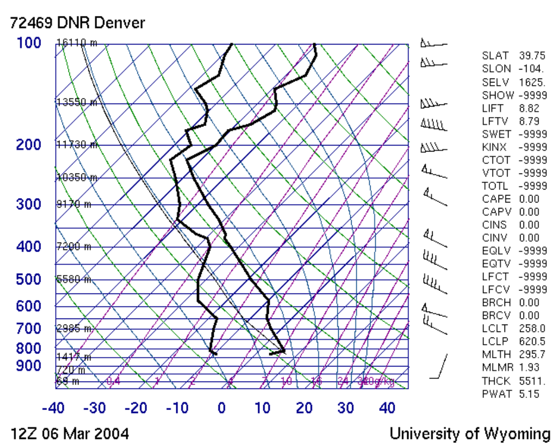

Figure 6: Sounding from Denver, CO at 1200Z 06 March 2004.

By overlaying the turbulence reports on the water vapor imagery, a visual graphic was obtained displaying the turbulence intensity for pilot reports during a certain hour along with the lee wave signatures. Figure 7 shows the same Aqua MODIS channel 27 image from above with turbulence severity from pilot reports during the hour of 1800Z on 06 March 2004. A number of three or higher indicates moderate to severe turbulence, with six or higher being severe. This shows that a large number of moderate to severe turbulence reports were located in the vicinity of the lee wave signature.

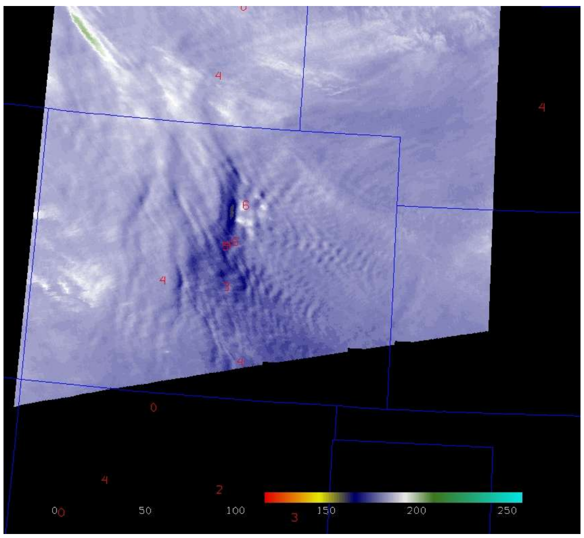

Figure 7: Turbulence intensity from the hour of 1800Z on 06 March 2004 overlayed on MODIS water vapor image from 1950Z 06 March 2004.

4. Results and Conclusions

A similar analysis was performed on additional cases with a high number of turbulence reports and lee wave signatures in the satellite imagery. One case was studied where lee waves were seen in the satellite imagery, but there was a very low amount of turbulence reported. Preliminary evidence shows that the most turbulent days in the Colorado area are correlated with lee waves as seen in the satellite imagery. Secondly, the lee wave signatures on the most turbulent days seem to have a consistently different appearance than the lee waves seen on the less turbulent days. The waves on turbulent days appear more complicated in nature with many crossing wave fronts and a good deal of wave interference. The waves on less turbulent days appear to be more linear in shape and distribution with clear and well-defined troughs and crests. It is postulated that certain patterns in the water vapor imagery can be used to detect turbulent mountain waves. However, the ideal situation would be the ability to forecast the occurrence of the waves.

With the combination of model data and satellite imagery, it may be possible to forecast lee waves. An algorithm could be developed that would define prone areas for mountain waves based on the wind and stability data from the model output. The algorithm could then monitor the satellite imagery from these areas for the development of lee waves. As a safety net, the algorithm could also input pilot reports of turbulence as a secondary first alert data source.

In order for this method to work, the satellite imagery must be of adequate spatial and temporal resolution to capture the lee waves. At present, satellites only come with one capability or the other, i.e., good spatial resolution or good temporal resolution. This situation is reportedly going to change in the future with the launch of the next generation GOES satellite, the GOES-R. This satellite will include the Advanced Base-Line Imager, or ABI, with 2km spatial resolution in the water vapor channel as opposed to the current 4km resolution on GOES-12. Simulations using IDV have shown that 2km resolution would be as effective at detecting and distinguishing lee wave patterns as the 1km resolution on the MODIS instruments.

5. Future Work

The most important work left to be completed is to find a way to quantify the differences between the lee wave signatures of turbulent versus non-turbulent waves. In order to do this, more case studies will be examined. Special attention will be paid to those where lee waves were seen in the imagery, but little or no turbulence was reported. It is hoped that the further study will serve to clarify some of the remaining uncertainties between the imagery and the actual occurrence of turbulence. Another area of improvement will come with the addition of potential temperature cross sections from archived GFS and Eta model output. Currently, Don Murray of Unidata is collaborating with NOMADS to allow for the potential temperature fields from the GFS model to be displayed in IDV. This ability will greatly aid in the determination of atmospheric stability since a measurement may be taken anywhere in the model’s domain, as opposed to only radiosonde launch sites.

6. Acknowledgements

This work would not have been possible without the aid of Tom Whittaker (SSEC, Unidata) on the use and manipulation of data using the Integrated Data Viewer, or the willingness of Bob Sharman et al. (NCAR-RAP) to share ideas and data.

7. References

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