Semi-empirical methods for the prediction of mountain wave turbulence (MWT)

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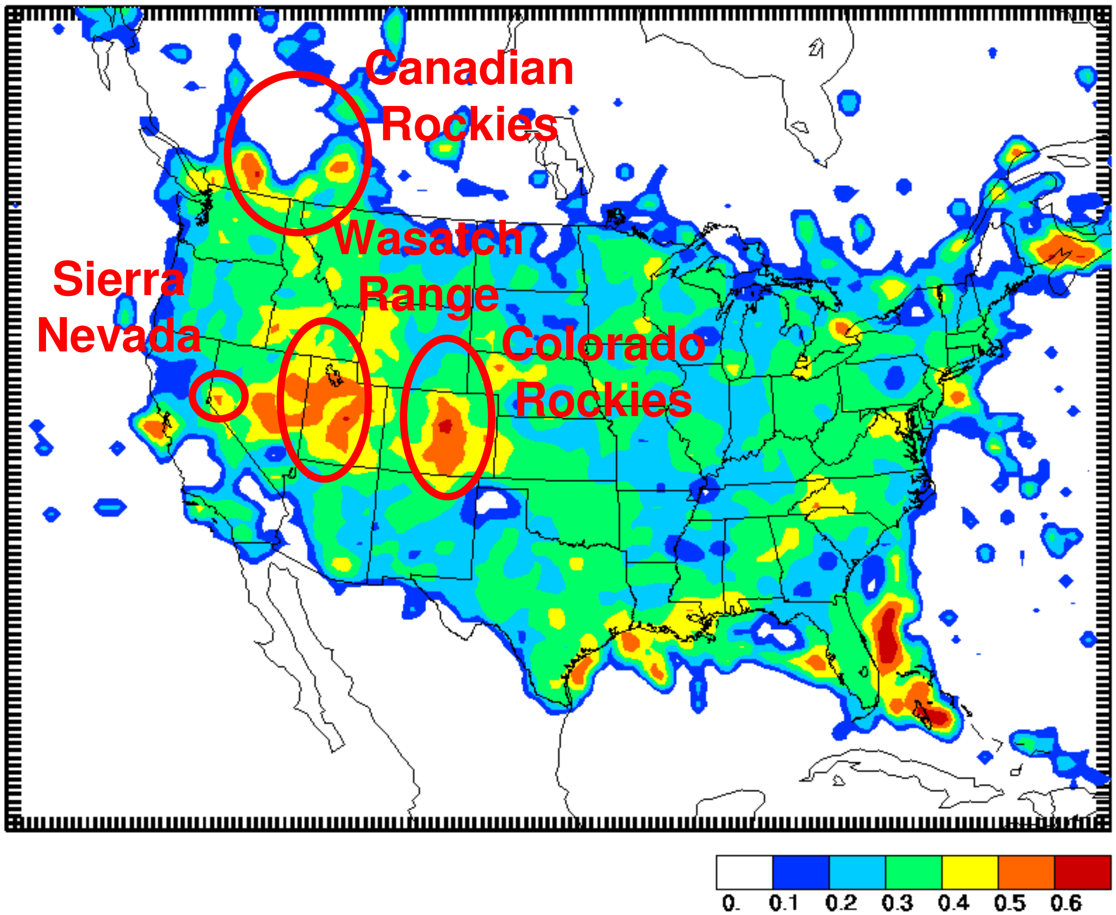
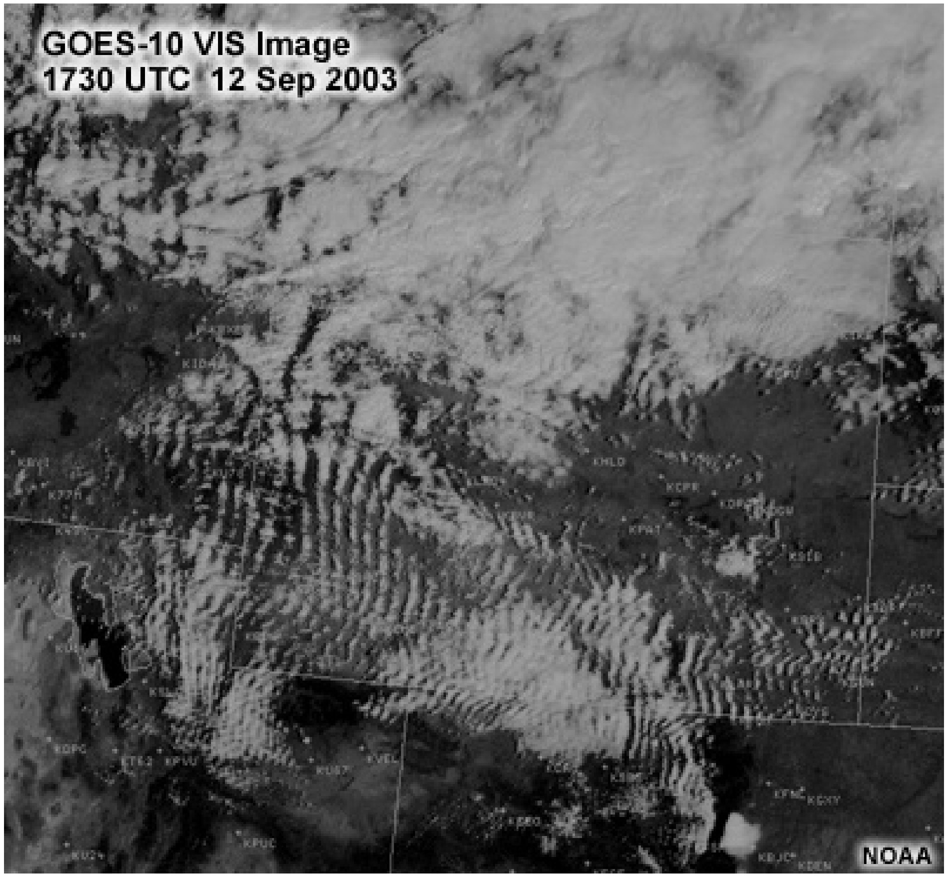
Observations show high incidence of turbulence and gravity waves over the Western U. S.



MOG/Total PIREPs 1-60,000 ft
1993 – 2007



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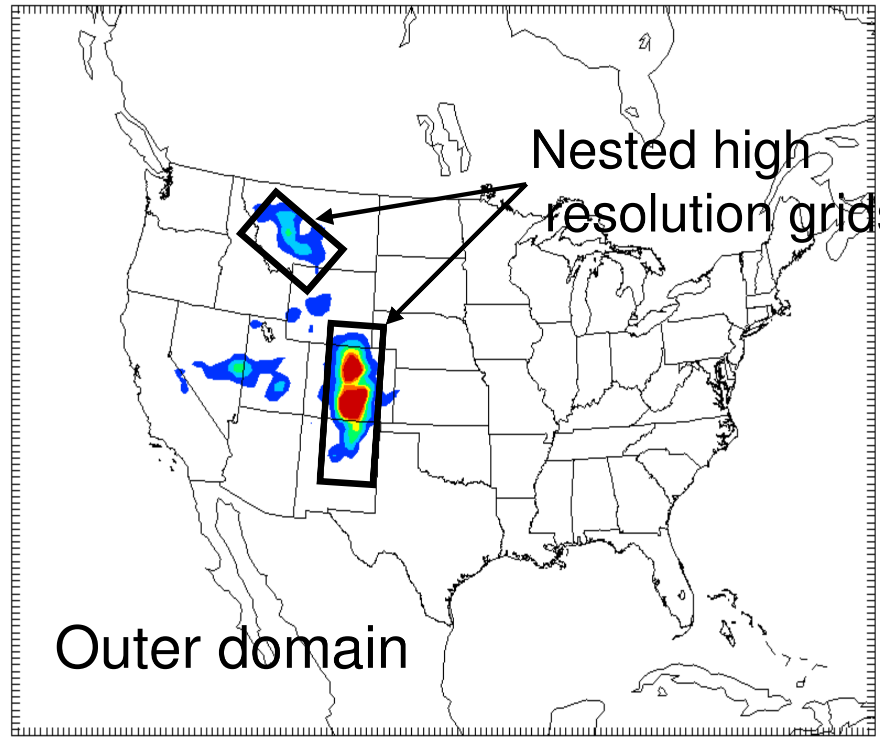
Forecasting MWT: Approach 1 - Forecast directly with NWP model



- Use nonhydrostatic model
- Case studies have been highly successful in reproducing turbulent events
- Use nests in MWT-prone areas
- Need at least 6-8 grid points per wave to resolve -> Requires at least 1-5 km resolution to "resolve" waves
- To maintain computational stability most models have some amount of explicit or implicit filtering which causes underrepresentation of the smallest "resolvable" scales
- Therefore requires still finer grid spacings to resolve wave breaking

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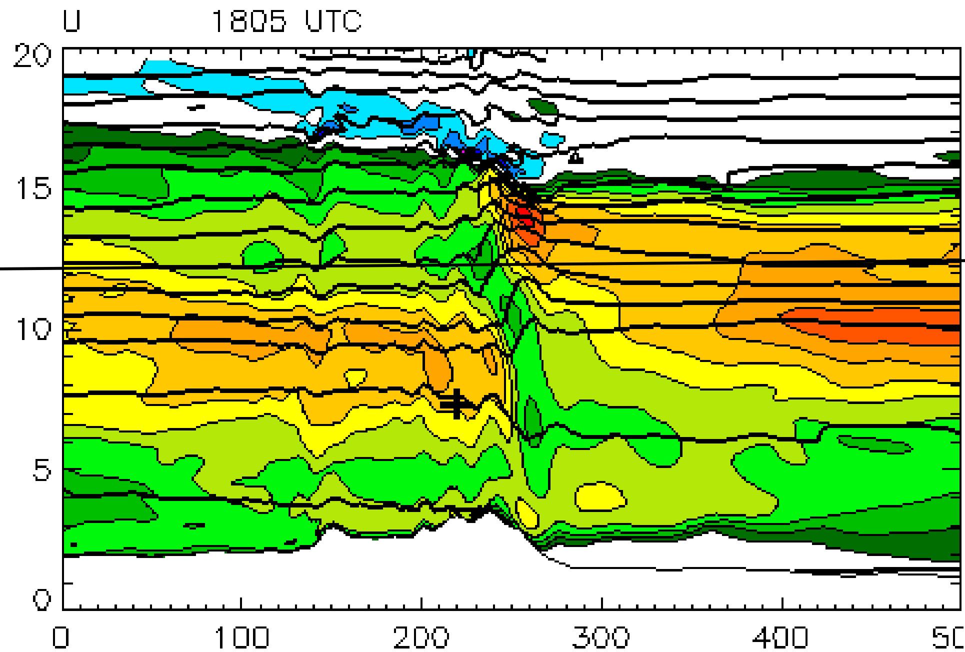
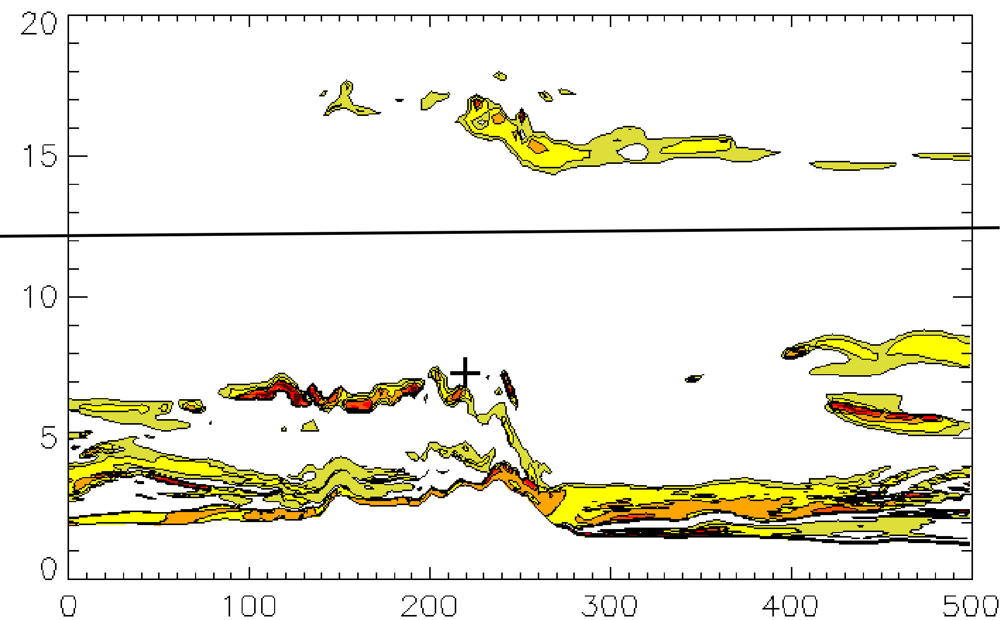
Example of Approach 1: Simulations of ~3 km have successfully reproduced MWT events associated with wave steepening and breaking

15 Mar 2006 B757 encounter with MWT (-.4g,+.8g) over CO at 12km
Several injuries, flight diverted



U (m/s)

white |U|<5 m/s cint 5 m/s



Richardson # < 1

Red < 1/4

Clark-Hall anelastic model simulation, 3 km horizontal resolution

East-west cross-section, 15 min frames 18Z-23Z   3 km resolution (event – 22:14).

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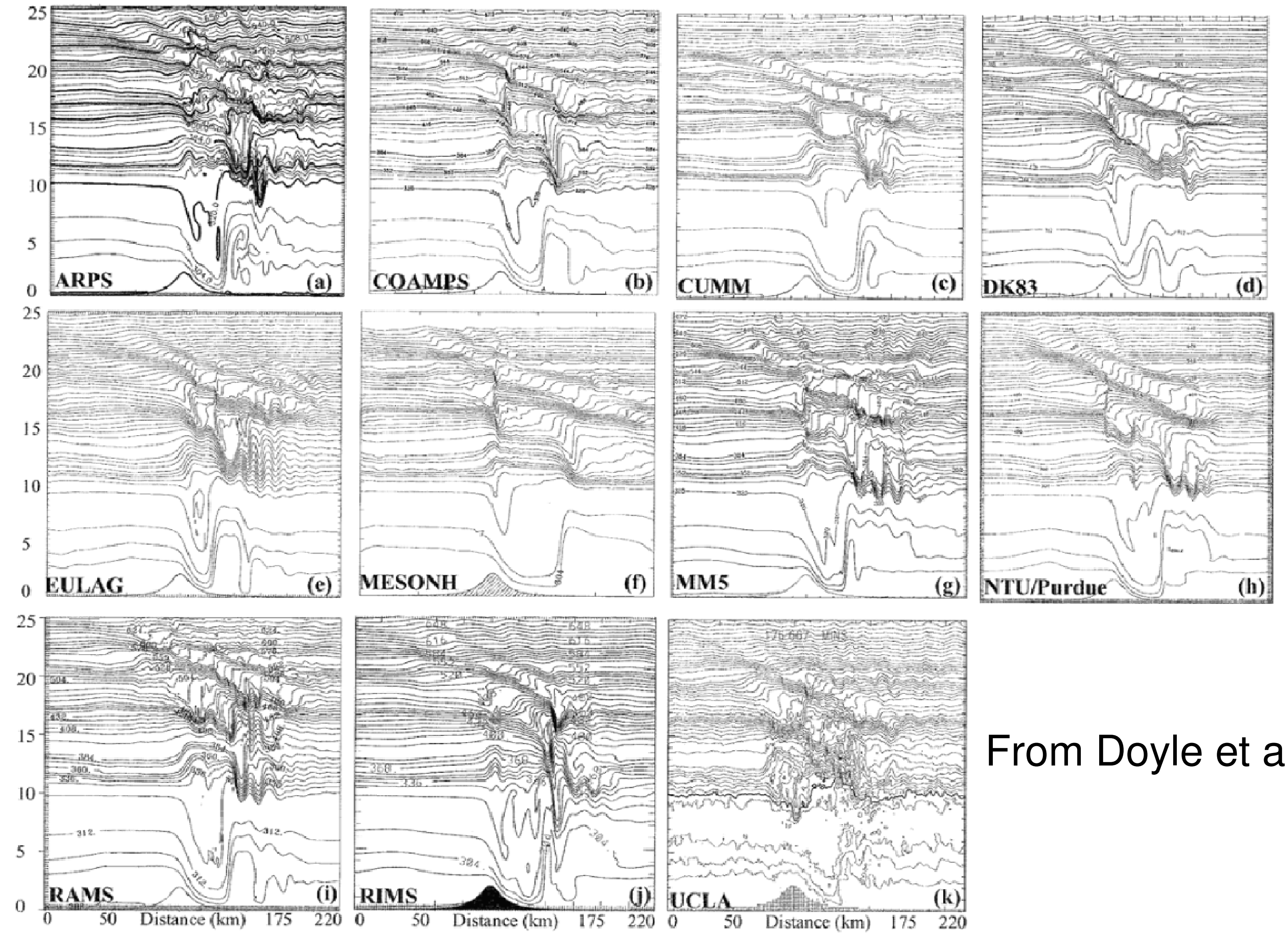
Ensemble approach would be preferable. Example: simulations of downslope windstorm – large spread!



G. 3. Vertical cross section of the simulated potential temperature after 3 h for (a) ARPS, (b) COAMPS, (c) CUMM, (d) DK83, (e) EULAG, (f) MESO-NH, (g) MM5, (h) NTU/Purdue, (i) RAMS, (j) RIMS, and (k) UCLA models. The contour interval is 8 K.

From Doyle et al.,MWR, 2000

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Approach 2: Empirical MWT forecasting

- Derive MWT diagnostics as a postprocess to operational NWP model output
  - But these are course resolution (~ 10 km) and may be hydrostatic
  - Problem is then to develop diagnostics that identify larger scale features that are related to MWT
  - Need to be altitude dependent, so traditional 2d indicators are insufficient:
    - Strong wind component normal to ridge
    - Terrain characteristics (mean height, variance, etc.)
  - Use several 3D discriminators to provide ensemble
- Verify using MWT PIREPs
  - Pilot specifically mentioned mountain wave in the remarks section

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MWT PIREPS: Wave vs turbulence

- Many mountain waves are nonturbulent

  UA /OV RLG/TM 1418/FL150/TP C172/WV 30050KT/

  TB NEG/RM TREMENDOUS MTN WAVE

- Others have strong correlation between wave amplitude and turbulence

  UUA /OV MVA 085050/TM 1835/FL400/TP B737/

  TB SEV/RM SEV MTN WAVE/FULL TILT ON THROTTLES. +/- 40KTS

- Some do not report turbulence level

  UA /OV INW045050/TM 2239/FL330B/TP A319/TB MOD MTN WAVE/RM PUSHED RED LINE/3000FPM CLIMB ZAB

  UA /OV ALS 285030/TM 2105/FLUNKN/TP LJ45/RM SEV MTN WAVE FL470

- Some do not report wave amplitude

  UA /OV SUN360035/TM 1837/FL125/TP PA31/TA M10/

  TB MOD/RM MTN WAVE

- So turbulence ≠ waves
- But for hazard it may be the same

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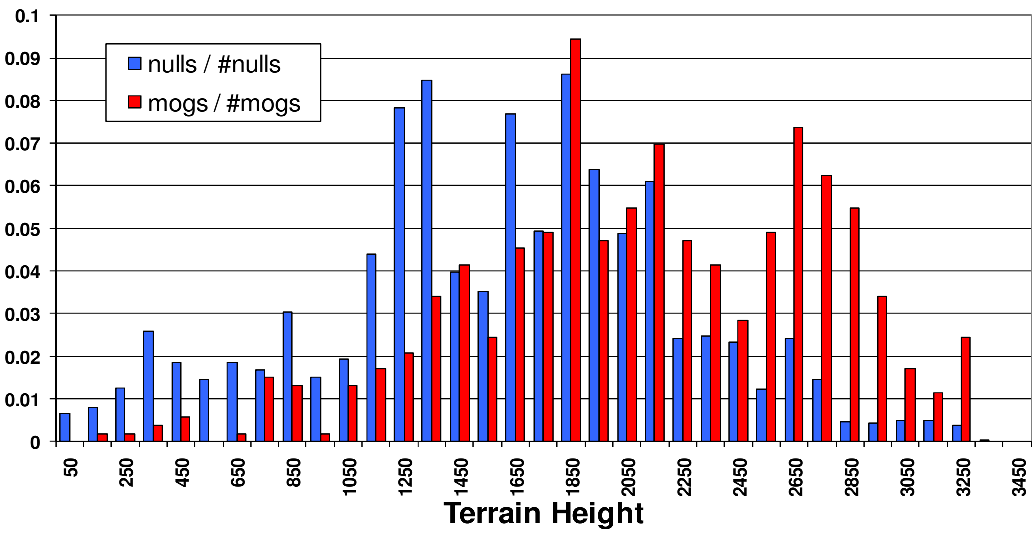
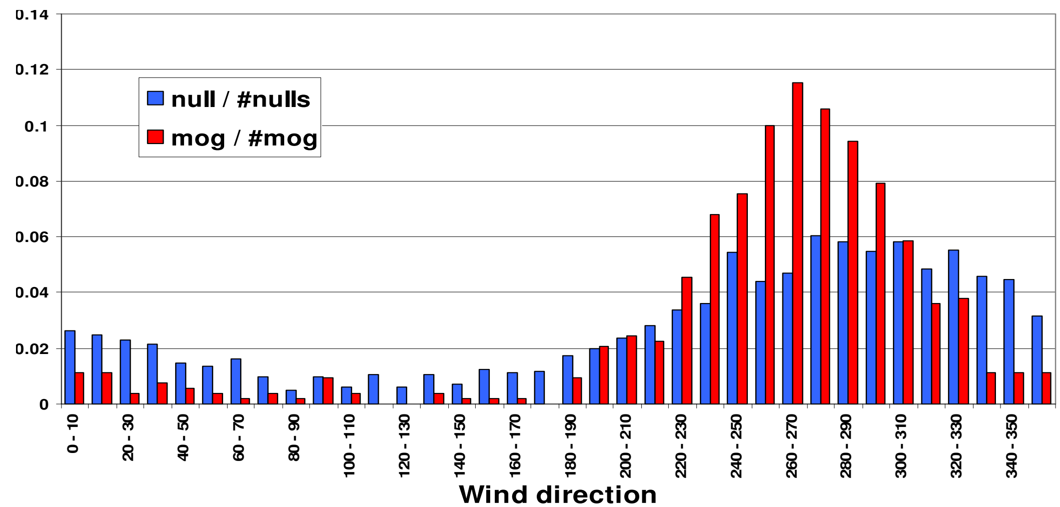
2D diagnostics

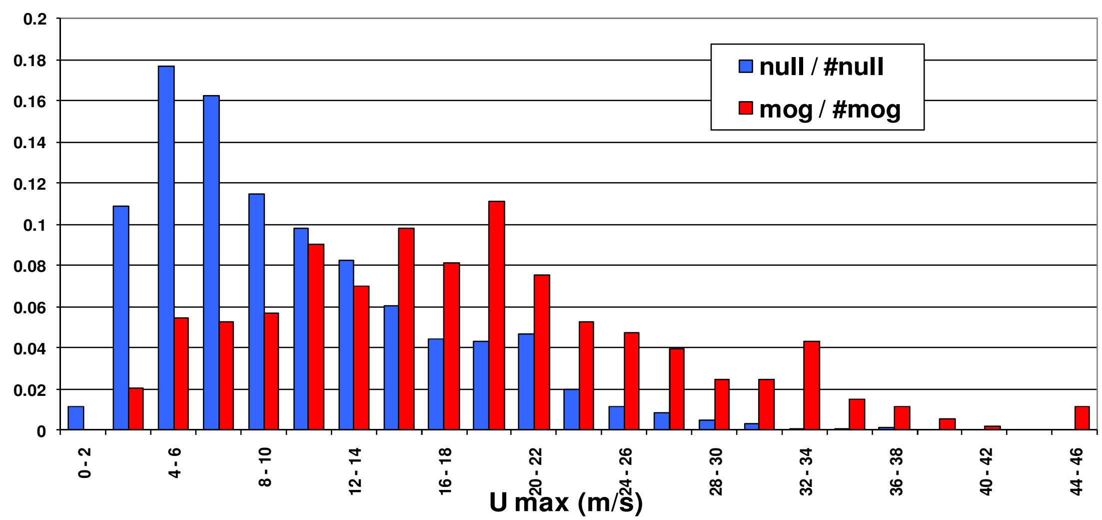
Terrain height



Wind direction



Umax in lowest 1500m



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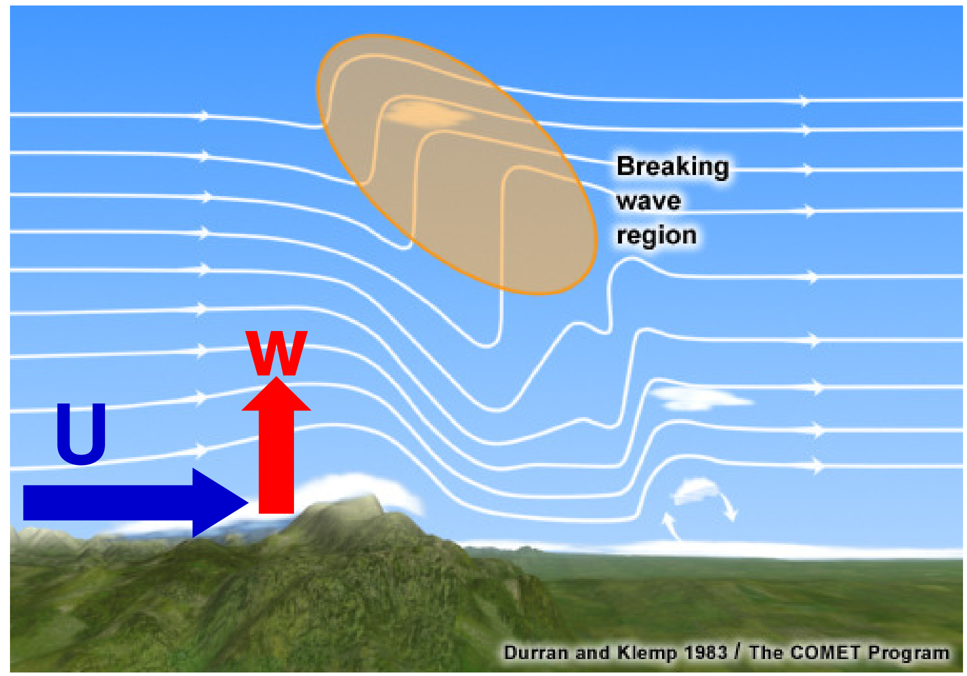
Key 2D diagnostic = low level w

Wave amplitude forcing

- w=U dh/dx
- Large amplitudes favored by
  - Strong wind normal to ridge (U)
  - Large slope
- Wave “breaking” favored in large amplitude waves



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3D diagnostics

- **Vertical gradients, e.g. Ri**
  - **But turbulent structures tend to be larger horizontally than vertically**
- **Horizontal spatial variability**
  - Temperature (e.g. $|\Delta T|$, C_T^2, Ri with du/dz from thermal wind)
  - Horizontal divergence
  - Eddy dissipation rate (edr or ε) derived from 2nd order structure functions (Frehlich and Sharman, MWR, 2004)
  - Horizontal variance of vertical velocity (Frehlich and Sharman, 11th ARAM, 2004)
- Multiply these be w_0 or w_o*h_o

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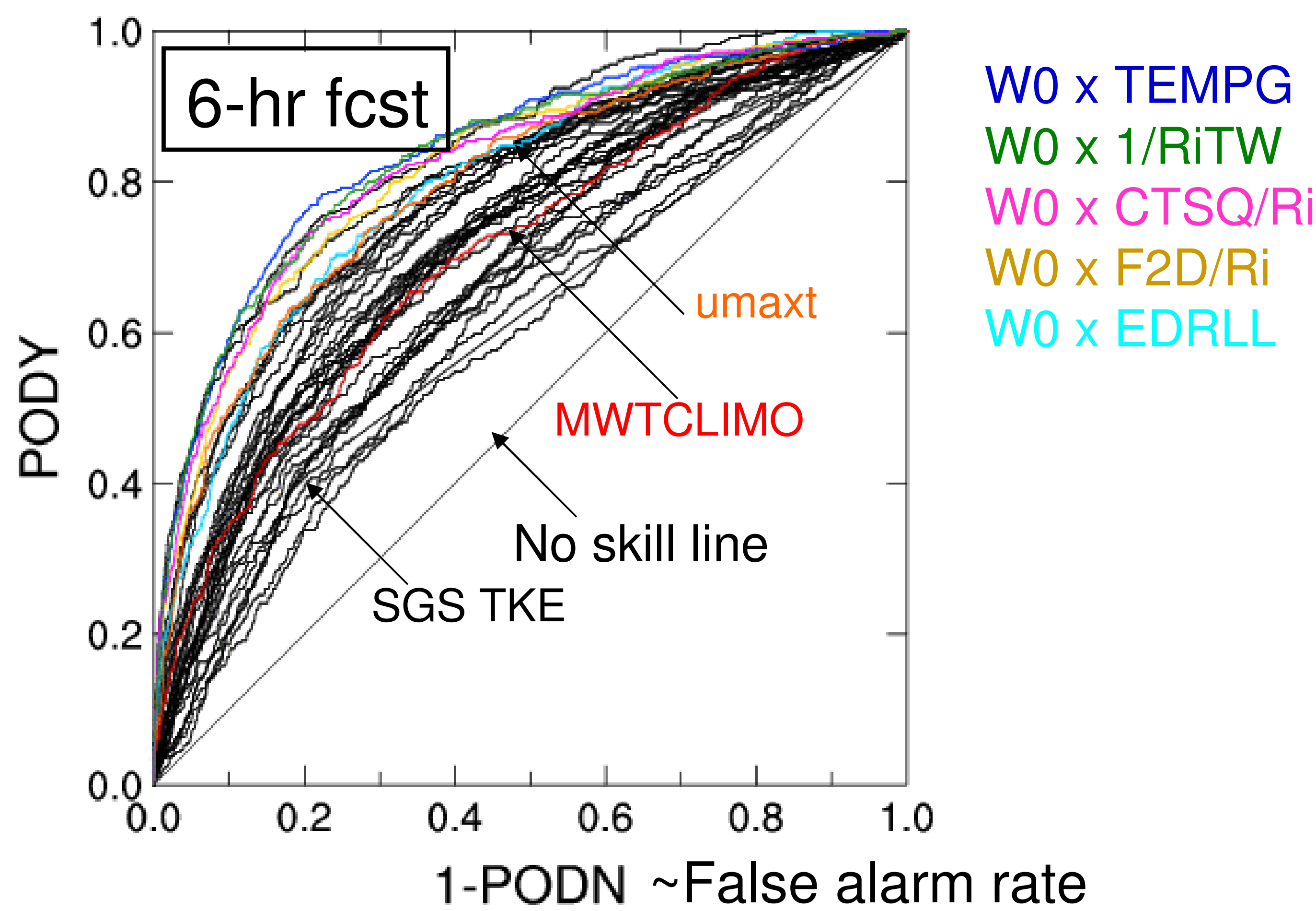
WRF-based null-MOG diagnostic discrimination performance evaluated against MWT PIREPs

15 Nov 2009-
31Aug2010
15Z,18Z
6 hr forecasts from
12,15,18Z
37313 reports
- NULLS + 362 MOG MWT
- 20-45 kft only



High threshold ↔ Low threshold

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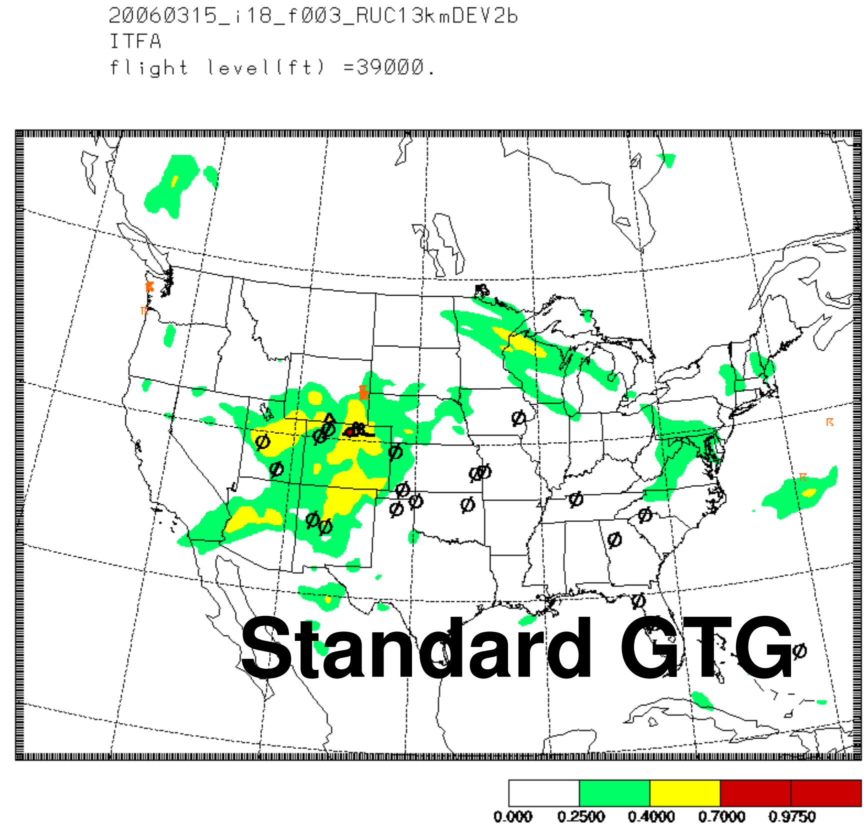
Example1: Mountain Wave GTG3 is Combination of GTG and



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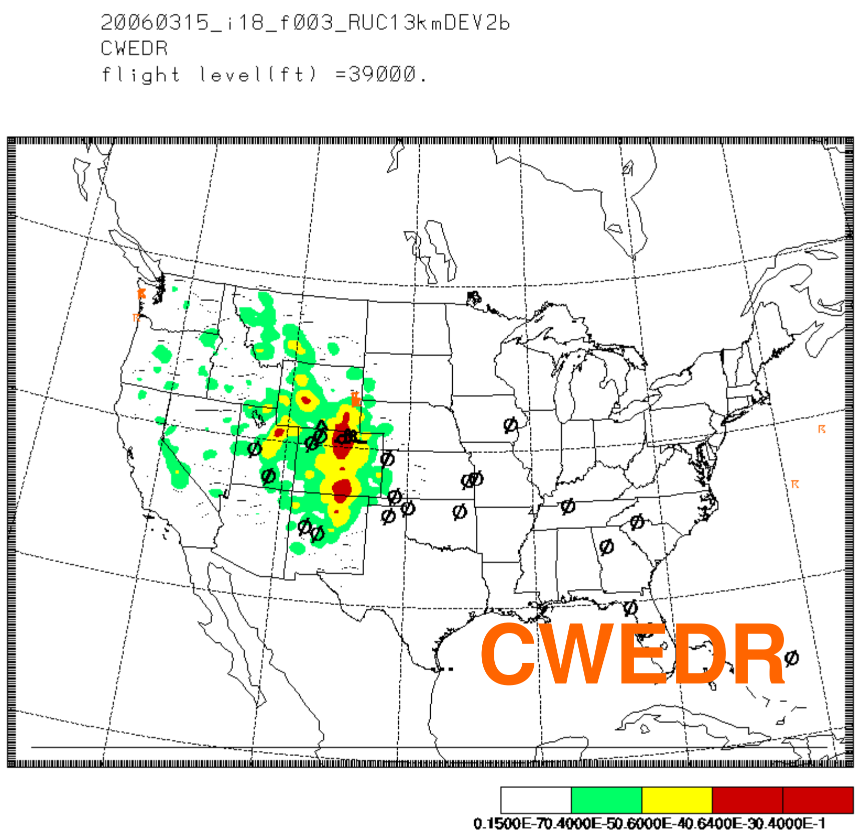

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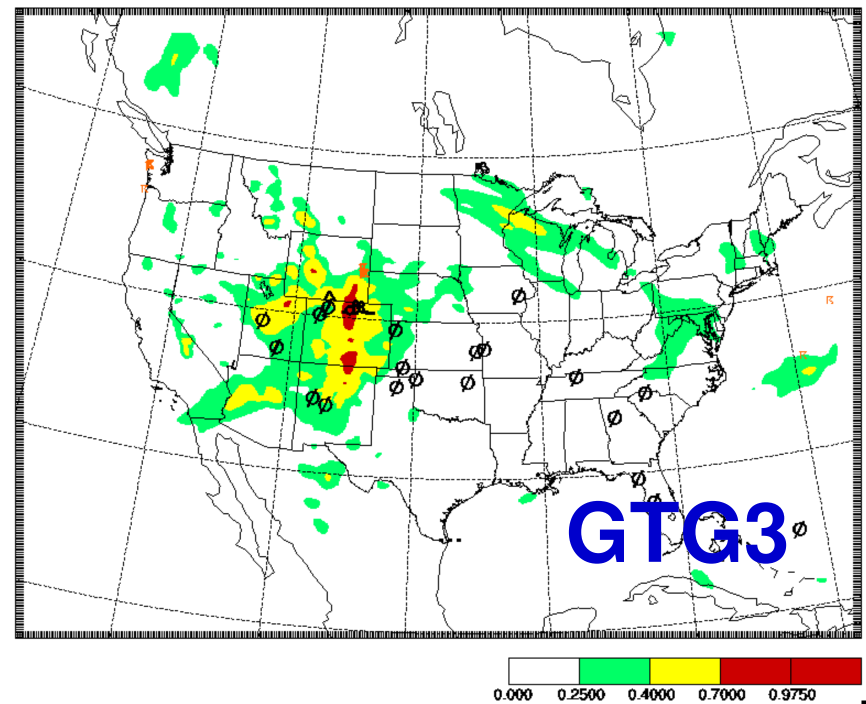

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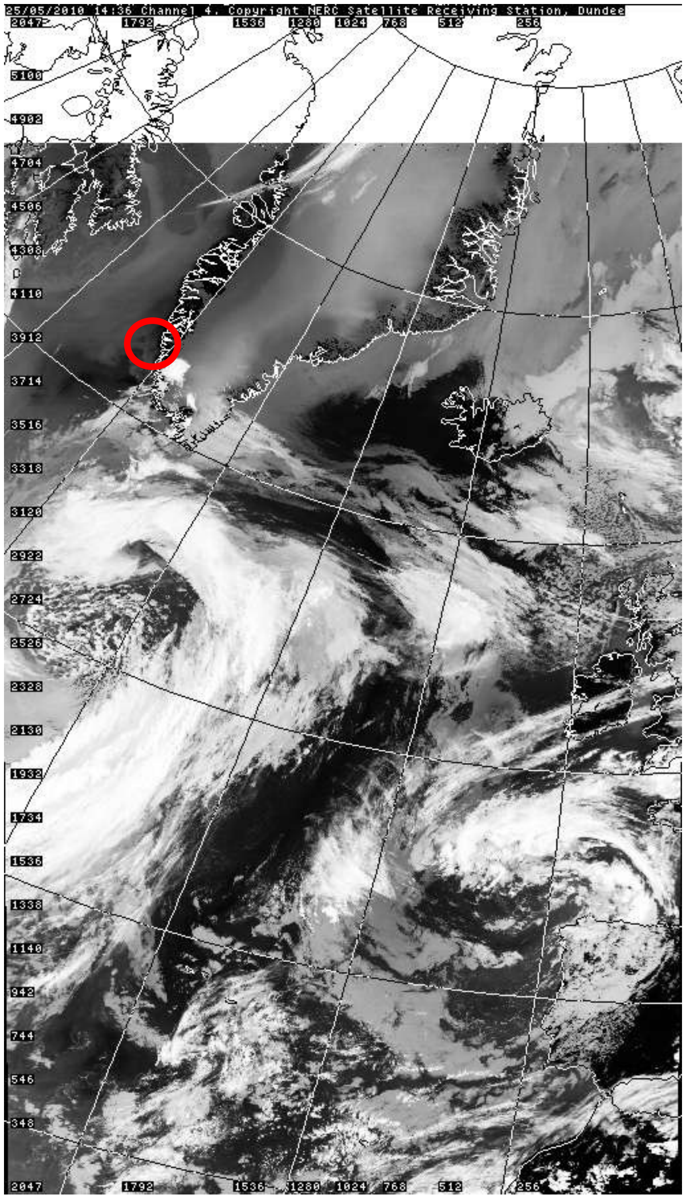
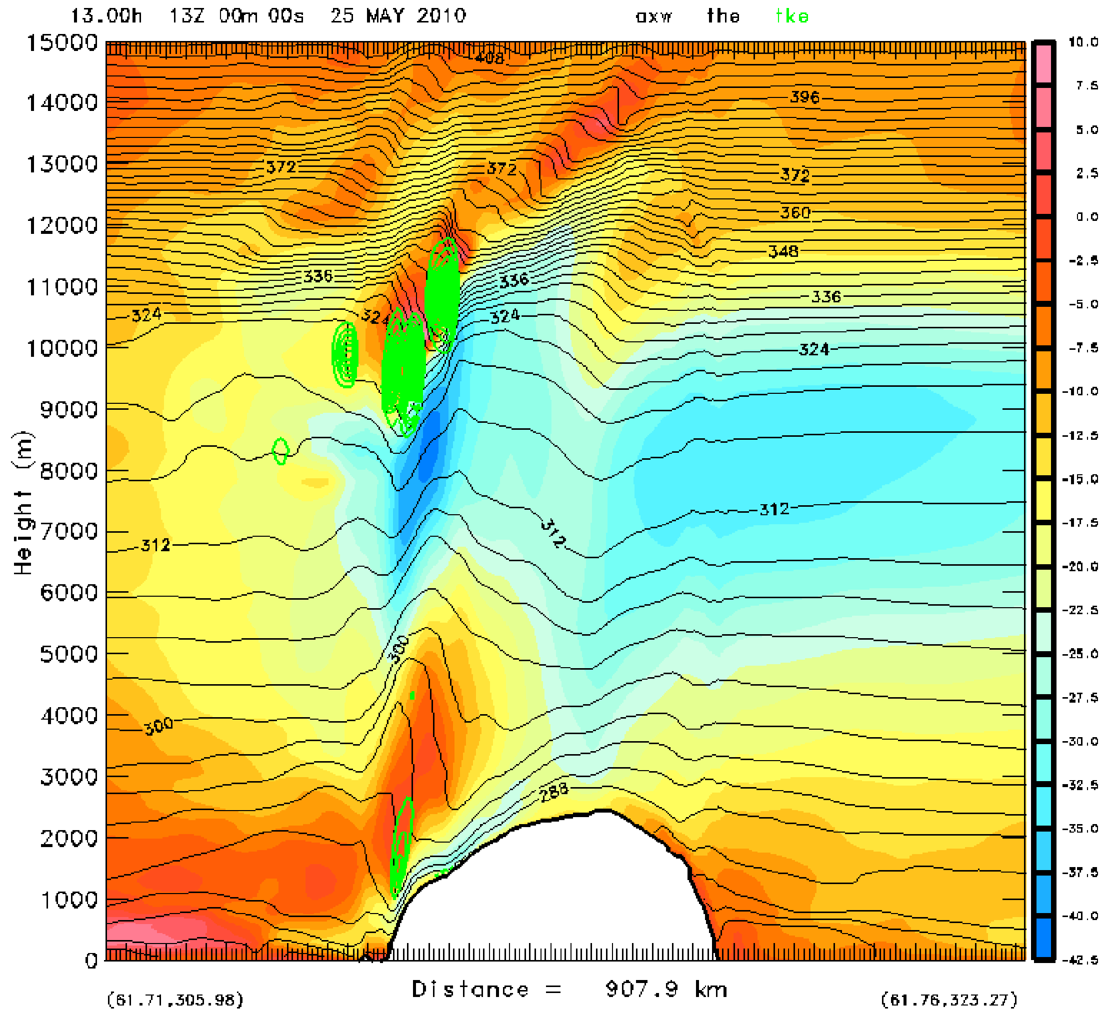
Example 2: B777 on 25 May 2010 1305 UTC over western Greenland





Courtesy Jim Doyle, NRL Monterey

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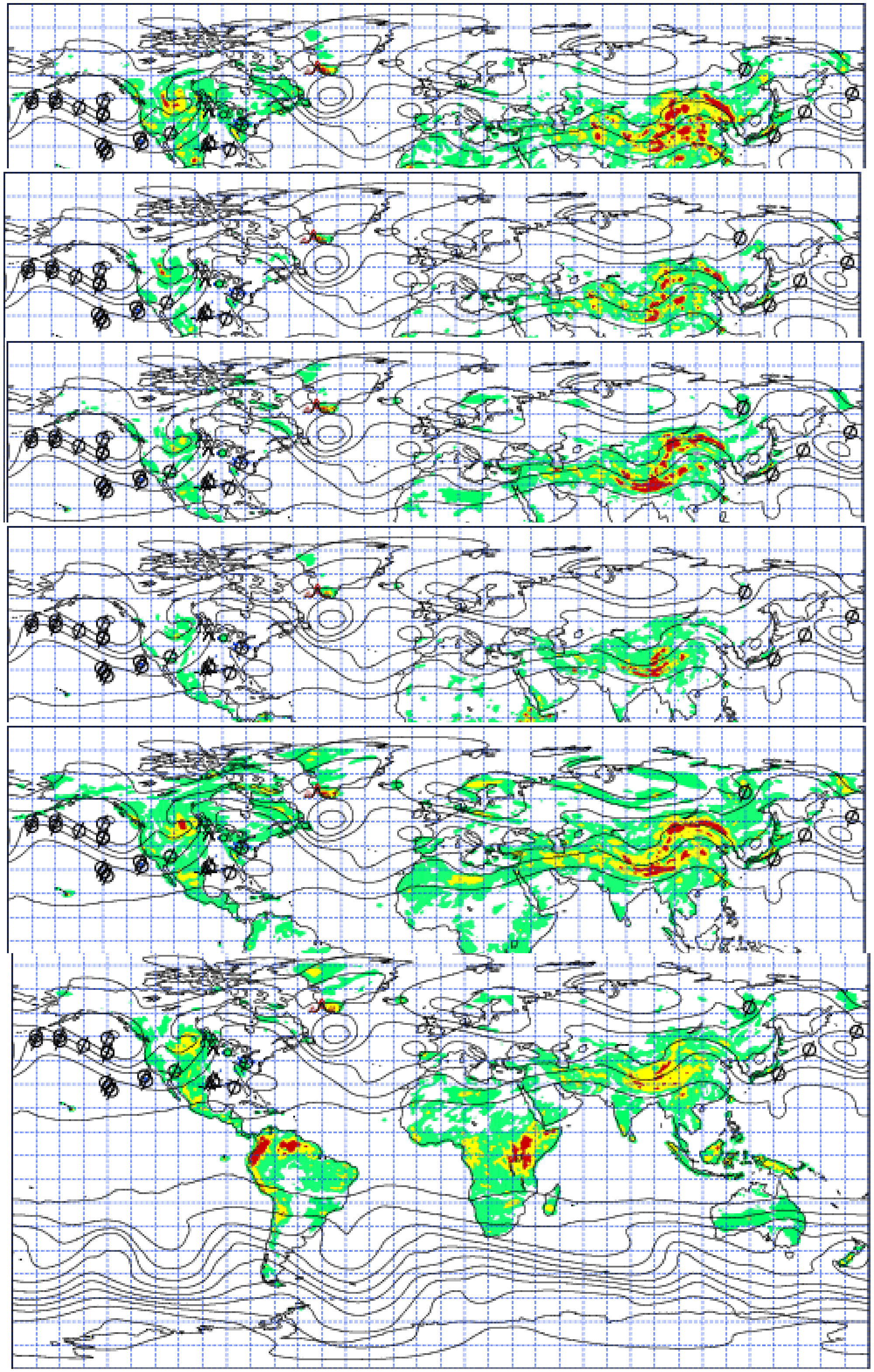
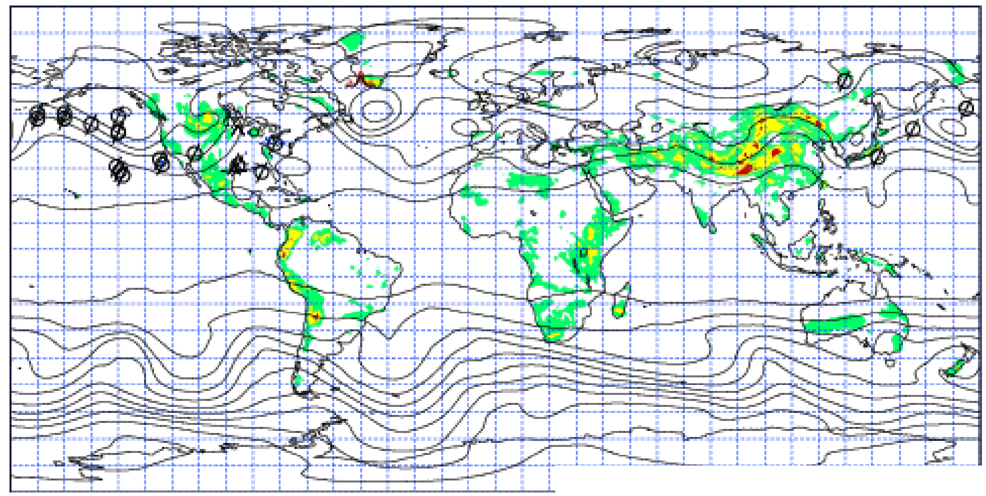
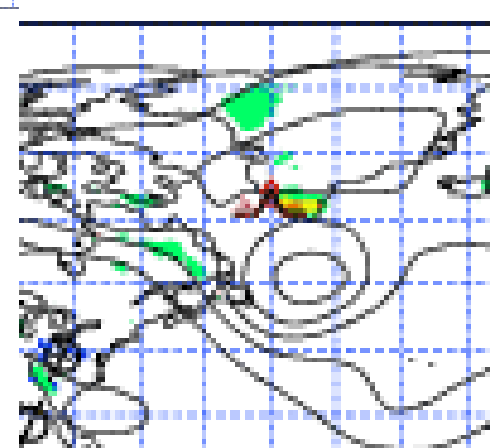
Example 2: Empirical approach: Greenland case: 6 MWT diagnostics (lt) + consensus (rt.)





6-hr fcst
valid 12Z



Conclusions

- For near-term applications, empirically based diagnostics can provide useful forecasts of MWT
- For WRF, based on comparisons to MWT pireps, best discriminators for null vs MOG turbulence are:
  - Best single 2D diagnostic = Umax (in lowest 1500 m)
  - Best 3D diagnostics

    |wmax| (in lowest 1500m) x terrain ht x

    1. C_T^2
    2. Frontogenesis fun
    3. EDR
    4. $|\Delta T|$
    5. div
    6. σ_w
- Not so good discriminators are
  - Existence of critical level
  - PIREPs-derived MWT climatology
  - Model-produced SGS TKE GWD parameterizations

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Backups

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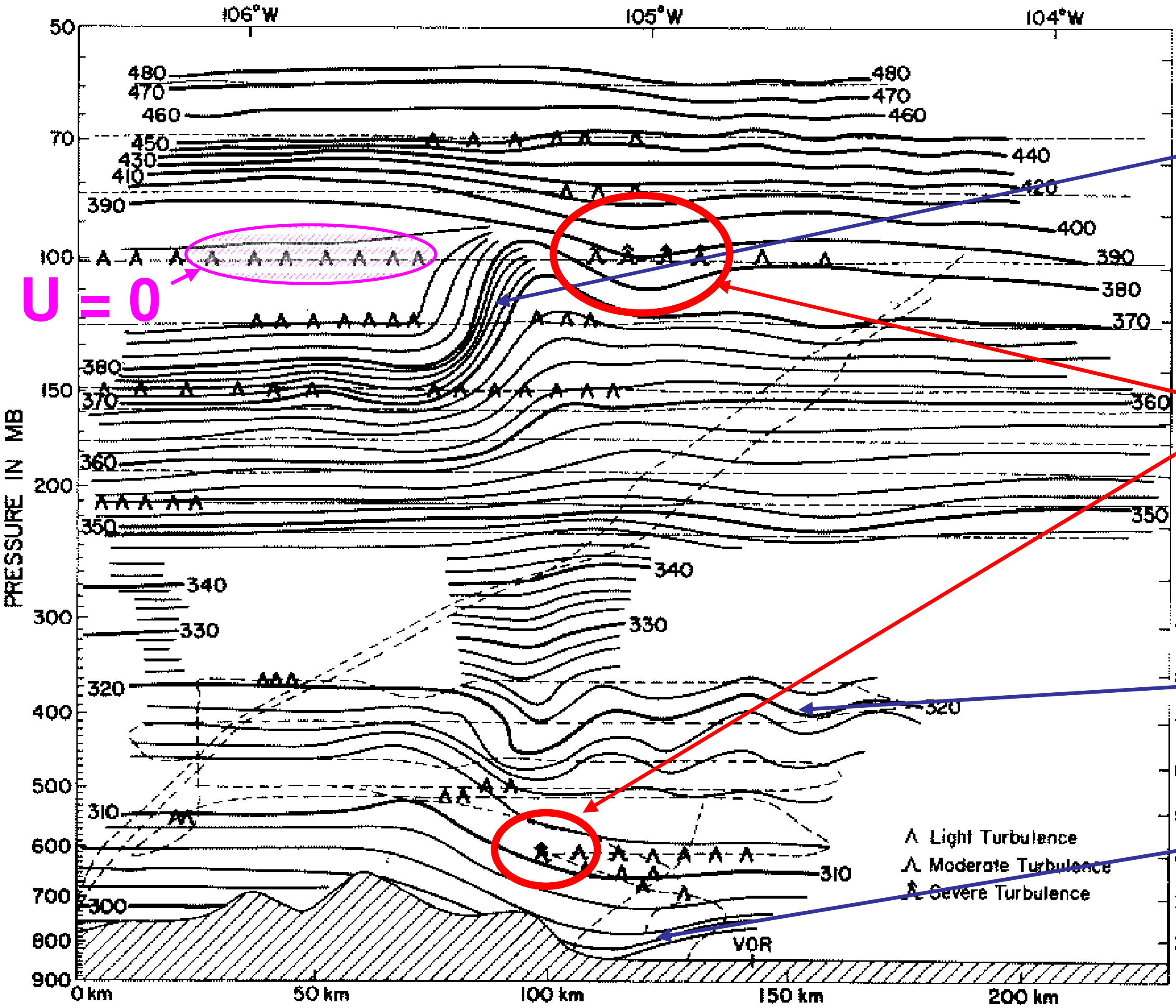
Observations of Mountain Wave Turbulence



steepening of waves leading to wave breaking and turbulence

Regions of severe turbulence

trapped lee waves

High surface winds

Potential temperature cross-section over the Rocky mountains on 17 February 1970. Solid lines are isentropes (K), dashed lines aircraft or balloon flight trajectories (from Lilly and Kennedy 1973)

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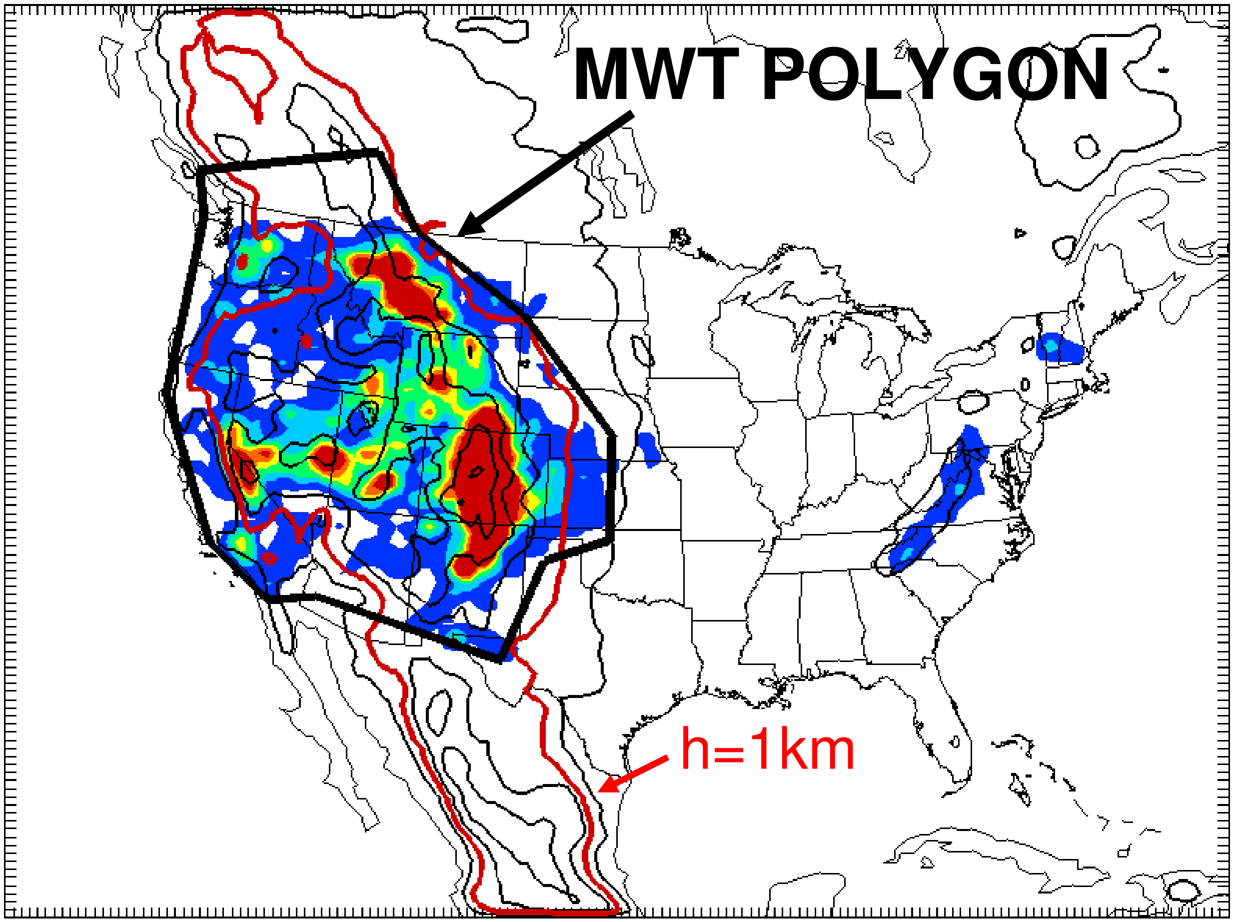
MWT Pireps climatology over U.S.



 # MWT MOG PIREPs
sfc-60,000 ft
1993 – 2007 (15 yrs)

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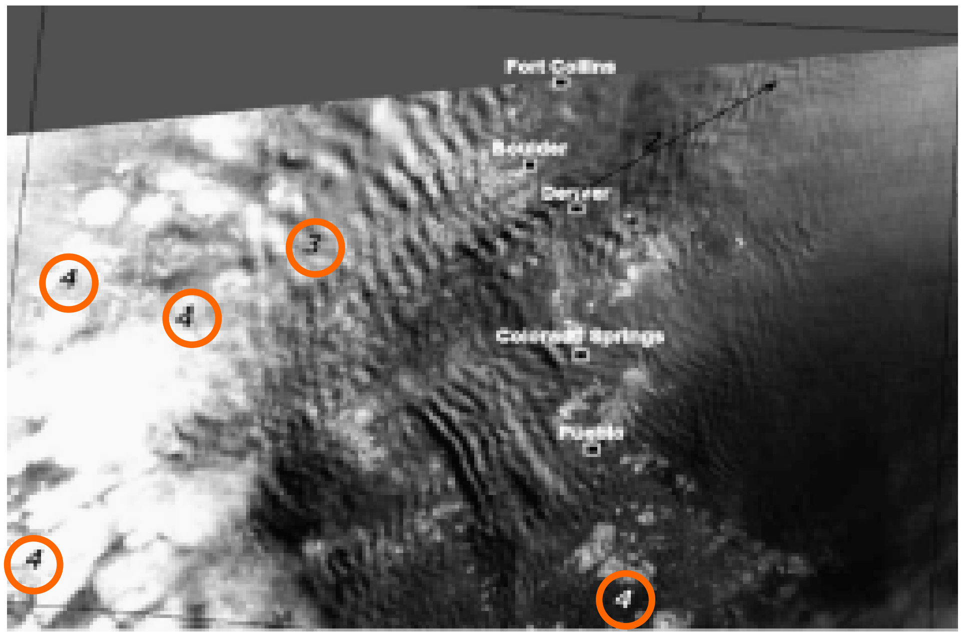
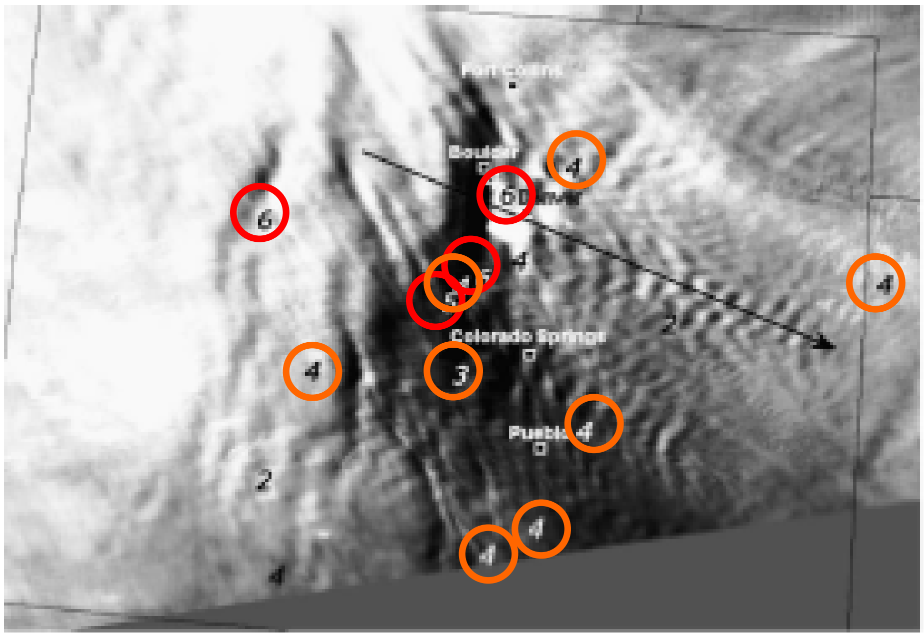
Another possible MOG discriminator: Wave pattern complexity?

Some evidence that turbulence may be related to complexity of lee wave pattern as observed in satellite imagery (Uhlenbrock et al.,2007)



Simple wave pattern
3 Sep 2004 2010 UTC



Complex wave pattern
6 Mar 2004 1950 UTC

MODIS WV (6.7 u) imagery Courtesy Wayne Feltz, CIMSS/SSEC, UW Madison

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