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THE USE OF MODIS WATER VAPOR IMAGERY, NWP MODEL ANALYSIS, AND PILOT REPORTS TO DIAGNOSE TURBULENT MOUNTAIN WAVES

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1. Introduction

A technique for diagnosing turbulent mountain waves was investigated using MODIS and GOES-12 water vapor (6.7um) imagery combined with hourly analyses from the RUC model and pilot reports of turbulence. The geographic domain of Colorado was chosen as the study site. Upon examining MODIS water vapor imagery daily for all of 2004 within this domain, it was found that wave signatures related to orography were present approximately 25% 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 had unique characteristics in the imagery different 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 hourly RUC analyses along with radiosonde soundings showed that the atmosphere during the turbulent wave events had wind and temperature profiles appropriate for mountain waves. The RUC data combined with the MODIS water vapor imagery shows that, with high spatial and temporal resolution satellite imagery, it may be possible for turbulent situations due to mountain induced wave activity to be nowcasted and forecasted. Ultimately, an algorithm could be developed incorporating model data and satellite imagery to automate the mountain wave induced turbulence forecasting.

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2. Methods

The first step in studying the waves and their signatures was to develop a climatology of waves as seen in the satellite water vapor imagery. All Aqua and Terra MODIS overpasses for 2004 over Colorado were analyzed for lee wave patterns. Approximately 25% of the days analyzed displayed lee wave patterns of varying intensity and extent. The imagery was available for quick analysis 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 used to determine the extent of the turbulence associated with the lee waves seen in the imagery. Bob Sharman at the National Center for Atmospheric Research (NCAR) provided archived pilot reports for the United States during 2004. 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. However, it was also found that the presence of mountain wave signatures in the imagery did not necessarily signify a day with greater than average turbulence. Thus, an extremely turbulent day almost certainly exhibited mountain wave signatures, while a day that exhibited mountain wave signatures was not necessarily reported as extremely turbulent.

The image analysis and interpretation portion of the climatology also revealed information about the relationship between turbulence severities and wave patterns. It was found that two characteristics were most coincident with the most turbulent waves. First, mountain waves with higher amplitudes were more likely to be more turbulent than average than those with lower amplitudes. Second, mountain waves that exhibited interference patterns in the imagery were considerably more likely to be more turbulent than average.

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 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 over relatively short periods of time. Due to the constraints on the necessary spatial and temporal resolution, the RUC model was used to analyze the appropriate fields.

Two case studies were performed to examine the possibility of using models to predict wave conditions. The days chosen for the case studies were March 06 and December 20. These days were chosen because they were not only the two most turbulent days in 2004 in Colorado, but also exhibited strong and complex wave signatures. On both of these days, the number of turbulence reports over Colorado exceeded the daily mean number by over six standard deviations (see figure 1). 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 and Case Studies

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.

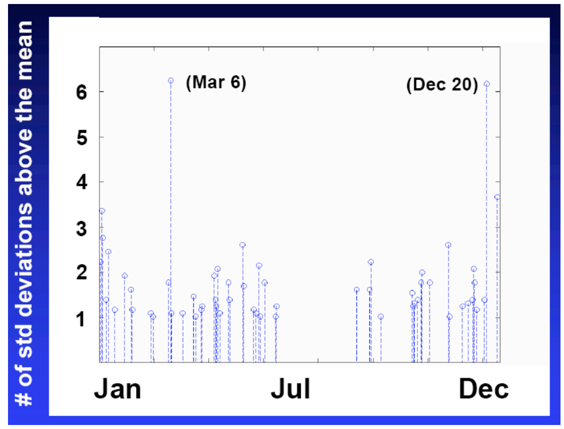

Figure 1: Number of standard deviations above the mean number of moderate or greater turbulence reports in 2004 by day.

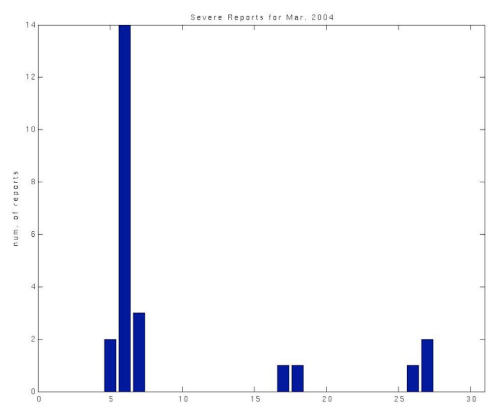

Figure 2: Severe turbulence reports in March 2004 plotted by date.

The numbers of severe turbulence reports during the month of March 2004 are shown in Figure 2. Figure 2 clearly shows that 06 March 2004 was by far the most severely turbulent day of that month. The MODIS overpasses on 06 March 2004 were analyzed to determine if any unique features were present in the lee wave signatures. 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 in the visible channel 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, and points to the necessity for using remote sensing to monitor lee waves.

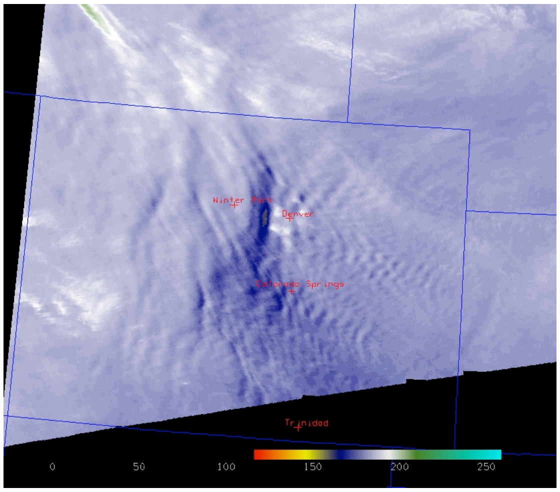

Figure 3: Aqua MODIS channel 27 at 1950Z on 06 March 2004 over Colorado.

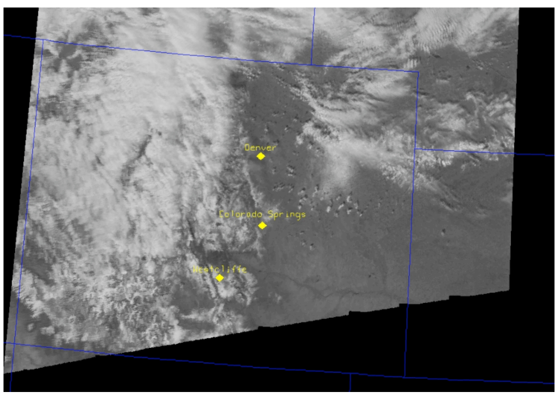

Figure 4: Aqua MODIS channel 1 scan at 1950Z on 06 March 2004 over Colorado.

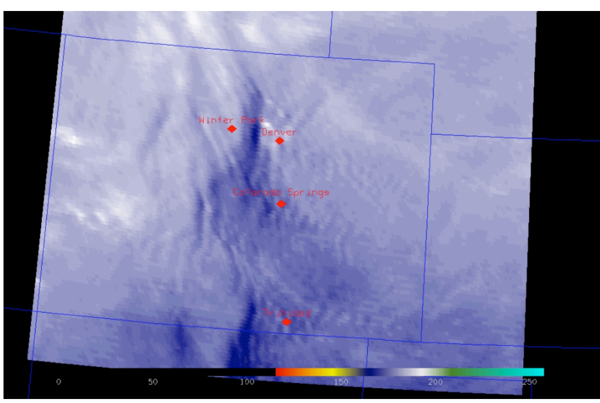

Figure 5: GOES-12 channel 3 water vapor image over CO at 1945Z on March 06, 2004.

Figure 5 is the GOES-12 water vapor image over Colorado during the same time as the MODIS imagery on March 06. The GOES image, as expected, does not show the wave signatures in as great a detail. Many of the finer details, such as the amount of interference present in the waves, are lost in the lesser resolution GOES image (4km at nadir).

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 (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 across-mountain wind speeds were increasing steadily with height, thus satisfying the speed shear requirement for lee wave formation.

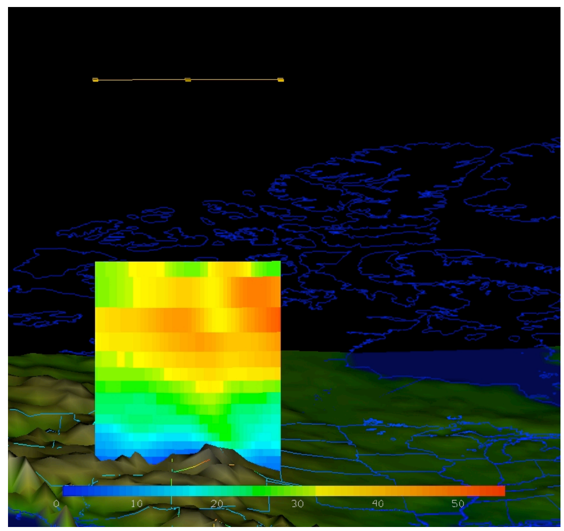

Figure 6: RUC model output of zonal winds over Colorado at 1900Z on 06 March 2004 in IDV.

The second parameter of interest from the model output was atmospheric stability; however, it is difficult to obtain model based stability measurements at the vertical scale needed. Instead, soundings from radiosondes around the lee wave area were used to determine the degree 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, thus 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 06.

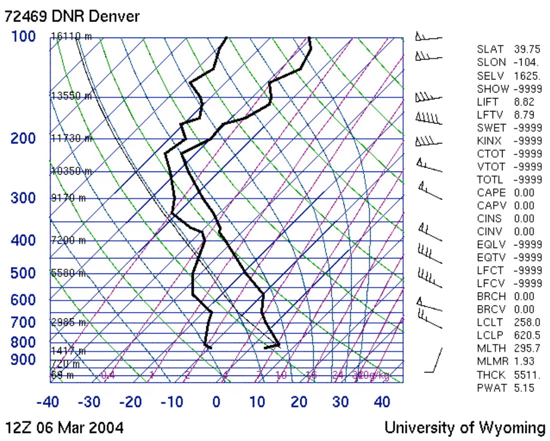

Figure 7: Sounding from Denver, CO at 1200Z 06 March 2004.

Figure 7 shows all of the turbulence reports over Colorado for March 06. 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 centered over the regions favorable for lee wave formation, such as the continental divide and the Front Range. The mass of turbulence reports is also collocated with the lee wave signatures in the imagery from March 06.

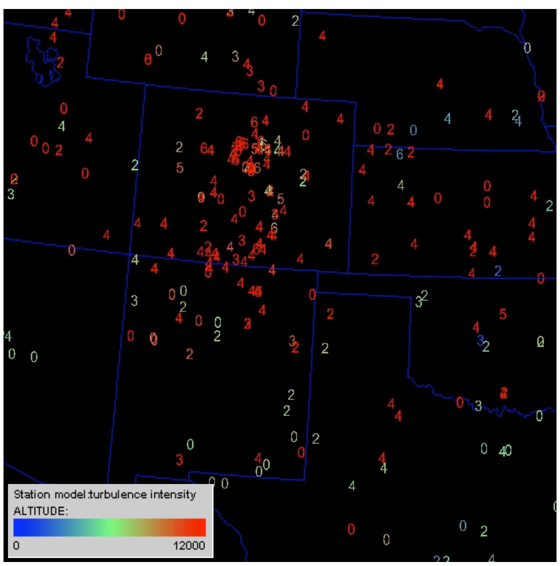

Figure 8: All turbulence reports for March 06 displayed and colored by altitude of the report. The color scale for the turbulence reports is shown in the image (in meters).

4. Results and Conclusions

A similar analysis was performed on the December 20 case, which also had a high number of turbulence reports along with strong lee wave signatures in the satellite imagery. The most turbulent days in the Colorado area are correlated with lee waves as seen in the satellite imagery. Also, 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 will be remedied in the near 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. Remaining 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. It is hoped that further study will serve to clarify some of the remaining uncertainties between the imagery and the actual occurrence of turbulence.

6. Acknowledgements

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