The SLAT (index) as an indicator of vertically propagating mountain waves using WRF 15km data, and its potential as a turbulence forecast product

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It is believed that manifestations of Vertically Propagating Mountain Waves (VPMW) are seen in the Air Force Weather Agency's 15 km Weather Research Forecast atmospheric model. VPMW are believed to be a significant cause of severe aviation turbulence events. In the immediate vicinity of mountain ranges, with upper tropospheric jets and troughs in the vicinity, 15-km WRF temperature and wind structures believed to be indicative of VPMW are seen in both the troposphere and the stratosphere. The temperature structure in the stratosphere has been published as the Stratospheric Layer Advanced Turbulence (SLAT "index"). SLAT has informally been shown to correspond to upper level turbulence. Maps of SLAT are used operationally in Air Force Weather as a predictor of turbulence. Should SLAT be shown to be a valid indicator of VPMW, detailed 3-hourly forecast maps of SLAT would be useful in pinpointing both the locations and times of suspect VPWM events, allowing safer and more efficient air travel.

1. INTRODUCTION

It is generally believed that turbulence due to Vertically Propagating Mountain Waves (VPMW) is a primary cause of damage and injury in aviation incidents. Case studies following damage to aircraft, such as Clark et al. 2000 have found that VPMW are present. On a day with the most turbulence reports in ten years in South Korea, Kim and Chun 2010 also found that VPMW were a likely mechanism for some of the reports.

Accordingly, the Air Force Weather Agency (AFWA) acquired and implemented the Mountain Wave Forecast Model II (MWFM II) from the Naval Research Laboratory (Eckermann et al. 2004). The MWFM II was intended to be used at AFWA mostly as a forecast of turbulence that occurs in the stratosphere, the domain of military reconnaissance aircraft.

The training module on mountain waves (METED/COMET cited 2011) notes VPMW are accompanied by downslope winds near the surface. Fig. 1 from the mountain wave module shows a cross section from a 9km horizontal resolution COAMPS model.

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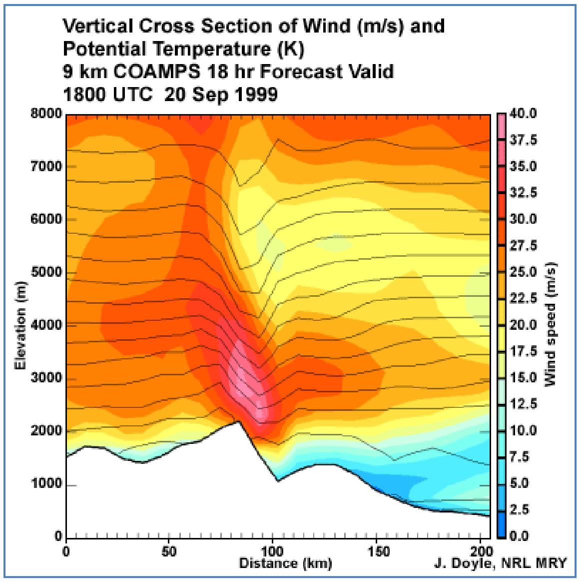

Figure 1. From the METED module "Mountain Waves and Downslope Winds"

Lindley et al. 2006 showed a similar cross-section of a high surface wind event associated with VPMW over the Guadalupe Mountains of West Texas/New Mexico (Fig. 2). Lindley et al. noted that the pattern was quite replicable, and created a list of characteristic features of model data that National Weather Service forecasters should look for to identify damaging downslope winds. Note that the VPMW feature in both Fig. 1 and Fig. 2 leans slightly westward with height.

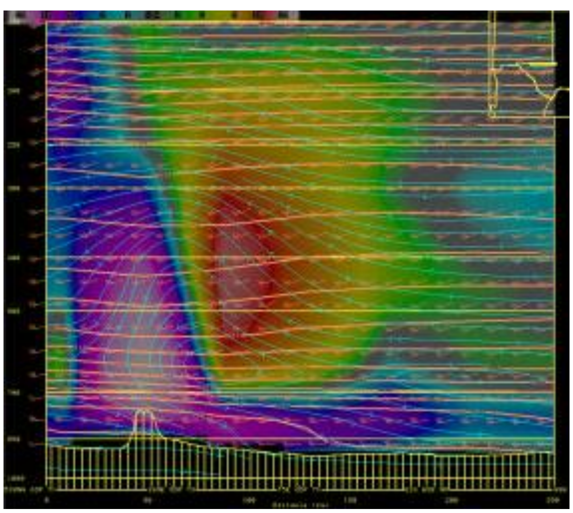
Figure 2. From Lindley et al 2006: VPMW from 40km NAM. Vertical velocities: warm colors upward, cool colors downward.

Explicit modeling of VPMW with high-resolution models has been attempted to forecast VPMW. Sharman 2010 noted an attempt to explicitly model VPMW with a 3km horizontal grid (Fig. 3).

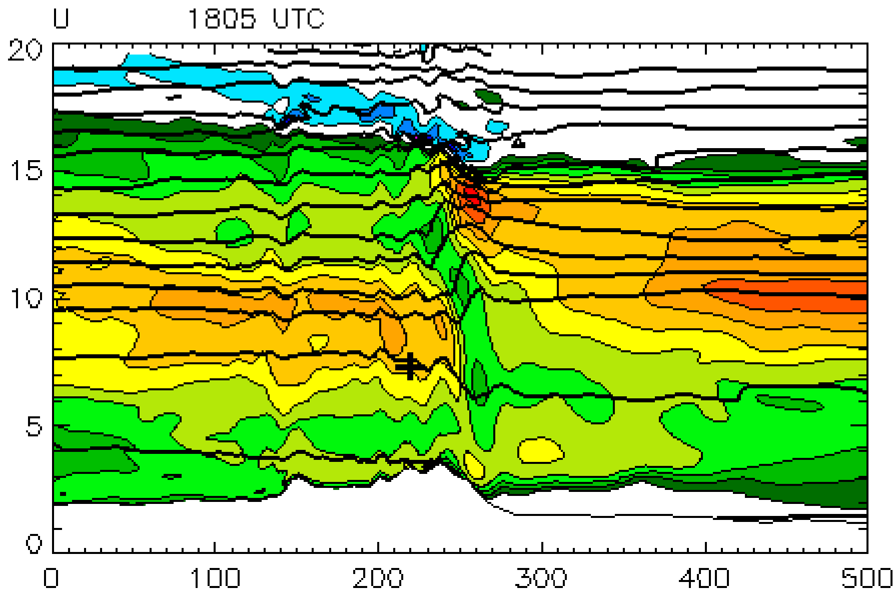

Figure 3. From Sharman 2010: VPMW, Clark-Hall anelastic model simulation, 3 km horizontal resolution.

Mahalov 2011 presented a methodology for modeling VPMW using unique model equations and extremely fine resolution grids nested both horizontally and vertically.

A technique within the MWFM II is to utilize digitized representations of mountain ridges as an aid to forecasting VPMW caused by winds flowing over the digitized ridges.

A different type of stratospheric turbulence forecast, the SLAT index, was derived by Sinclair and Kuhn 1991. SLAT is a temperature profile in the stratosphere shown to have a high correspondence to stratospheric turbulence in the High Altitude Clear Air Turbulence (HICAT) experiment. SLAT was implemented operationally at the Air Force Weather Agency on the one-degree latitude GFS model in 2009.

2. OBSERVATIONS

The Stratospheric Layer Advanced Turbulence (SLAT) index was created following analysis of rawinsonde soundings taken during HICAT flights experiencing turbulence. In their data, Sinclair and Kuhn found that 100% of CAT reports had a characteristic SLAT temperature profile, and 95% of SLAT cases experienced CAT.

SLAT is simply an “S” shaped temperature profile in the stratosphere, as shown by the idealization in Fig. 4. The formulation of the SLAT index is shown in equation 1.

$$\mathrm{SLAT} = \frac{[\mathrm{gamma}_{ML} - (\mathrm{gamma}_{U} + \mathrm{gamma}_{L})]\,[20{,}000\mathrm{ft} - DZ]}{10C - DT}$$

Equation 1. Gamma$_{ML}$ is the lapse rate in the Mixing Layer, gamma$_{U}$ and gamma$_{L}$ are the lapse rates of the upper and lower inversions, DZ is the height of the Mixing Layer in feet, and DT is the warmest minus the coldest temperature in the Mixing Layer.

The unitless index typically ranges from 0 to 10, apart from mountain wave areas which will be discussed in section 3. The most influential factors in the SLAT equation are 1) the temperature difference from maximum to minimum in the mixed layer (where a higher difference increases SLAT), and the depth of the mixed layer (where less depth increases SLAT). An example sounding from the Air Force Weather Agency (AFWA) WRF 15km model is in Fig. 5, showing a distinct S-shaped temperature structure in the stratosphere.

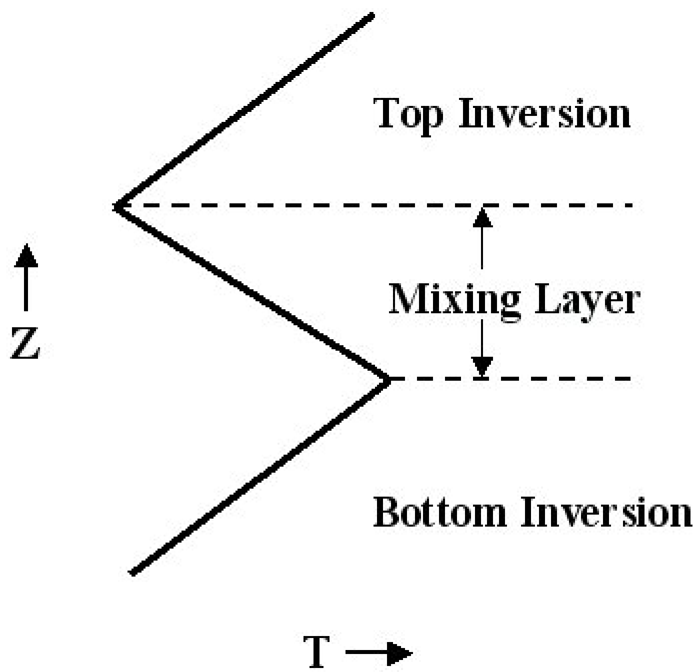

Figure 4. Illustration of SLAT, an S shaped temperature profile in the stratosphere.

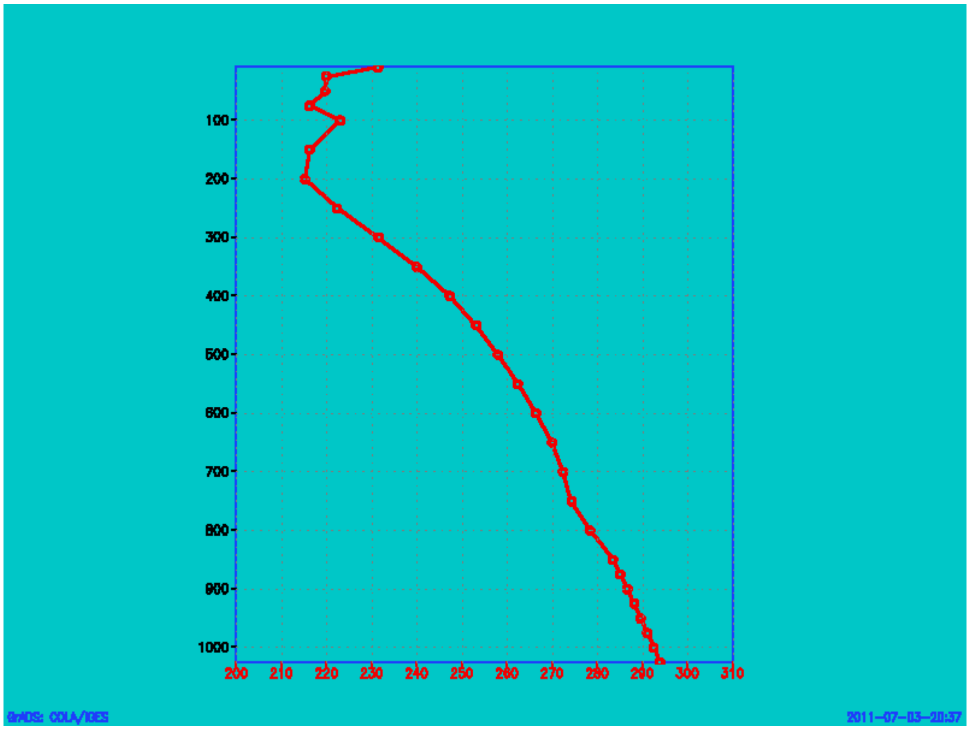

Figure 5: Temperature profile from WRF 15km over the Sierra Nevada mountain range of California and Nevada border, United States, an "S" shape in the stratosphere triggering positive values of the SLAT index. WRF model run date 2011 June 1 06Z.

SLAT calculations had previously only been found in the commercial off-the-shelf analysis program called RAOB, according to Allen 2003. Since RAOB used the most recent rawinsonde data, the turbulence analysis was actually a hindcast. According to a personal communication from Allen 2003, "RAOB is considered the first option in determining the presence of Stratoturb when briefing flight crews". Sinclair and Kuhn found that 100% of turbulence events were confined to the mixing layer portion of the 'S' layer, where the inversions act to contain the turbulent mixing and minimize the escape of this energy to the surrounding atmosphere.

Seeing the need for a forecast-model version of the SLAT index, AFWA programmed the SLAT index and applied it to the one-degree GFS model. During the development phase, meteorological support forecasters of high-flying aircraft at Beale AFB grew to like the SLAT index, stating: "when SLAT is forecast, the yellow light goes on", referring to a turbulence indicator in the Global Hawk aircraft (Williams 2005).

Since specific flight times of Air Force high-flying reconnaissance aircraft missions are classified, validation of the SLAT has been through indirect means. Other indirect means of SLAT validation follow.

In a blind challenge from a Terrain-Induced Rotor Experiment (T-REX) investigator, AFWA was asked where the SLAT index had forecast turbulence on a particular flight. The flight was from California to Wyoming and back. Positive (turbulent) SLAT values were forecast at only one location along the flight path, in the southwestern corner of Wyoming. The forecast in that case was correct.

An internal study performed at AFWA showed that SLAT locations were typically forecast between upper level (100-400mb) troughs and the location of the jet streak. This pattern appeared consistently, and suggested that the physical processes involved behind SLAT might be consistent as well.

One other sign that SLAT has value is that it is has high values consistent with the tropospheric turbulence season, generally from November through May, and lower values the rest of the year.

Note that the utilization of SLAT has been intended for application to very high levels, that is, in the stratosphere.

3. ANALYSIS

In this section maps and cross sections derived from model data will be shown in the vicinity of suspected VPMW features. Cross sections and maps will show the vertical and horizontal structure of these features, and will help to determine the likelihood that the AFWA WRF 15km model shows some aspect of a VPMW.

From the AFWA WRF 15km model run of 2011 June 1, 06Z, the 9 hour forecast, a typical SLAT pattern was seen along the Calfornia/Nevada border in the lee of the Sierra Nevada range (Fig. 6).

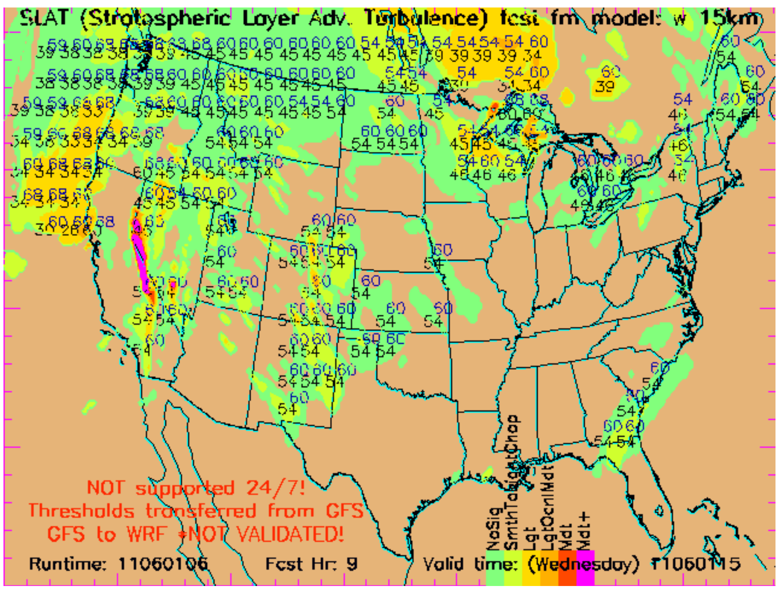

Figure 6. SLAT from WRF 15km model. Probable VPMW event indicated by high values of SLAT (magenta) over the Sierra Nevada range. Numbers are heights in thousands of feet of the lower and upper bounds of the SLAT "mixing layer".

This example is very typical of cases seen on an almost daily basis throughout the 2010-2011 cold season. The location of SLAT bands of high value relative to the mountain ridges is common. Lower values of SLAT are seen across the CONUS, which tend to match the large-scale upper tropospheric trough. As jet cores approach mountain ranges, the high-value SLAT bands will appear. Sometimes the high value SLAT bands will initiate somewhat ahead (eastward) of the apparent trough. High values of SLAT over mountain ridges will typically continue with strong intensity until the passing of the upper-level system. The existence and persistence of the high-value SLAT bands appear to be most closely associated with the jet maximum winds, typically located between 400 and 150mb.

An east-west cross section through the area of high SLAT was generated showing the temperature, wind, and vertical velocity structure (Fig. 7). The bottom of the cross section is set to 500mb; the purpose of this is to emphasize temperature patterns in the stratosphere.

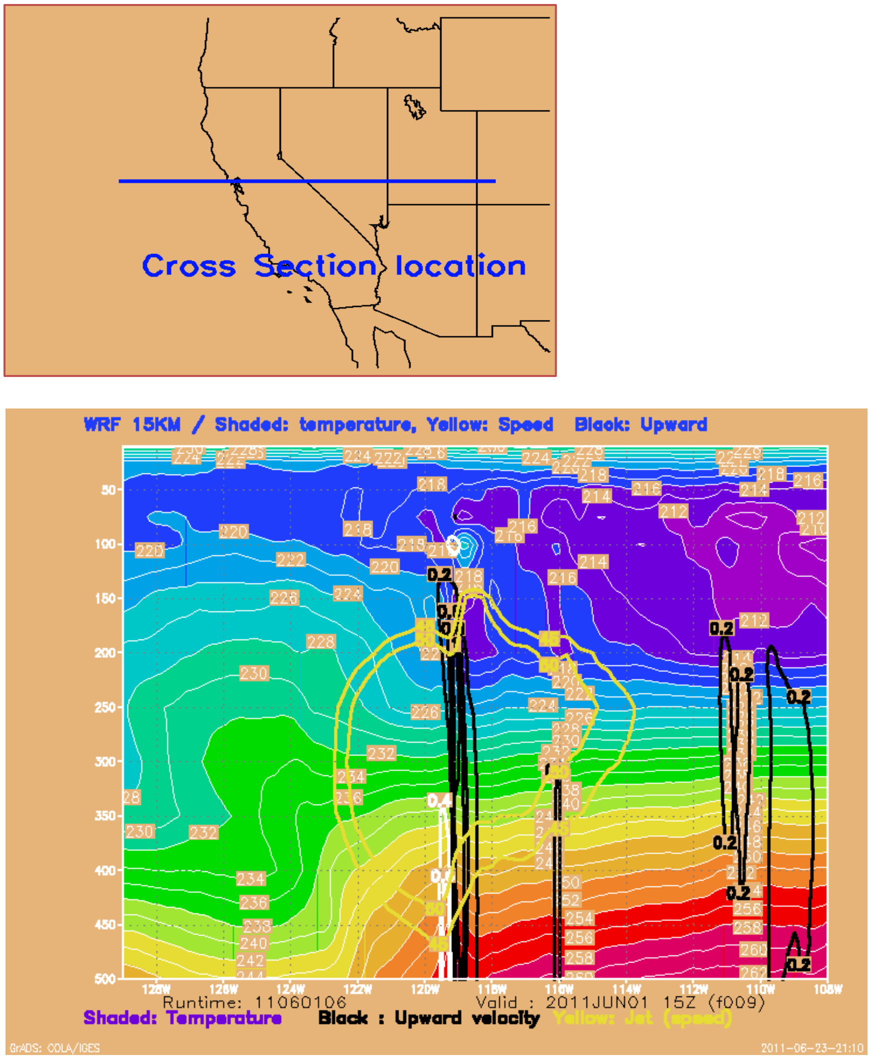

Figure 7. a) Cross section location. b) Vertical Cross section through VPMW event (from WRF 15km model). Lowest cross section level is 500mb. Temperature (degrees Kelvin, shaded), vertical velocity, m/s, black (downward) and white (upward), and wind speed (45 and 50 m/s, yellow).

This cross-section pattern is quite typical of the temperature, wind speed, and vertical velocity seen in the WRF 15km model during VPMW events. The prominent feature, located very near the Sierra Nevada range, is the couplet of downward and upward vertical velocity located in the middle of the cross section near 119 West longitude. Peak magnitudes of WRF model upward vertical velocity are typically 1.0 m/s. It is common for the vertical velocity feature to be tilted slightly westward with height.

Total wind speed contours of 45 and 50 m/s are shown to indicate the jet core. It is common that the jet is higher in the atmosphere to the east of the velocity feature. The jet propagates through the vertical velocity feature, with model vertical velocities diminishing as the jet moves past the mountain ridge.

From the temperature contours, the SLAT pattern can be discerned. Above the upward motion, again near 119 West longitude, the temperature drops steadily with height to a minimum between 200 and 150mb. There is a temperature inversion with a peak temperature at 100mb (light blue concentric contours). The temperature drops sharply at 70 mb (purple shading), then increases above that level, forming the “S” shaped SLAT profile such as the one portrayed in Fig 5.

Waco 1972 noted that sharp horizontal temperature gradients can be an indicator of stratospheric turbulence. The SLAT signature, such as in the cross section of Fig. 7, may be an instance of such a horizontal temperature gradient.

It should be noted that while the SLAT and vertical velocity signatures are very highly correlated, the correspondence is not always perfect. Sometimes the SLAT temperature pattern remains in the stratosphere 3-6 hours after the vertical velocity signature diminishes.

It is tempting from this and many other cases to suggest that a forecast of high values of SLAT in the vicinity of mountain ranges is a good proxy feature for forecasts of VPMW. The SLAT has a very high correspondence to the distinctive vertical velocity feature seen in cross sections.

Since the SLAT however seems to be a "side effect" of the suspect VPMW, the use of the vertical velocity signature itself may be a more direct indicator of the VPMW event. An algorithm to identify vertically consistent columns of upward motion within the WRF model should be developed. Such an algorithm would have to take into account the possibility that the "column" typically tilts westward with height, as in Figs. 3 and 7. A simple attempt to identify this vertical velocity signature is shown in Fig. 8, where the black shading is the location where a number of upward model velocities over 0.2 meters per second are observed at the same model gridpoint. The value 0.2 was selected by noting that it seemed to delineate the suspect VPMW feature in the vertical cross section.

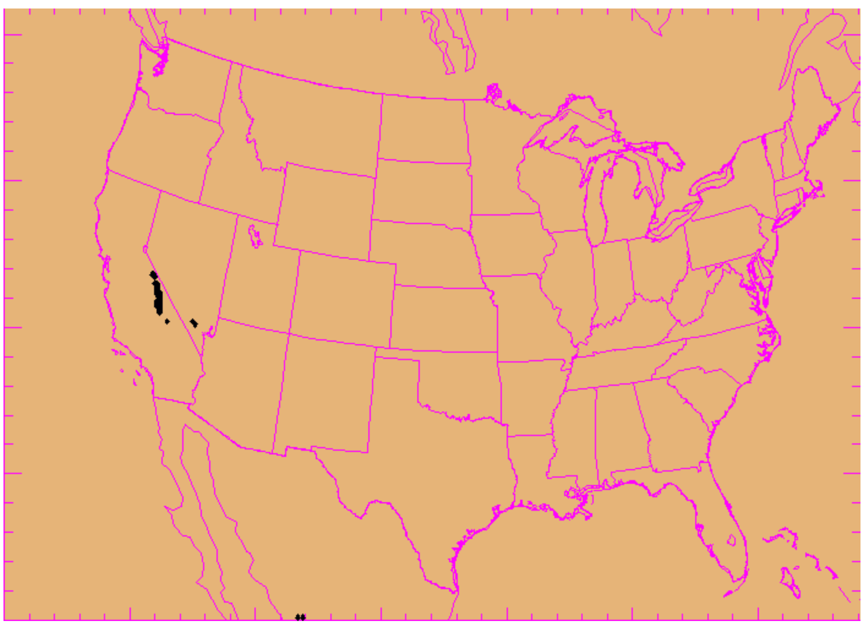

Figure 8. Potential VPMW forecast from WRF 15km. Over the Sierra Nevada range, shaded in black: location of several consecutive model sigma levels with model upward velocity over 0.2 m/s.

4. POSSIBLE RELATION TO TURBULENCE

In order to relate SLAT to turbulence, simple graphs were made plotting model derived values of SLAT along with turbulence probabilities for that SLAT value. Pilot reports (PIREPS) and model data collected during the winter of 2010-11 were examined. The SLAT values, mostly ranging from 0 to 10, were sorted. Probabilities of light-or-greater turbulence were plotted along with the sorted SLAT values. These graphs differ however depending on the intensity level of turbulence and the height layer considered. At publication, only the combinations of turbulence levels and intensity shown below have been plotted. In Fig. 9 (top), the probability of any intensity of turbulence occurring between 30 and 40 thousand feet increases with higher values of SLAT. In a variation of this graph, Fig. 9b was done for moderate-or-greater (MOG) turbulence, also between 30-40k ft. Fig. 9c was done for MOG turbulence, all height levels.

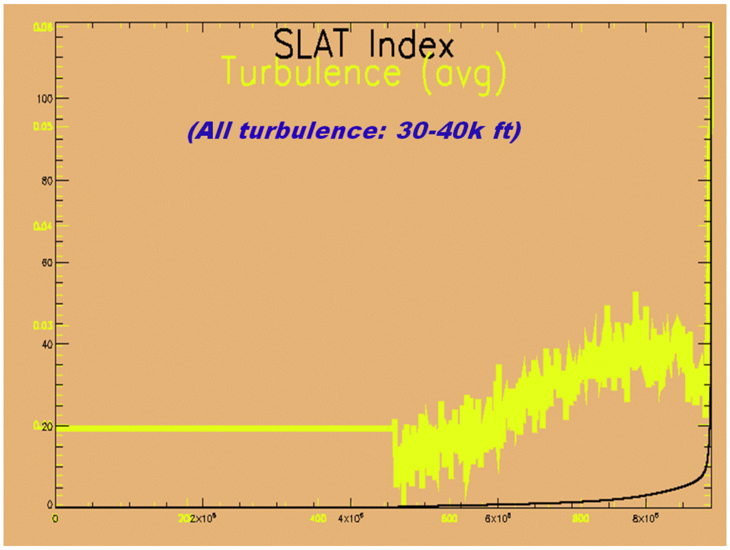

Figure 9a

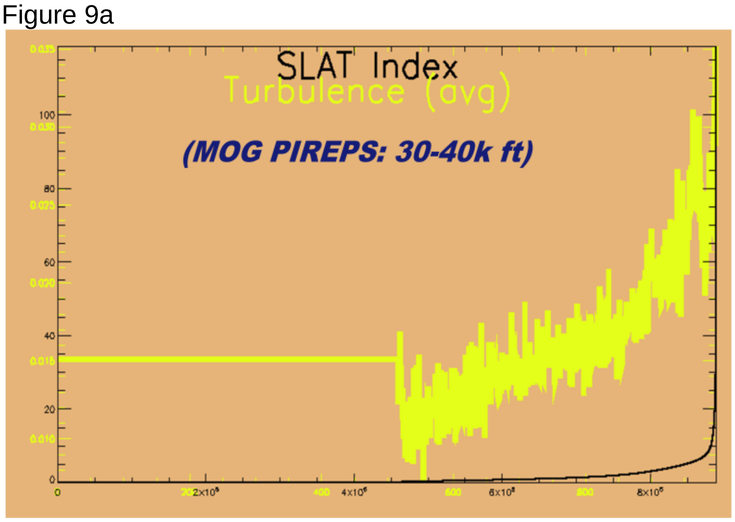

Figure 9b

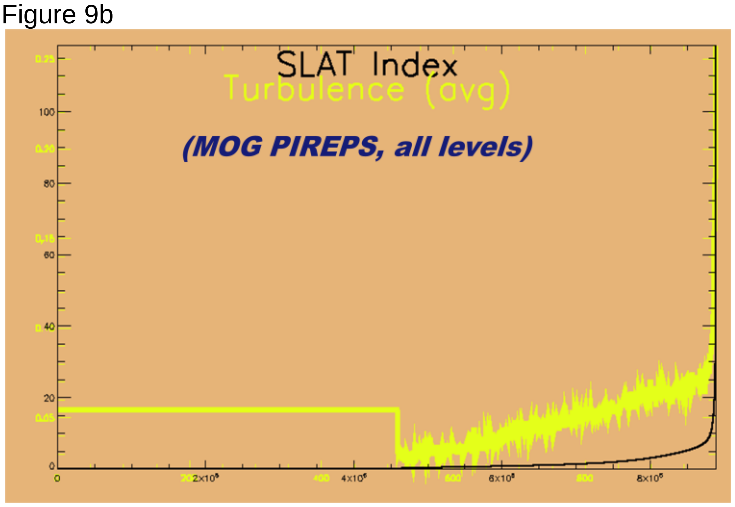

Figure 9c

Figure 9. WRF model SLAT value, sorted, in black line. Black y-axis numbers indicate the SLAT value. Yellow line: probability of turbulence (fraction). The flat yellow line, occurring where SLAT is zero, is set arbitrarily to the climatological value of turbulence. a) (top): yellow line is all turbulence intensities, level 30-40k ft. b) (middle): MOG turbulence between 30 and 40 thousand feet. C) (bottom): MOG turbulence at all height levels. SLAT values, 0 to over 100, labeled in black; turbulence probabilities in yellow (y axis).

The black SLAT lines in Figs 9 a, b, and c show a spike in SLAT values on the far right, with values well beyond 10 units and occasionally exceeding 100. Coincident with this spike in Figs 9a and 9c is a spike in the frequency of MOG reports (yellow line), but not in Figure 9b. In Figure 9c, the probability of turbulence occurring within several WRF model gridpoints is 0.25, that is, one in four. It is tempting to attribute the spike in MOG turbulence frequency to VPMW events indicated by SLAT, but further investigation is warranted. The possibility remains that the WRF 15km model shows a signature of a VPMW, but not the likelihood of the wave "breaking" which is believed to be the primary cause of the associated turbulence incidents.

Support for a relationship between SLAT and turbulence can be seen in Fig. 10. Fig 10a from Sharman 2010 shows the frequency of MOG turbulence over a 15 year period, where some mention of a mountain wave was mentioned in the PIREP comment. Fig. 10b shows the frequency of SLAT values over 15 units. 15 units is an arbitrary dividing line between "everyday" SLAT values such as seen in much of Fig. 6, and SLAT values over mountain ridges which may exceed 100 units. A difference between Figs. 10a and 10b are that the MOG PIREPS were collected over a 15 year period, and the SLAT frequencies were only over the cold season of 2010-11. The good correspondence between MOG PIREP mountain wave frequency and SLAT values does however suggest that SLAT is related to MOG turbulence associated with VPMW.

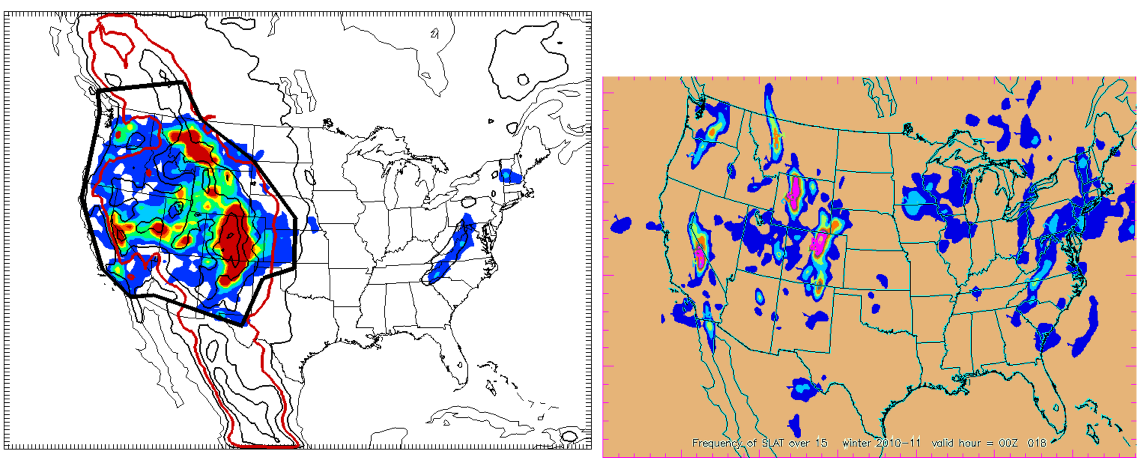

Figure 10. Left: From Sharman 2010: Number of MOG PIREPS, all height levels, with "mountain wave" in comments. Right: WRF model frequency of 15+ values of SLAT index. Sharman includes fifteen years of data, WRF SLAT one cold season.

5. SUMMARY

It appears that there is a strong relationship between the operational AFWA WRF 15km SLAT index, used as a forecast of stratospheric turbulence, and VPMW. High values of SLAT appear in the close vicinity of mountain ridges in the Appalachians and western CONUS. Cross sections of these high-value SLAT events have distinct up-and-downward vertical velocity signatures generally attributed to VPMW, as well as jet winds consistent with VPMW. The cross sections show the very close relationship between VPMW and SLAT temperature profiles.

The relationship of the VPMW/SLAT events to turbulence is uncertain at this moment. From the data presented, it is probable that these events have a statistical relationship to turbulence events. While the relationship is encouraging, it appears that the WRF 15km forecasts VPMW signatures by themselves are not sufficient to guarantee turbulence.

It would however appear to be quite simple to use the existing SLAT maps as forecasts of VPMW turbulence, if desired, or to design an algorithm to use the model vertical velocity signature as an indicator of VPMW.

Future work should be done to examine data in the regions of these mountain ridges. Other model output besides SLAT from the AFWA WRF 15km model should be studied to determine conditions under which these VPMW events in the model have actual turbulence.

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