Department of Meteorology

Lagrangian diagnostics for analysing budgets of heat, moisture, and potential vorticity in extratropical cyclones

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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 water 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 layers.

Diabatic processes are not directly resolved in numerical weather forecast models. Instead, they are parameterised in terms of resolved variables at grid scale. 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. 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 a North Atlantic cyclone observed during the DIAMET 'pilot' field campaign on 23-25 November 2009.

Example case: A cyclone on 23-25 November 2009

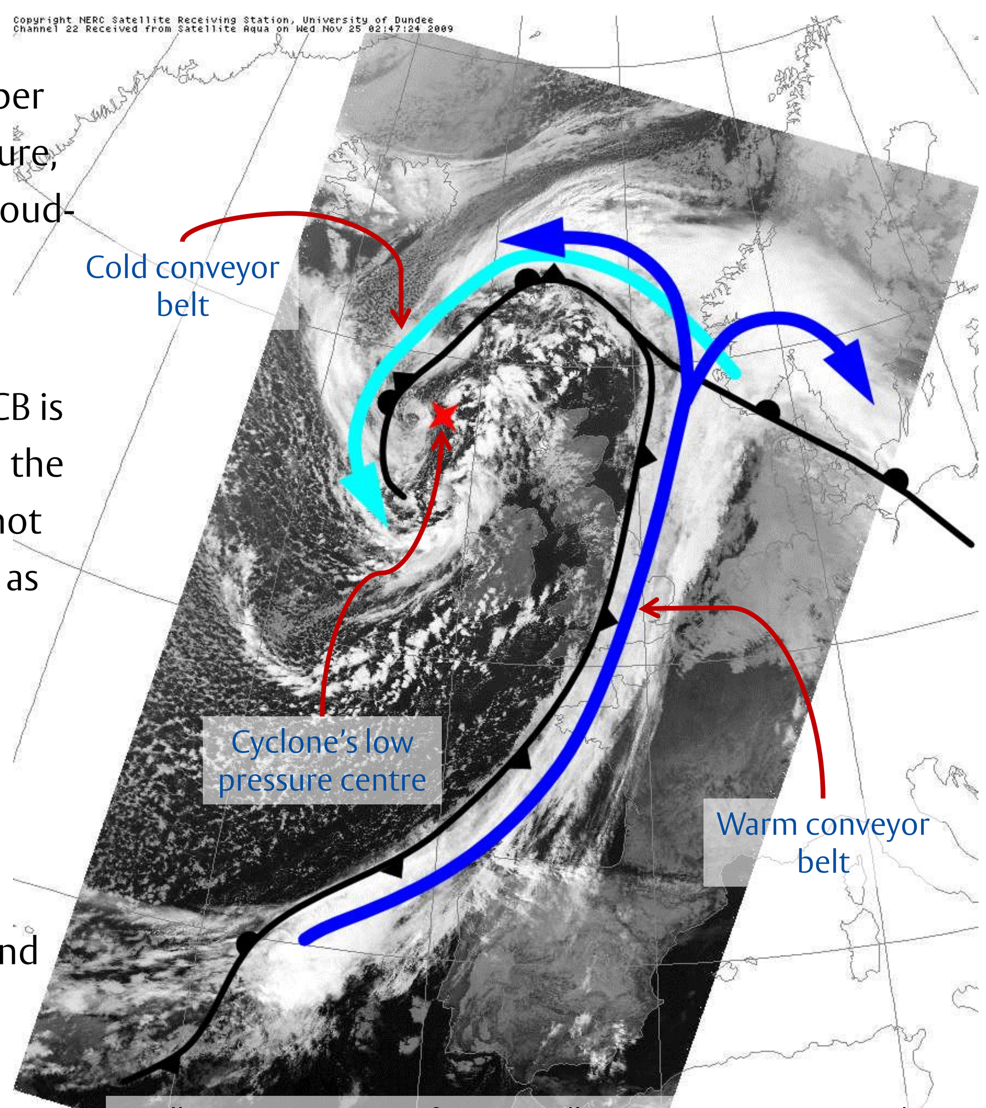
The *warm conveyor belt* (WCB) is a coherent, moist airstream ascending from the boundary layer to the upper troposphere. It transports large amounts of heat, moisture, and westerly momentum polewards. It is the primary cloud- and precipitation-producing flow within extratropical cyclones (Wernli 1997).

The low-level moisture convergence zone along the WCB is sometimes referred to as an *atmospheric river*, although the concept of the WCB is a more general one comprising not only the transport of water but of other quantities such as energy and momentum.

We study the WCB associated with this cyclone with emphasis on the following

KEY QUESTIONS

- What are the physical processes leading to heating and cloud formation in a warm conveyor belt?
- To where are the effects of heating and moistening transported?
- Do these transports influence the large-scale dynamics of the storm?



Satellite image courtesy of NERC Satellite Receiving Station, Dundee University, Scotland http://www.sat.dundee.ac.uk

Surface fronts based on the Met Office analysis at 00 UTC 25 Nov 2009 (archived by http://www.wetter3.de/fax)

Lagrangian tracers

Tracers track changes in potential vorticity (PV), potential temperature (θ), specific humidity (q), cloud liquid water (q_{cl}) and cloud ice content (q_{cf}) due to the processes in the numerical model (Stoelinga 1996). 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.

FORMULATION

The variables of interest (PV, θ, q, q_{cl} and q_{cf}) are decomposed as

$$\varphi(x,t)=\varphi_0(x,t)+\sum_{i=\text{proc}}\Delta\varphi_i(x,t)$$

proc = {parameterised processes}

where φ_0 represents a conserved initial field and $\Delta\varphi_i$ represents the accumulated tendency of φ due to a parameterised process.

Thus, there are evolution equations for φ_0 and for each $\Delta\varphi_i$

$$\frac{D\varphi_0}{Dt}=\frac{\partial\varphi_0}{\partial t}+\mathbf{v}\cdot\nabla\varphi_0=0$$

The initial field is affected by advection only

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

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

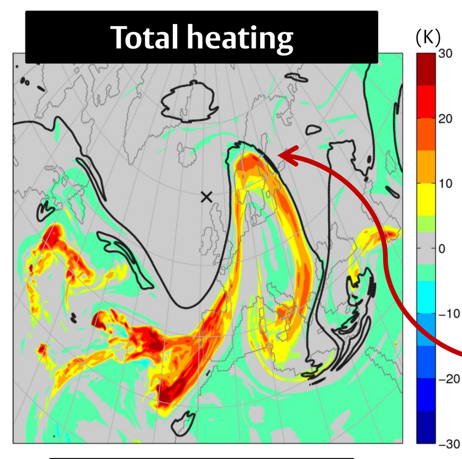
The evolution equation for the relevant variables can then be written as

$$\frac{\partial\varphi}{\partial t}=-\mathbf{v}\cdot\nabla\varphi_0-\mathbf{v}\cdot\nabla\sum_{i=\text{proc}}\Delta\varphi_i+\sum_{i=\text{proc}}S_{\varphi_i}$$

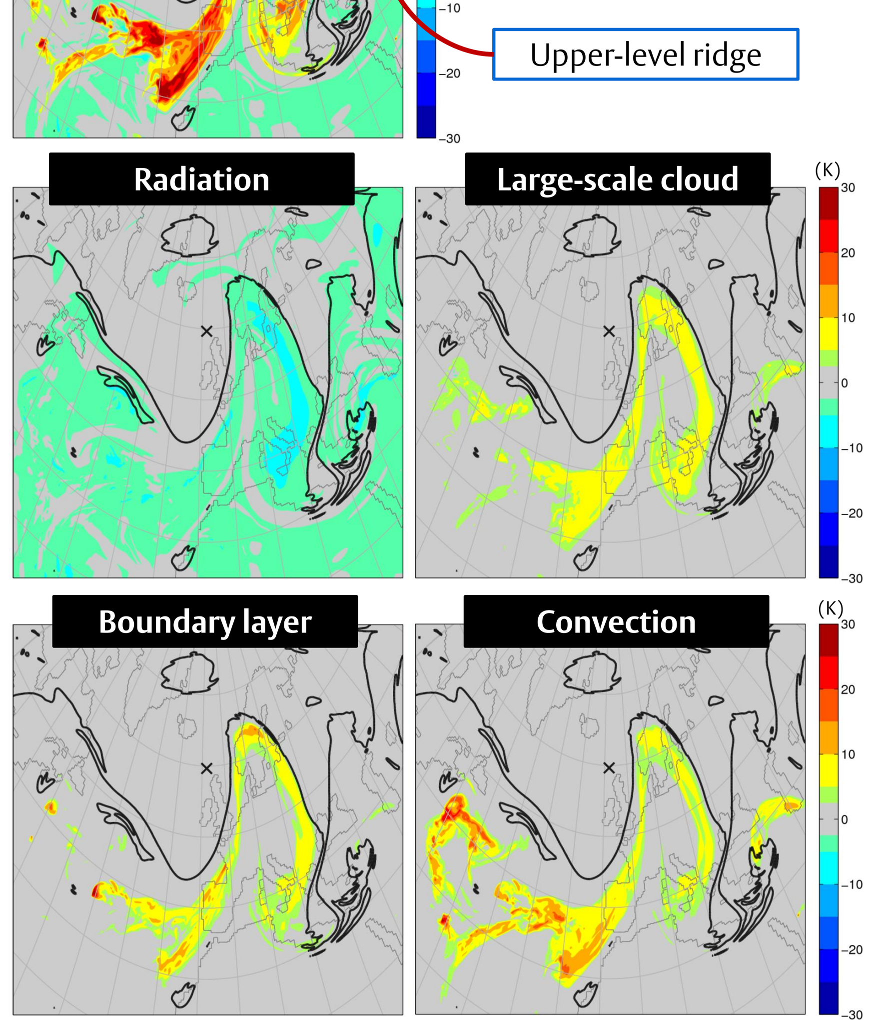
Total rate of change | Advection of initial field | Advection of accumulated tendencies | Sources

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

Diabatic potential temperature in the WCB

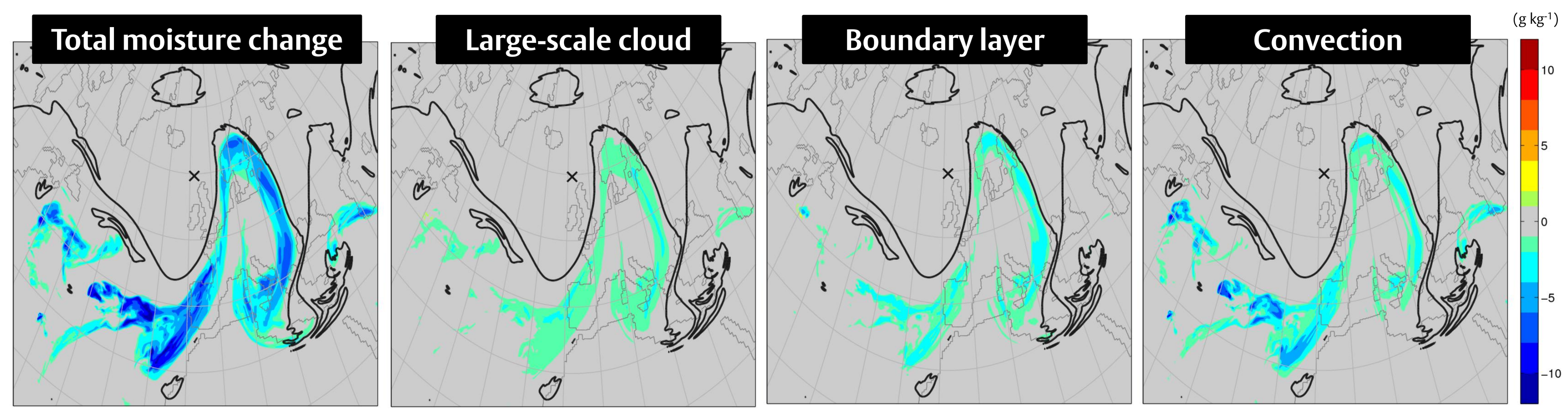


All fields in these and subsequent figures are shown on a fixed model level corresponding to an altitude of 9.68 km. The black line represents the intersection of the tropopause (PV=2PVU) with the level shown.



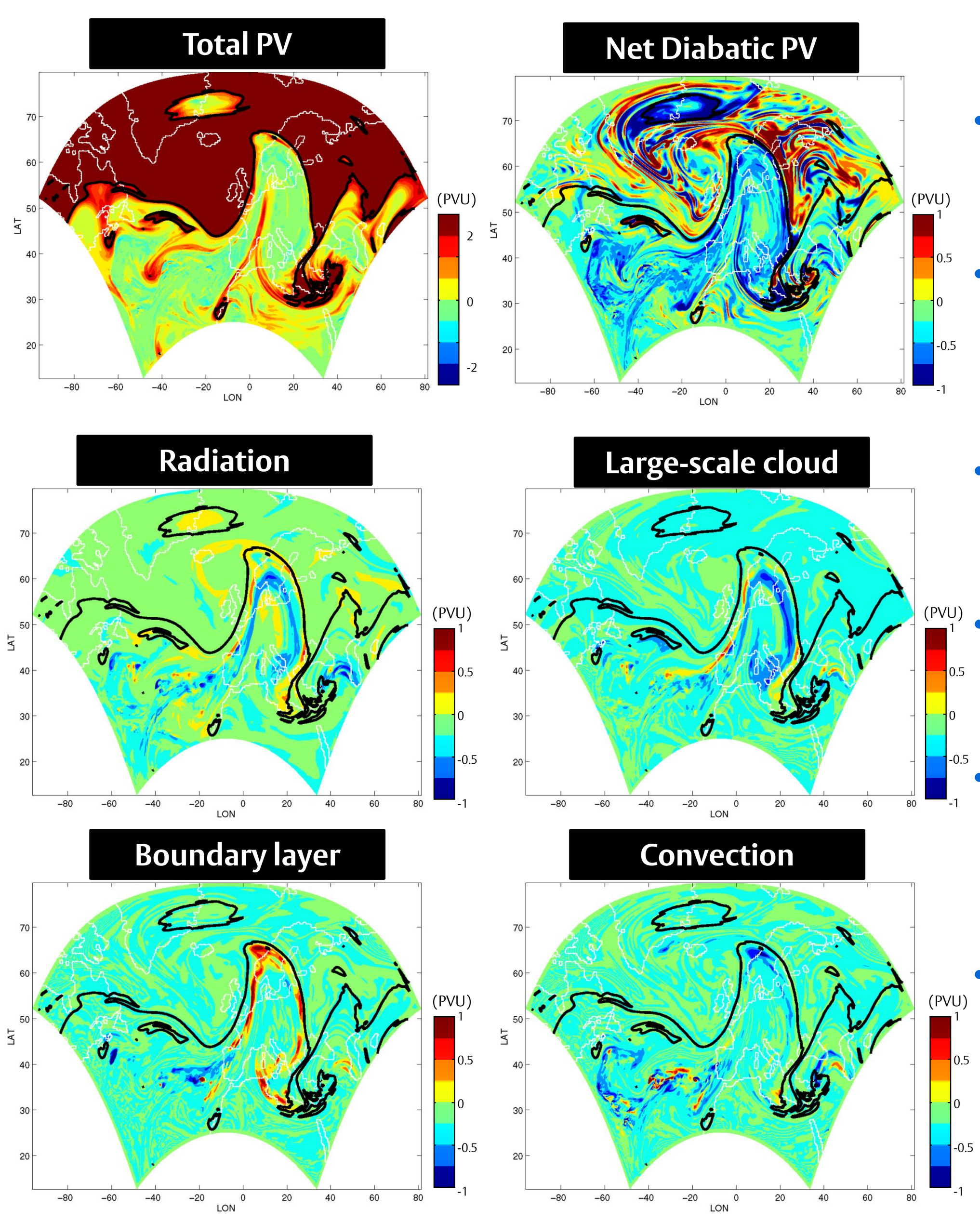
- Potential temperature is a rescaled temperature, related to entropy, with the important property of being conserved in adiabatic flow.
- The figures show the contributions of different processes to the total heating in the MetUM simulation of this cyclone.
- Strong heating occurs along the WCB and accumulates around an upper level ridge.
- The most important contributions come from the formation of large-scale cloud, from boundary layer turbulence and from convection.
    - The presence of BL accumulated tendency at this altitude demonstrates the advection of low-level material by the WCB.
- Radiation has a widespread cooling effect .
- Heating produces changes in the large-scale circulation by changing the structure of potential vorticity (see section 'Diabatic potential vorticity' below).

Moisture in the WCB



- Atmospheric moisture is here measured by specific humidity.
- The figures show the contributions of different processes to the total moisture change.
- Total moisture changes are primarily negative along the WCB and bordering the upper level ridge.
- Cloud formation and precipitation reduce the water vapour.
- This is consistent with latent heat release due to the lifting of moist air being the main source of heating along the WCB.

Diabatic potential vorticity in the WCB



- Potential vorticity (PV) is a measure of the rate of spin of fluid particles. Positive PV is associated with cyclonic vorticity.
- PV is conserved for adiabatic frictionless flow: i.e., the non-conservative portion of PV indicates the effect of diabatic processes on dynamics.
- The figures show the partitioning of non-conservative PV in the MetUM simulation of this WCB cyclone.
- Large values of negative diabatic PV accumulate in the upper-tropospheric ridge.
- This negative diabatic PV changes the structure of the ridge. It may also affect the evolution of the ridge and a downstream trough.
- The convection, radiation, and large-scale cloud schemes all contribute to this region of negative PV.

Conclusions

- A comprehensive suite of diagnostics has been developed to investigate diabatic effects within numerical models.
- The tracers accumulate source terms for diabatic processes along the flow. Sources include the formation of large-scale layer cloud, convection, boundary layer processes and radiation.
- Large-scale cloud, boundary-layer processes and convection all contribute significantly to heating along the WCB and the upper-level ridge, while radiation produces cooling over a broader area.
- In contrast, radiation, large-scale cloud and convection contribute to a negative PV feature along the upper-level ridge, whereas boundary-layer processes tend to oppose it.
- The accumulated tendencies can be used in combination with trajectory analysis to investigate the origin of the most important diabatic changes.
- These new diagnostics can also provide insight into many other meteorological systems: e.g. the authors will also use them to study evaporative descent of sting jets.

Acknowledgements

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