Department of Meteorology

Diabatic processes in numerical simulations of extratropical cyclones

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1 Introduction

Diabatic processes are those in which heat is produced, such as radiation and latent heat release. These determine the evolution of the atmosphere through the modification of mesoscale circulations. Due to the inherent nonlinearity of the atmosphere, these modified circulations may in turn modify the subsequent development of diabatic processes.

The main sources of heating and cooling are phase changes from vapour to liquid and ice, as air masses ascend to form regions of cloud and precipitation, and from evaporation and sublimation, when precipitation falls through relatively dry air.

Diabatic processes are not directly resolved in numerical weather forecast models. Instead, they are parameterised in terms of grid-scale variables. Understanding how, when and where in the atmosphere these processes take place and how they affect the dynamics of the atmosphere is essential to achieve more accurate weather forecasts and climate projections. The improved accuracy would be of benefit for the general public and for many other areas that depend on these results including hydrology and engineering, policy making and the insurance/re-insurance industry.

We have developed a new set of diagnostics to investigate diabatic processes in numerical weather forecast models. Here we apply the diagnostics to study the simulation of a North Atlantic cyclone on 30 September 2011. Our analysis focuses on the effects of the parameterisation of convection on precipitation and the cyclone's development. To this end, we contrast two simulations, one with the standard CAPE closure timescale of 1800 s (CONTROL) and the other with a longer CAPE closure timescale of 15000 s, thereby reducing the convective heating (REDCV). This work is part of the DIAMET project.

2 DIAMET (DIAbatic influences on Mesoscale structures in ExTratropical storms)

DIAMET is a science consortium involving four British universities: Manchester, Reading, Leeds and East Anglia, and the Met Office. Its focus is the understanding and prediction of mesoscale structures in synoptic-scale storms. Such structures include

- Fronts
- rain bands
- secondary cyclones
- sting jets

By a combination of measurements, mainly using the FAAM research aircraft (Figure 1), and modelling, mainly using the Met Office Unified Model (MetUM), we aim at better understand how mesoscale processes in cyclones give rise to severe weather and how they can be better represented in numerical climate and forecast models.
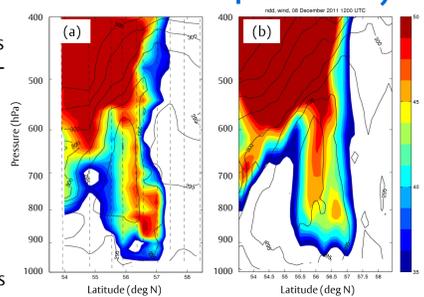
Figure 1. (a) Dropsonde measurements v (b) forecast for a sting-jet cyclone observed on 8 Dec 2011 during the 2nd DIAMET field campaign.

3 Case-study: A cyclone on 30 September 2011

The selected case is a low-pressure system centred to the southwest of Iceland with a long-trailing cold front. The system began its development around 0600 UTC 28 September 2011 at 43°N 28°W. From there it travelled northwards to be located around 62°N 25°W at 1200 UTC 30 September 2011, deepening from 997 hPa to 973 hPa in 54 hours. The system's trailing cold front reached Ireland around 0600 UTC 30 September 2011 and kept travelling eastwards producing precipitation over the United Kingdom later in the day. Figure 2 shows the frontal structure in the vicinity of the cyclone's low-pressure centre.
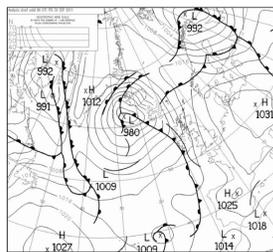
Figure 2. Met Office operational analysis chart at 06 UTC 30 Sep 2011 (archived by http://www.wetter3.de/fax)

4 Lagrangian tracers

Tracers track changes in potential temperature (θ) due to diabatic processes in a numerical model. These processes include: short- and long-wave radiation, large-scale cloud formation, convection parameterisation, boundary layer parameterisation, as well as several changes related to necessary re-balancing of moisture and energy within the model [1,2].

Potential temperature is decomposed as

$$\theta(x,t) = \theta_0(x,t) + \sum_{i=\text{proc}} \Delta\theta_i(x,t), \text{ proc} = \{\text{parameterised processes}\}$$

where θ_0 represents a conserved initial field and $\Delta\theta_i$ represents the accumulated tendency of θ due to a parameterised process.

Thus, there are evolution equations for θ_0 and for each $\Delta\theta_i$

$$\frac{D\theta_0}{Dt} = \frac{\partial \theta_0}{\partial t} + \mathbf{v}\cdot\nabla\theta_0 = 0$$

The initial field is affected by advection only

$$\frac{D\Delta\theta_i}{Dt} = \frac{\partial \Delta\theta_i}{\partial t} + \mathbf{v}\cdot\nabla\Delta\theta_i = S_{\theta_i}$$

Each accumulated tendency is affected by advection and by a particular source of θ given by S_{θ_i}

The evolution equation for potential temperature can then be written as

$$\frac{\partial \theta}{\partial t} = -\mathbf{v}\cdot\nabla\theta_0 - \mathbf{v}\cdot\sum_{i=\text{proc}}\Delta\theta_i + \sum_{i=\text{proc}}S_{\theta_i}$$

Total rate of change | Advection of initial field | Advection of accumulated tendencies | Sources

This method has been implemented in the UK Met Office Unified Model (MetUM) version 7.3.

5 Diabatic potential temperature at 250 hPa
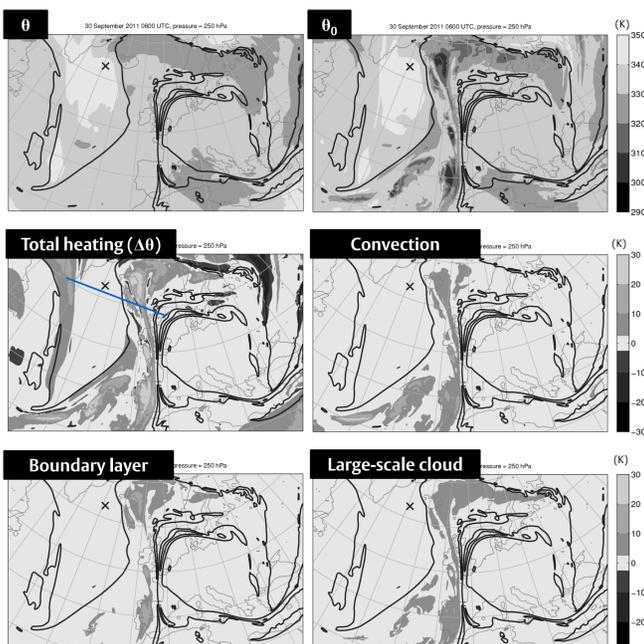
Figure 3 shows θ and θ_0 at upper levels (250 hPa) in CONTROL after 24 hours into the simulation. The difference between these two fields is the total heating (Δθ). This is most intense to the east of the cyclone centre following a branch that appears to turn anticyclonically along an upper-level ridge (2-PVU contour). This branch corresponds to the system's warm conveyor belt. The diabatic processes responsible for this configuration in the model appear to be convection, boundary layer and large-scale cloud.

Figure 3. θ decomposition at 250 hPa on 06 UTC 30 Sep 2011. Bold black lines represent the 2-PVU contour. Black crosses indicate the position of the mean sea-level low-pressure centre. The blue line in the 'Total heating' panel represents the position of the vertical section in Fig. 4.

6 Diabatic potential temperature (Vertical structure)
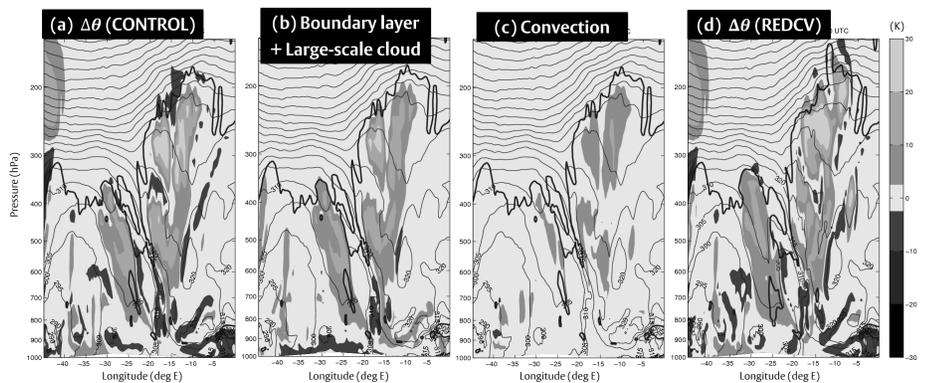
Figure 4. Vertical section along the blue line in Fig. 3 showing changes in potential temperature for (a, b, c) CONTROL and (d) REDCV on 06 UTC 30 Sep 2011. Bold black lines represent the 2-PVU contour. Thin black lines represent equivalent potential temperature contours with a 5-K separation.

The anticyclonic branch along the upper level ridge (Fig. 3) is prescribed on its western flank by the cold front. It extends vertically from 800 hPa to 200 hPa (Fig. 4a). The diabatic processes that contribute the most to the formation of this structure in the model are latent heating within the boundary layer, large-scale cloud formation and convection (Figs. 4b and c). There is a second branch to the west of the cold front, which only extends from 800 hPa to 350 hPa. On this branch the boundary layer latent heating and large-scale cloud are the main contributions.

Based on these results, it is conjectured that the additional heating that allows the eastern, anticyclonic branch to reach higher levels has been provided by parameterised convection. However, proving this is not a simple task due to the strong inter-relationships between parameterisation schemes in numerical models.

7 Convective–large-scale precipitation split
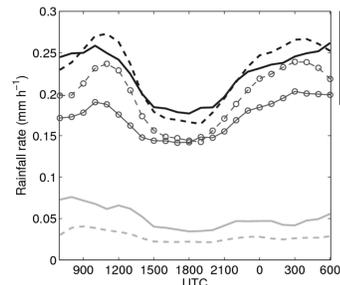
Figure 5. Rain rate averaged over an area of 1500-km radius centred on the low-pressure centre, showing the contributions from convective (cvrain) and large-scale rain (lsrain) to the total precipitation (total) for CONTROL and REDCV.

Figure 5 shows the convective–large-scale precipitation split in CONTROL and REDCV. The longer CAPE closure timescale does indeed reduce the activity of parameterised convection.

Although the precipitation split is clearly different the total precipitation amount is similar in both cases. The available moisture lifted on the warm conveyor belt determines the total precipitation amount but is split into different proportions depending on the parameterisation schemes' formulation and settings. If parameterised convection is reduced, the large-scale cloud scheme is then required to remove convective instability by releasing latent heat at the grid scale.

8 Trajectory analysis

A comparison between the simulations using trajectory analysis [3] shows that ascent is gradual and continuous in CONTROL (Fig. 6a), taking place throughout the 24-hour period, whereas it occurs more abruptly around 21 UTC on 29 Sep in REDCV (Fig. 6b). This behaviour is consistent with the heating rates exhibited by the trajectories. In the CONTROL case the total heating is apparent at a range of times on individual trajectories, spanning the whole 24-hour period (Fig. 6c). In the REDCV case the total heating becomes important only after 19 UTC on 29 Sep (Fig. 6d). The main contributors to total heating in CONTROL are boundary layer latent heat, large-scale cloud and convection (Figs. 6e to g), whereas in REDCV total heating has been produced by boundary layer latent heat and large-scale cloud (Fig. 5f and h).

As well as being more abrupt, the release of latent heat by the large-scale cloud scheme in REDCV appears to be allowing the anticyclonic branch to reach higher altitudes, thereby modifying the structure of the upper-level ridge (Fig. 3d). This modification could lead to significant differences in subsequent forecasts.
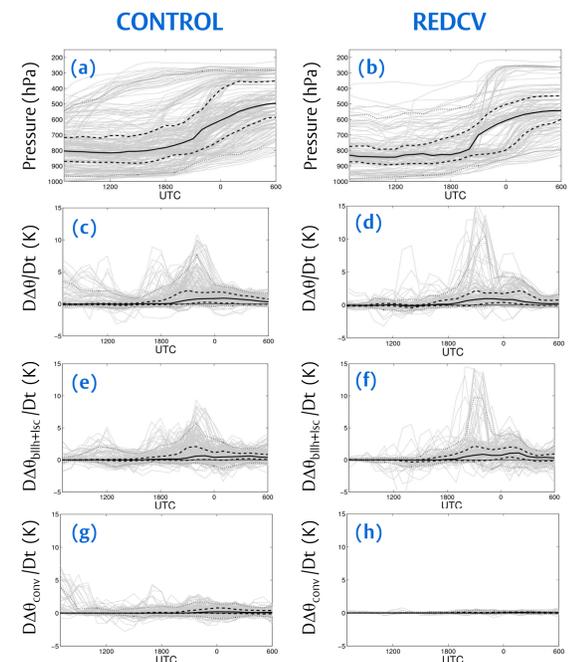
CONTROL   **REDCV**

Figure 5. Evolution along trajectories that have strong accumulated heating and which intersect the cross-section in Fig. 3. Results for CONTROL (left) and REDCV (right). Solid lines represent the median; dashed lines represent the 25th and 75th percentiles; dotted lines represent the 5th and 95th percentiles of the trajectory ensemble. Grey lines represent individual trajectories.

9 Conclusions

- A comprehensive suite of diagnostics, consisting of tracers tracking and accumulating changes in potential temperature due to diabatic processes, has been developed to investigate diabatic effects within numerical models. Sources include the formation of large-scale cloud, convection, boundary layer processes and radiation.

- Two simulations of a case study, one with the standard MetUM convection parameterisation (CONTROL) and the other with reduced parameterised convection (REDCV), have been contrasted.

- The simulations produced a similar amount of total precipitation. However, the convective–large-scale precipitation split was different leading to differences in the details of the spatial and temporal precipitation distribution.

- In the CONTROL case, large-scale cloud, boundary-layer processes and convection all contribute significantly to heating around the cyclone's low-pressure centre, along the warm conveyor belt and within an upper-level ridge. In the REDCV case, only the first two processes contribute significantly to heating in these same structures.

- Trajectory analysis showed that ascent in REDCV was more abrupt than in CONTROL. This is consistent with REDCV heating taking place over a shorter period of time. This heating was also stronger allowing trajectories to reach higher altitudes and so modifying the upper-level ridge.

- The modification to the upper-level ridge has the potential to lead to noticeable differences in subsequent forecasts.

References

1 Martínez-Alvarado, O. and Plant, R. S., 2012: Diabatic processes in a numerical simulation of an extratropical cyclone. In preparation.
2 Stoelinga, M. T., 1996: A potential vorticity-based study of the role of diabatic heating and friction in a numerically simulated baroclinic cyclone. *Mon. Wea. Rev.* **124**, 849–874
3 Wernli, H., 1997: A Lagrangian-based analysis of extratropical cyclones. II: A detailed case-study. *Q. J. R. Meteorol. Soc.* **123**, 1677–1706