Modelling clouds for weather, climate and beyond...

Ian Boutle
+ many collaborators...
Computer models used for weather forecasts and climate simulations need to represent all of this complexity.

BUT, they need to do so in a very efficient manner...
The forecast problem

• Core of the model solves the Navier-Stokes equations
• Must discretise these onto a finite-difference grid to solve

• Weather forecasts take 30-60 minutes (of computer time)
  • Anything shorter, you may as well do things better
  • Anything longer ceases to be a forecast

• Current global forecast model runs on 4752 processors
  • New supercomputer (Cray XC40) installed in 2016

• So to fit a 7-day forecast into those resources, we can afford 2560 x 1920 x 70 grid points – approx 10km horizontal resolution!

\[
\frac{Du}{Dt} = -2\Omega \times u - \frac{\nabla p}{\rho} + g + S^u \\
\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \mathbf{u}) = 0 \\
\frac{D\theta}{Dt} = S^\theta \\
p = \rho RT
\]
Many processes exist on a scale <10km, but have an important influence on the weather or climate:

- Clouds and precipitation
- Turbulence
- Radiation
- Orography (hills and valleys)
- Surface characteristics (trees, grassland, buildings, ocean)

The “bulk” effect of these processes, at the grid-scale, needs to be included in the governing equations via source/sink terms.

Parametrizations compute these source/sink terms.

Some processes (e.g. Turbulence) only need parametrizing because of the resolution of the model, whilst others (e.g. Radiation) will always be needed.
1. Very high-resolution modelling for aviation at Heathrow airport
2. Cloud parametrization improvements for the latest climate model
3. Beyond Earth – adapting the model for exoplanet atmospheres
1. Very high-resolution modelling for aviation at Heathrow airport
Heathrow and fog

• Heathrow is one of the busiest airports in the world – runs at ~99% capacity
• When visibility is low, space between aircraft must be increased -> lower capacity -> cancelled flights
• 75% of delays are weather related, half of this is due to low visibility
• Very expensive + lots of grumpy passengers
• With accurate forecasts, can plan ahead to mitigate the effects
• How can we improve our forecast accuracy?
Don’t just run 10km global model
Region of interest is UK, so nest a 1.5km model inside this
HUGE benefit in detail and accuracy
What if we added another level?
The London Model

- Enhanced detail in terrain features, land-surface characteristics
- Better resolution of atmosphere
- Less reliance on parametrizations

Boutle et al. (2016, QJRMS)
An example from last winter:
Not just an HD picture

• The enhanced resolution genuinely alters the evolution of the fog
• Why?

Boutle et al. (2016, QJRMS)
Smoothed terrain

- Use the lower resolution orography field from the UKV in the LM, gives big change in fog evolution

*Boutle et al. (2016, QJRMS)*
A turbulence feedback

- Rougher terrain strongly affects the near surface wind field
- This extra variability in the wind-shear affects the structure of the atmosphere:
  - More turbulent
  - Extra turbulence mixes warmer air down from aloft
  - Warmer air prevents fog formation
- A genuine benefit of higher resolution, but could we parametrize it at lower resolution?

Boutle et al. (2016, QJRMS)
2. Cloud parametrization improvements for the latest climate model
Clouds and climate

- Clouds represent the single biggest uncertainty in climate models.
- How they respond to a warming climate could EITHER significantly reduce the amount of warming OR significantly increase it!
- Hence a strong requirement to improve their modelling.

### Radiative Forcing by Emissions and Drivers

<table>
<thead>
<tr>
<th>Emitted Compound</th>
<th>Resulting Atmospheric Drivers</th>
<th>Radiative Forcing by Emissions and Drivers</th>
<th>Level of Confidence</th>
</tr>
</thead>
<tbody>
<tr>
<td>CO₂</td>
<td>CO₂</td>
<td>1.08 (1.33 to 2.03)</td>
<td>VH</td>
</tr>
<tr>
<td>CH₄</td>
<td>CO₂, H₂O, O₃, CH₃</td>
<td>0.97 (0.74 to 1.20)</td>
<td>H</td>
</tr>
<tr>
<td>Halocarbons</td>
<td>HFCs</td>
<td>0.18 (0.01 to 0.35)</td>
<td>H</td>
</tr>
<tr>
<td>N₂O</td>
<td>N₂O</td>
<td>0.17 (0.13 to 0.21)</td>
<td>VH</td>
</tr>
<tr>
<td>CO</td>
<td>CO₂, O₃</td>
<td>0.23 (0.16 to 0.30)</td>
<td>M</td>
</tr>
<tr>
<td>NMVOC</td>
<td>CH₄, O₃</td>
<td>0.10 (0.05 to 0.15)</td>
<td>M</td>
</tr>
<tr>
<td>NO₃</td>
<td>Nitrate, CH₄, O₃</td>
<td>-0.15 [-0.34 to 0.03]</td>
<td>M</td>
</tr>
<tr>
<td>Aerosols and precursors</td>
<td>Nitrate, Organic Carbon, Black Carbon</td>
<td>-0.27 [-0.77 to 0.23]</td>
<td>H</td>
</tr>
<tr>
<td>Cloud Adjustments due to Aerosols</td>
<td></td>
<td>0.95 [1.33 to 0.36]</td>
<td>L</td>
</tr>
<tr>
<td>Albedo Change due to Land Use</td>
<td></td>
<td>-0.15 [-0.23 to -0.09]</td>
<td>M</td>
</tr>
<tr>
<td>Natural Changes in Solar Irradiance</td>
<td></td>
<td>0.05 [0.00 to 0.10]</td>
<td>M</td>
</tr>
</tbody>
</table>

**IPCC AR5**

**Radiative Forcing relative to 1750 (W m⁻²)**

- 2011: 1.25 [0.64 to 1.95] (H)
- 1980: 0.57 [0.29 to 0.89] (M)
- 1950: 0.26 [1.13 to 3.33] (H)
Existence and effect in the climate system

Low clouds are the most prevalent cloud type on the planet. They provide a cooling to the climate system. Whether there are more (wetter) or less (warmer) of them could create a negative or positive feedback.
Why is modelling low clouds so difficult?

- Combination of many different physical processes
- Most of which are parametrized
- Fundamental physics of many is poorly understood

Wood (2012, MWR)
“Dreary” state of precipitation in climate models

- CloudSat sees the cloud and precipitation falling below it
- Higher reflectivity -> bigger drops

Californian Stratocumulus - DJF 2006

- Continuous transition from cloud to rain

- Not unique to our model!

Bodas-Salcedo et al, (2008, JGR)
Equations for droplet growth are well known and understood – easy to solve

Each grid-box contains a spectrum of particles of different sizes

Could model each different sized particle explicitly – bin scheme (too expensive ~30+ prognostic variables)
• Hence have to assume a size distribution of particles and integrate over it – bulk scheme (2 prognostic variables, cloud water & rain water)

• Assume the number of rain-drops \( N \) is related to their diameter \( D \) by:

\[
N(D) = N_0 \exp(-\lambda D)
\]

• Most models use Marshall & Palmer (1948):

\[
N_0 = 8 \times 10^6
\]

• Doesn’t appear to match reality very well…

\[Abel & Boutle (2012, QJRMS)\]
Relationship between $N_0$ and rain-rate

- Many in-situ aircraft observations + surface radar/lidar/distrometer observations
- Suggests a relationship between $N_0$ and $\lambda$:

$$N_0 = 0.22 \lambda^{2.2}$$

- $\lambda$ is a physical quantity, related to the total mass of rain

$$N_0 = 8 \times 10^6$$

Abel & Boutle (2012, QJRMS)
How precipitation physics depends on this

- Evaporation of rain-drops
  - Old-method under-estimated the evaporation rate
  - New-method greatly improves this

- Fall-speed of rain-drops
  - Old-method over-estimated the fall-speed
  - New-method greatly improves this

Abel & Boutle (2012, QJRMS)
Rain creation processes

- Conversion of cloud to rain treated by a simple power-law:
  \[
  \frac{\partial (q_{rain})}{\partial t} = C(q_{cl})^A (N_d)^B
  \]

- \(q_x\)=mass of cloud/rain, \(N_d\)=number of cloud droplets

- \(A, B \& C\) are empirically determined constants

- Old scheme (TC) over estimated rain-creation compared to observations – replace with new scheme (KK)

Wood (2005, JAS)
Do we understand this?

Continuous transition from cloud to rain

Two distinct modes – one for cloud, one for rain

- Model over-estimates rain creation, over-estimates rain fall-speed, under-estimates rain evaporation...
- Un-surprising that there is excessive rain and two distinct modes.
Zoom in on the low cloud

(b) 03 UTC, 13 November 2008

(d) 03 UTC, 13 November 2008

Obs

Old Model

Boutle & Abel (2012, ACP)
Zoom in on the low cloud:

- Slower rain-creation lowers the peak reflectivity produced as rain is forming.

- Slower fall-speed and more evaporation stops fast falling to the surface and gives reduction in reflectivity below cloud.

Boutle & Abel (2012, ACP)
• Old climate model actually gave the correct mean surface rain-rate
• Cloud processes are highly nonlinear, so increasing model resolution increases the surface rain-rate (to excessive amounts)
But... There’s a problem

• What I’ve just showed you was fixing the high-resolution version

• Applying the same thing at low resolution would significantly under-estimate the rain-rate!

*Boutle et al. (2014, MWR)*
Back to rain creation

• Already showed earlier that rain creation is parametrized as:
  \[ \frac{\partial (q_{\text{rain}})}{\partial t} = C(q_{\text{cl}})^A (N_d)^B \quad \text{OR} \quad M = aq^b \]
  For simplicity

• In a climate model, we want the grid-box averaged process rate (M), but only have the grid-box averaged q

• Hence for \( b \neq 1 \):
  \[ \bar{M} = a\bar{q}^b \neq a\bar{q}^b \]

• This introduces a systematic bias into the model
Analytically correcting the process rates

- Suppose we have some information about the sub-grid distribution of \( q \), e.g. that it can be represented by a log-normal distribution:

\[
P(q) = \frac{1}{\sqrt{2\pi}\sigma q} \exp \left( -\frac{(\ln q - \mu)^2}{2\sigma^2} \right)
\]

- Then we can integrate over the PDF to obtain:

\[
\bar{M} = E(f, b) a \bar{q}^b
\]

\[
f = \frac{\sigma}{\bar{q}}, \quad E(f, b) = (1 + f^2)^{-b/2}(1 + f^2)^{b^2/2}.
\]

- We can improve our estimate of \( M \) by just knowing \( f \) and the PDF shape.
Parameterizing the variability ($f$)

- Variability increases with scale
- Biggest change at smallest scales
- Variability also effected by cloud size (smaller $\rightarrow$ more variable)

Bouffe et al. (2014, QJRMS)
Process rate bias

- At a given scale (here ~50km), compute the exact process rate from high-resolution data, and the process rate based on mean inputs.
- Exact rate is under-estimated by a factor of ~4.
- Correction is almost exact using PDF method and observed \( f \).
- And very good using parametrized \( f \).

*Boutle et al. (2014, QJRMS)*
• Now the rain rate is approximately constant, regardless of resolution!

Problem solved!

Boutle et al. (2014, MWR)
New climate model

- Include these changes in the new climate model
- Transition of cloud to rain is significantly improved
- Greater confidence that model is doing the right thing for the right reason

Walters et al. (2017, GMD)
3. Beyond Earth – adapting the model for exoplanet atmospheres
Diversity of the universe

• In the early 1990’s, the first planet orbiting a star other than the sun was found
• Since then, 3584 such planets have been found:
  • 1418 Neptune-like
  • 1205 Gas giant (Jupiter-like)
  • 883 Terrestrial (Earth-like)
  • 53 Super-earth (somewhere between Earth and Neptune)
• Modelling provides a method of interpreting the (limited) observations, understanding the planetary universe, and hunting for life...
Hot Jupiters

- Best observed – large gas giants orbiting very close to parent star – tidally locked – same side always facing the star
- Some observations of temperature (~1000 K) and wind-speed (~5000 m/s)
- Change the stellar-spectra and planetary parameters (orbit, mass, radius, ...) and the model can produce a credible simulation of this environment!
- Raises all sorts of further questions about structure of the atmosphere - at this temperature metal species (e.g. TiO$_2$) will condense

Cloudy exoplanets

- Couple model to metallic cloud formation code developed at St Andrews University
- Produce simulated observations from model and compare to actual observations
- Cloudy model is better fit than clear sky, but differences suggest the physics is still incomplete
- Role of chemistry?

Terrestrial planets

• The holy-grail, but observations currently limited to “it’s this big, in this orbit” – nothing about structure or composition of atmosphere
• Doesn’t stop us speculating!
• E.g. Proxima Centauri B - ~Earth mass planet orbiting our nearest star
• Given an Earth-like atmosphere (N$_2$, CO$_2$, H$_2$O), modelling suggests planet would have temperate climate and liquid water

*Boutle et al. (2017, A&A)*
How might we know?

- Plenty of interesting science that can be done studying the climate of such a planet
- Key question though is how would we ever know?
- Again, can produce simulated observables (the kind that could be possible with future telescopes).
- Small changes to the atmosphere can show up the signals of important gases, e.g. Ozone and Oxygen

*Boutle et al. (2017, A&A)*
Conclusions

The same (very large) code can be used for highly detailed simulations of small parts of this planet, to planetary scale simulations of gas-giants many light years away.

Efficiency is a key driver – we’re always doing the best we can with the computer time we have available.