Use of inverse and ensemble modelling techniques for improved volcanic ash forecasts

Meelis Zidikheri, Richard Dare, Rodney Potts, and Chris Lucas

*Australian Bureau of Meteorology*
Aim is to highlight ongoing research at the Australian Bureau of Meteorology focussed on improving volcanic ash forecasts by

- quantifying uncertainties in meteorological fields using ensembles
- improving the ash source term and quantifying uncertainties thereof using satellite observations

Will use the 13 February 2014 eruption of Kelut in Java, Indonesia, as a case study
13 February 2014 Kelut eruption

Eruption commenced ~ 1600 UTC

• CALIPSO identifies ash at over 18 km with stratospheric ash reaching over 25 km
• How well can we forecast the locations of ash over 24 hours or so using meteorological ensembles?
• Can we deduce the ash profile using the MTSAT ash distribution alone?
Dispersion ensemble prediction system

- Makes use of the Bureau's global ensemble model
  - Based on UK Met Office MOGREPS model
  - Employs ETKF and stochastic physics to generate perturbations
  - 24 ensemble members
- HYSPLIT run with each ensemble member to produce ensemble ash forecast
- Line source employed to 19 km
6-24 hour forecasts

Inverse modelling approach for source term

In the new paradigm observations are directly integrated into the modelling process using an inverse model.
Inverse modelling algorithm

- A grid of all possible values of the model parameters (represented by \( p \)) is formed.
- Pattern correlations are used as a measure of model agreement with observations for all gridded parameter values:
  \[
  r(p) = \frac{\sum_{i=1}^{N}(x_i(p) - \bar{x}(p))(y_i - \bar{y})}{\sqrt{\sum_{i=1}^{N}(x_i(p) - \bar{x}(p))^2 \sum_{i=1}^{N}(y_i - \bar{y})^2}}
  \]
- In the deterministic scheme, parameters yielding highest pattern correlations are chosen as the solution.
- In the probabilistic scheme, parameters yielding pattern correlations above a specified threshold are chosen as members of the solution ensemble.
Source top estimation

Line source extending from summit with uniform mass distribution

Variable top altitude
Inverse model results (source top)

<table>
<thead>
<tr>
<th>Time (UTC)</th>
<th>1630</th>
<th>1730</th>
<th>1830</th>
<th>1930</th>
<th>2030</th>
<th>2130</th>
<th>2230</th>
</tr>
</thead>
<tbody>
<tr>
<td>Top altitude (km)</td>
<td>20.0</td>
<td>23.0</td>
<td>28.0</td>
<td>29.0</td>
<td>22.0</td>
<td>24.0</td>
<td>24.0</td>
</tr>
<tr>
<td>Pattern corr.</td>
<td>0.84</td>
<td>0.76</td>
<td>0.72</td>
<td>0.77</td>
<td>0.79</td>
<td>0.78</td>
<td>0.71</td>
</tr>
</tbody>
</table>

Scaled pattern correlation

1830 UTC analysis

Discrete probability distribution

2230 UTC analysis
Source base estimation

Line source with non-uniform mass distribution

Fixed top altitude

Variable base altitude
Using inverse model to infer source base altitude

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<th>2030</th>
<th>2130</th>
<th>2230</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bottom altitude (km)</td>
<td>6.0</td>
<td>6.0</td>
<td>8.0</td>
<td>7.0</td>
<td>7.0</td>
<td>7.0</td>
<td>8.0</td>
</tr>
<tr>
<td>Pattern corr.</td>
<td>0.88</td>
<td>0.78</td>
<td>0.78</td>
<td>0.82</td>
<td>0.82</td>
<td>0.81</td>
<td>0.75</td>
</tr>
</tbody>
</table>

1830 UTC analysis

2230 UTC analysis
### Two-dimensional inversion

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<th>2130</th>
<th>2230</th>
</tr>
</thead>
<tbody>
<tr>
<td>Base altitude (km)</td>
<td>8.0</td>
<td>6.0</td>
<td>8.0</td>
<td>6.0</td>
<td>6.0</td>
<td>8.0</td>
<td>8.0</td>
</tr>
<tr>
<td>Top altitude (km)</td>
<td>20.0</td>
<td>24.0</td>
<td>22.0</td>
<td>26.0</td>
<td>26.0</td>
<td>22.0</td>
<td>26.0</td>
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<tr>
<td>Pattern corr.</td>
<td>0.89</td>
<td>0.79</td>
<td>0.78</td>
<td>0.82</td>
<td>0.82</td>
<td>0.81</td>
<td>0.75</td>
</tr>
</tbody>
</table>

1830 UTC analysis

2230 UTC analysis

![Image](image1.png)

![Image](image2.png)
Umbrella cloud

Line source

100 km 'disc'

200 km 'disc'

Vary source altitude and diameter
# Umbrella cloud 2D inverse model

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<th>2130</th>
<th>2230</th>
</tr>
</thead>
<tbody>
<tr>
<td>altitude (km)</td>
<td>18.0</td>
<td>18.0</td>
<td>18.0</td>
<td>18.0</td>
<td>18.0</td>
<td>18.0</td>
<td>18.0</td>
</tr>
<tr>
<td>Diam. (km)</td>
<td>100.0</td>
<td>250.0</td>
<td>250.0</td>
<td>250.0</td>
<td>250.0</td>
<td>200.0</td>
<td>150.0</td>
</tr>
<tr>
<td>Pattern corr.</td>
<td>0.82</td>
<td>0.84</td>
<td>0.83</td>
<td>0.80</td>
<td>0.87</td>
<td>0.83</td>
<td>0.74</td>
</tr>
</tbody>
</table>

![1830 UTC](image1.png)

![2230 UTC](image2.png)
Ash forecasts (14/0630 UTC) from 13/1830 UTC analyses compared

Forecasts of ash probabilities at 14/0630 UTC based on different analyses at 13/1830 UTC
Conclusion

- Have shown that the meteorological ensemble increases spread of ash forecasts, leading to better agreement with observations.
- Have shown that top altitude of ash column can be estimated quite well with inverse model – generally > 20 km consistent with CALIPSO.
- Have shown that low-altitude cut-off can also be estimated – generally about 6-8 km here – which is a crude model of non-uniform vertical emission rates.
- Have shown that the inversions can be performed simultaneously i.e. 2D inversion.
- Have shown that umbrella cloud span (diameter) may be estimated. Generally > 100 km in this case.
- Have demonstrated the importance of quantifying uncertainties via a probabilistic description.
Future work

• Integrate inverse modelling of source term with meteorological ensemble model

• Introduce continuous variations into emission profile by making use of VOLCAT mass loading retrievals

• Estimate optimal particle size distributions

• ETC
Thank you…

Presenter's name: Dr Meelis J. Zidikheri
Presenter's phone number: +61 03 9669 4427
m.zidikheri@bom.gov.au