A new approach to forecasting mountain wave induced Clear Air Turbulence

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Overview

Background: Forecasting mountain wave induced turbulence for aviation

A new diagnostic for predicting Mountain CAT

Verifying the new Mountain CAT predictor

Conclusions
Forecasting mountain wave turbulence for aviation

- Atmospheric turbulence encountered in commercial aviation – cause of most weather-related aircraft incidents
- Mountain wave breaking in the lower stratosphere is one of the major causes of it
- For clear air turbulence (CAT), there are no visual clues – pilots reliant on
  - operational forecasts
  - reports from other aircraft.
- Mountain waves typically sub-grid-scale in global forecast models
- Due to recent developments some NWP models (e.g. UK Met Office Unified Model; MetUM) now able to resolve mountain wave activity explicitly
  - allows forecasts of mountain wave induced turbulence with greater accuracy and confidence than possible before.
Mountain CAT predictors in the MetUM: Parameterized to resolved

Previously: “WAFC CAT predictor” – diagnose mountain wave turbulence from subgrid GW stress diagnosed from orographic drag parameterization scheme. Not ideally fit for purpose as:

- Stress realism limited by simplifications used in drag scheme
- Stress divergence, rather than stress, is associated with wave dissipation and turbulence

Proposed new method:

- latest version of MetUM dynamical core (ENDGame) and increased operational global model resolution (N768 ~17km at mid-latitudes)
- allows significantly improved representation of gravity waves
- Consequent possibility now of turbulence prediction based on model-resolved fields.
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Mountain CAT predictors in the MetUM: A new diagnostic

- Propose a **modified TKE diagnostic** using **model-resolved** fields
- Despite the improvements, the characteristically **fine-scale** phenomenon of mountain wave **breaking** is still unlikely to be resolved by global models
- Grey zone? – likely to resolve waves but under-predict dissipation
- To account for this, the modified TKE diagnostic
  - uses a long tail stability function
  - gives greater mixing ($k_m$) at higher stabilities than unmodified.
Mountain CAT predictors in the MetUM: A new diagnostic

Diagnostic derived via bulk formula based on eddy diffusivity for momentum, $\kappa_m$, as:

$$TKE = \left( \frac{\kappa_m}{lC} \right)^2,$$

where $C$ is a tuneable constant (set to 0.5) and $l$ is mixing length. Modified TKE uses a diagnosed eddy diffusivity which assumes a long tail stability function:

$$f(Ri) = \frac{1}{1 + 10Ri},$$

where $Ri$ is gradient Richardson number. $\kappa_m$ is then defined as

$$\kappa_m = l^2 S f(Ri),$$

where $S$ is modulus of vertical wind shear.
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Methodology for verifying new diagnostic

Use automated commercial aircraft turbulence reports as observations (Global Atmospheric DataSet – GADS)

- over Greenland (mountain wave induced turbulence an identified hazard in this region)
- Derived Equivalent Vertical Gust (DEVG) metric
- Light / Moderate / Severe turbulence categories

Two approaches:

- **Case studies**
  - May 2010 Severe (Sharman et al. 2012)
  - GADS Moderate, widespread
  - GADS Severe, strong shear

- **Long-term verification** (17-month)
Severe Localised Turbulence
Case study

Wave-induced critical level breaking -- momentum deposition interacts with mean flow

Case details see Sharman et al. 2012
GADS Moderate Case

Tracks: No turbulence, Light, Moderate, Severe

Peak turbulence report height
GADS Severe Case

Shear-induced critical level breaking -- flow direction northerly to southerly

Wind vectors and $w$ at PTR height (9.1km)

Isentropes and $w$

Height (km)

Distance from obs (km)

TKE at PTR height (9.1km)

Isentropes and TKE

Height (km)

Distance from obs (km)

WAFC CAT at 250 hPa (~9.8 km)
Long-term verification: method

GADS reports

• over Greenland
• 17 month period (1st August 2014 to end December 2015).

Corresponding **model diagnostics:**

• closest forecast time, and must be within one hour of each report
• averaged over area within 100 km (radius) and over depth +/- 2 km of each report

Evaluated for:

• **All turbulence** reports:
  482 reports (16 of which moderate to severe)
• **1 % of no-turbulence** reports:
  2124 reports
## Long-term verification: results

### Number of reports and Mean TKE$_{mean}$

<table>
<thead>
<tr>
<th></th>
<th>No turbulence</th>
<th>Light turbulence</th>
<th>Moderate-severe turb.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of reports</td>
<td>2124</td>
<td>466</td>
<td>16</td>
</tr>
<tr>
<td>Mean TKE$_{mean}$</td>
<td>0.04</td>
<td>0.52</td>
<td>0.91</td>
</tr>
</tbody>
</table>

**Hit rate** = likelihood of detection = Hits / (Hits + Misses)

**False alarm rate** = FalseAlarms / (Hits + FalseAlarms)

Aim to **maximise hit rate** and **minimise false alarm rate**

### Forecast vs. Turbulence Reported

<table>
<thead>
<tr>
<th>Forecast</th>
<th>Turbulence Reported</th>
</tr>
</thead>
<tbody>
<tr>
<td>True</td>
<td>False</td>
</tr>
<tr>
<td>True</td>
<td>HIT</td>
</tr>
<tr>
<td>False</td>
<td>MISS</td>
</tr>
</tbody>
</table>
Define \[ \text{report} = 1 \] where \( \text{DEVG} \geq 2 \)
Define \[ \text{forecast} = 1 \] TKE threshold so that \textbf{hit rate} \( \geq 80 \% \)

Using mean TKE (within cylinder):

<table>
<thead>
<tr>
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<th>Reported 1 (DEVG ( \geq 2 ))</th>
<th>Reported 0 (DEVG &lt; 2)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Forecast 1 (TKE ( \geq 0.085 ))</td>
<td>386 (15 %)</td>
<td>237 (9 %)</td>
</tr>
<tr>
<td>Forecast 0 (TKE &lt; 0.085)</td>
<td>96 (4 %)</td>
<td>1887 (72 %)</td>
</tr>
</tbody>
</table>

\textbf{Hit rate} = 80 \%
\textbf{False alarm rate} = 38 \%
Conclusions

- Modern global NWP models are capable of representing a sufficient proportion of the gravity-wave spectrum to allow mountain wave CAT to be **directly diagnosed** from model **resolved wave** motions.

- TKE diagnostic has
  - demonstrated skill in predicting mountain CAT
  - superior skill compared with current operational product.