Do we need an Earth-system model for 1-day to 1-year weather prediction?

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Director of Science, Met Office
Improving forecast skill and use
Prediction Timescale vs. Resolution vs. Complexity

from Brown et al, BAMS, 2012
Summary of Met Office global configurations

Seamless physical atmosphere / land

Coupled NWP

Intermediate complexity aerosols

NEMO Ocean / CICE

Complex aerosols

ES processes

Week 1 NWP

Monthly-Seasonal

Year-decades

Hi-res long term climate

Long-term climate
Improving Global NWP Forecasts

500hPa Height Day 3 RMS Error vs. Analyses

12 Month running Average

~2% reduction in RMS error/year
55% over 24 years
Madden Julian Oscillation

Wheeler and Hendon (2003) Index

MJO Bivariate Correlation

CY31r1: Parameterisation of ice supersaturation
CY32r2: McRAD (radiation scheme)
CY32r3: Changes in convective scheme (Bechtold at al. 2008)
CY40r1: Improved diurnal cycle of precipitation
Sudden Stratospheric Warming

SSW index: Difference of temperature at 50hPa between 90N and 60N averaged over all the longitudes
How to move forwards?
General considerations for inclusion of new processes or more complexity

- Complexity we might want to include to be able to forecast new things:
  - Air quality forecasts
  - Seasonal Arctic sea-ice
  - Algal blooms

- Complexity we might want to include to be able to forecast traditional things better:
  - Better ‘traditional’ physics, dynamics etc
  - Aerosols, ice etc in as much as they matter for ‘weather’
Considerations in implementing a new scheme

1. Does it give benefit?
   - Necessary (probably)
   - Not sufficient (definitely)

2. Do we really understand where benefit comes from? Is any additional complexity truly better representing reality (or are we misleading ourselves)?
Understanding where benefit comes from

- Evaluation at detailed process level

- As implemented, is a scheme even doing what we think it is?
  - Numerical issues within scheme (limiters; vertical advection)
  - Are all aspects important or, even when we are using a full complex scheme, are simpler aspects actually dominant?
    - *Cloud fraction (Teixeira, MWR, 2000)*
    - *Strength of turbulent mixing (atmosphere and ocean)*

- Interactions with other parts of models and balancing of complexity
  - How much are we (consciously or subconsciously) compensating for / tuning against errors in other parts of the model (e.g. sea ice cf arctic cloud; detailed microphysics cf Semi-Lagrangian conservation issues)?
  - What does this mean for optimal choices of complexity of individual schemes?
Considerations in implementing a new scheme

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3. What is incremental cost in widest sense - HPC, people, system maintenance overhead, DA issues, trialling or operational scheduling complications?
   • Note potential for negative effective cost if better leverages other timescale effort or wider community effort

4. How does overall cost-benefit look cf other options (opportunity cost)?
Example case study: aerosols
Impact of aerosol complexity

Jane Mulcahy

- Direct & indirect aerosol effects:

Adapted from Haywood & Boucher (2000)

Pre-2007: NWP models assume fixed values for land/sea
2007-2014: Direct effect only uses 3D climatologies
Why go from monthly mean climatologies to prognostic aerosols?

The aerosol optical depth and global NWP model bias in surface SW radiation in W Africa

Mean = 56 Wm$^{-2}$

$\sim$50% due to dust, $\sim$50% due to smoke

Impact of aerosol complexity
Experimental design  
*Mulcahy et al, ACP, 2014*

Experiments run between 2009 and 2011:

• Test the impact of full prognostic (CLASSIC) aerosol scheme in operational-like NWP model

• N320 (~40km) forecasts using 4D-Var DA

**Operational aerosols (used from 2007-2014):**

• Direct effect used 3D speciated time-varying climatologies

• Indirect effects used simple land/sea split:
  • Potential CDNC (land) = 300cm$^{-3}$
  • Potential CDNC (sea) = 100cm$^{-3}$
Impact of aerosol complexity
Experimental design

*Mulcahy et al (2014)*

## Tests (hierarchy approach):

<table>
<thead>
<tr>
<th>Direct Effect</th>
<th>Indirect effects</th>
<th>Aerosol init.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cusack (1998)</td>
<td>Land/sea split (as op)</td>
<td>N/A</td>
</tr>
<tr>
<td>CLASSIC clims (op)</td>
<td>Land/sea split (op)</td>
<td>N/A</td>
</tr>
<tr>
<td>Prognostic CLASSIC</td>
<td>Land/sea split (as op)</td>
<td>Spun up/run free</td>
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<td>Prognostic CLASSIC</td>
<td>Prognostic CLASSIC</td>
<td>Initialised from MACC</td>
</tr>
</tbody>
</table>
Impact of aerosol complexity

Shows good aerosol simulations (dusty AOD)

Mulcahy et al (2014)
Impact of aerosol complexity
Surface SW: Prognostic CLASSIC - Cusack
Mulcahy et al (2014)

Impact of full CLASSIC aerosol scheme on surface SW (W/m²) at day 5 in 1 month of rerun global NWP forecasts (June 2012):
Impact of aerosol complexity
Zonal mean T+120 T errors

- Control has largest errors near surface at high latitude
- Much warmer in test with prognostic aerosol as fewer CCN means less bright cloud
Impact of aerosol complexity
An example of seamless model development

Tom Riddick

- Impact on operational implementation (alongside other model changes)
- High lat improvements obtained from aerosol climatologies
- Lower lat improvements from other changes
Impact of aerosol complexity

Lessons for the reader

- Running experiments with additional complexity teach you both about the potential benefits of complexity and the short-comings of your less complex approach.

- Adopting a traceable approach (e.g. to reproduce the mean behaviour of the fully complex scheme) may go a long way to achieving the benefits of the full scheme.

- Once this approach is adopted, one can ask again what the benefits are of the full complexity and implement key parts.
  - E.g. Prognostic dust operational and improves T_surfs.
Example case study: coupled ocean
Ocean Model Resolution

1/12° Eddy Resolving
1/4° Eddy Permitting
1°
N Atlantic surface heat fluxes

DEEP-C dataset

Model error in eddy-permitting

Model error in eddy-resolving
Asymmetric changes in SST biases linked to overturning circulation:

- Reduction in Southern Ocean warm bias (~20%)
- Reduction in cold biases in Northern Hemisphere
- Reduction in warm biases in upwelling regions

Model Resolution

- Reduced SST Biases and Overturning

Benefits of high resolution ocean appear substantial and robust

Important open questions re mixing parametrizations
Tropical Performance – Coupled NWP vs Control
453 NWP Cases 2008-2012 MSLP Verification vs. ERA-I

N216 (60km)
UM Atmosphere
¼ degree
NEMO ocean
Recent upgrade to atmosphere only NWP (dynamical core/resolution/physics) dramatically improved TC intensities and tracks.

Now for first-time beginning to see evidence of over-deepening as move into sub-tropics.

Experimental coupled results looking promising – example of real physical process that it is only appropriate to include when overall performance reaches a certain level of maturity.
Example case study: multi-layer snow
GL7.0 Global Land developments
Changes from GL6.0

- **Multilayer snow scheme**
- **Further albedo improvements**

**Current operational scheme 0-layer**
- Snow and first soil treated together
- Implicated in warm biases in NWP and poor simulation of permafrost in climate work

**Multilayer scheme**
- Explicit representation of the snow pack
- Mechanical compaction & thermal metamorphism
- Dependence of thermal conductivity on density included
- Liquid and ice stores

http://www.globalbedo.org

R. Essery
J. Edwards
M. Brooks
Global Land
Multilayer snow scheme

R Essery, J Edwards

- Current scheme treats snow and first soil layer together
  - Underestimates insulation of ground
  - NWP warm biases when temperature falls rapidly
  - Example from 2011/12
  - Poor simulation of permafrost and cold spring temperatures in the climate model

NAE area T+72 10 day rolling mean $T_{1.5m}$ bias (vs SYNOPS):

- Met Office
- ECMWF
- NCEP
Weather performance

NH T\textsubscript{1.5m} from winter N320 coupled/hybrid VAR trial

Bias vs SYNOP (K)

RMSE (K)

GA6.0

GA6\#136.11 (zero layer snow scheme)

GA6\#136.12 (three layer snow scheme)

M Brooks
Impact on 1.5m temperature in March-April-May (climate run)

Simpler scheme believed to be fundamentally incapable of representing (important aspects of) reality; complexity justified.
Priorities
Summary of Met Office global configurations

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**NEMO Ocean / CICE**

*Intermediate complexity aerosols*  
*Complex aerosols*

**ES processes**

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- **Long-term climate**
“Errors in the representation of fast physical processes remain a key limiting factor in the skill of our models across all timescales from short to sub-seasonal to seasonal timescales”

Report from 2010 WMO subseasonal to seasonal prediction workshop (available from WMO S2S page at http://www.wmo.int/pages/prog/arep/wwrp/new/S2S_project_main_page.html)
Convection Programme

Mass flux revisited

Updraught & downdraught dynamics

ParaCon programme

Convection Dynamics Coupling

Triggering

Turbulent approaches to grey zone

5 year joint programme between NERC and Met Office (£5M investment each)

http://www.metoffice.gov.uk/research/collaboration/paracon
subgrid orography

Surface torques – GWD+blocking terms

Zonally averaged torque (N m/degree)

Latitude (degrees)

CMC (GDPS)
MeteoFrance (ARPEGE)
UKMetO (GM)
CPTEC (AGCM)
CPTEC (AGCM-2)
JMA
ECMWF
INM-RAS

Thanks to:
Ayrton Zadra

Big uncertainties in many important aspects of model physics
Small community working on them
Scalability challenges big

Computational efficiency on future hardware driving science choices (numerical techniques, grids, DA...)

Issues needs to be front and central in thinking re extra complexity
Continue to invest (HPC, people) to do the ‘traditional’ things better (atmospheric and oceanic resolution, drag, convection, physics/dynamics coupling and stochastic physics, ensembles, DA.....)

Cross-timescale testing is hugely valuable, especially if fast physics common across systems, and strong focus on NWP ‘weather’ metrics as well as synoptic scores

Do invest in complexity, but selectively, taking (increased?) care to be sure to understand what the complexity is truly giving, and to consider overall cost-benefit compared to other investments
Final thoughts......

- Model development an exciting and important science in its own right
  - Operational centres and academia together

- Needs both insight into detailed processes and broad understanding of how whole modelling systems work as one

- International collaboration key (knowledge sharing; co-ordinated work to learn generic lessons)

- New WCRP/WWRP prize for model development in recognition of its importance

- A good career choice!