# 8A.3 2D ASSIMILATION OF DYNAMICAL INFORMATION FROM SATELLITE IMAGERY

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## 1. INTRODUCTION

UK winter weather is dominated by mid-latitude cyclones, which develop over in the North-Atlantic. Sequences of geostationary satellite imagery can depict the development of these major cloud systems over time. The evolving cloud signal contains dynamical information and it is hoped that this dynamical information can be extracted through 4D-Var assimilation of sequences of observed IR brightness temperature.

Li and Pullen (2005) investigated two case studies of rapid cyclogenesis. Case one, 19-21st April 2004, was well forecast and case two, 14-15th October 2002, was poorly forecast. They conclude that one needs to be able to detect the errors, early in the development of such a system, that turn out to be crucial. With rapid cyclogenesis, we get rapid growth of forecast errors from small initial condition errors.

Satellite imagery has been available for over 40 years, and there have been many improvements to the quality and frequency of the data over this time. To date it has not been possible to make use of much of the information effectively because data assimilation (DA) methods have taken a rather 'static' view of the data. There has been no regard for the temporal information contained in a sequence of satellite images; a set of observations around a given time has just been used to estimate the state of the atmosphere at that time. With the advent of 4D-Var this restriction is being lifted and we can start to think of extracting information from sequences of observations, as forecasters have done subjectively for many years. 4D-Var brings with it the opportunity to use sequences of satellite images in an objective and quantitative manner.

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## 2. AIM

The main aim of the research project is to investigate the potential of the 4D-Var method to extract dynamical development information, in addition to information about advection. Sequences of satellite images, even from a single IR window channel, provide excellent depictions of the development of major cloud systems. The development of the cloud top is linked to the vertical motion field and hence, to important aspects of the horizontal wind field (i.e. convergence field) at lower levels. Therefore, information on the low level wind field, although not directly present in the radiance emitted to space, is available indirectly through a sequence of satellite images interpreted together with the physical and dynamical constraints provided by a numerical weather prediction (NWP) model. It should be possible to fit the sequences of images by adjusting the vertical motion field that gives rise to the developments in the cloud field, as long as we have consistent adjustments to the horizontal wind field.

### 2.1 *Outline of work*

The Met Office's work involves developing a technique to extract the dynamical information from satellite imagery using their full 4D-Var system (Li and Pullen, 2005). The NWP model and data assimilation system must adequately represent the chain of processes converting:

- horizontal wind field (divergence/convergence) → vertical velocity profile
- vertical velocity profile → changes in the relative humidity profile
- relative humidity profile → cloud profile

- cloud profile → outgoing radiances

Moreover, models of all these processes must be amenable to linearisation, at least approximately, in order for the minimisation in the associated data assimilation problem to be practicable.

Our research involves investigating a simplified form of Met Office's 4D system in order to understand some of the mathematical properties of the problem that cannot easily be explored within the complex 4D system. We convert information on the vertical wind field to brightness temperatures using a 2D-Var system (vertical and time dimensions). Vertical profiles of temperature, $T(z,t)$, total water $q_t(z,t)$ are updated using a simple vertical advection scheme. We then use observation operators to convert the state vector to the observations we wish to compare. These observation operators are the simple cloud and radiative transfer (RT) schemes which calculate the fractional cloud cover ($f$) and brightness temperature ($TB$). We combine all the elements to construct a 2D-Var analysis.

# 3. BASIC TESTBED

We outline here an experiment to test the simplified form of the processing chain.

## 3.1 *The Original Advection, Cloud and RT Scheme Proposals*

The state vector $\mathbf{x}(z,t)$ contains the vertical profiles of temperature, $T$, total water substance, $q_t$ and vertical velocity, $w$ and is also a function of both space and time. There is a value of $T$, $q_t$ and $w$ for each model level $j$, and time level $i$, in our atmospheric column.

Forward integration in time is achieved through the general equations:

$$\begin{aligned} w_{j,i+\Delta t} =& w_{j,i} + \Delta w_{j,i}, \\ T_{j,i+\Delta t} =& T_{j,i} + \Delta T_{j,i}, \\ q_{tj,i+\Delta t} =& q_{tj,i} + \Delta q_{tj,i}, \end{aligned} \quad (1)$$

where the increments are given by;

$$\begin{aligned} \Delta T_{j,i} =& A(w_{j,i}, T_{j,i}, q_{tj,i}, \Delta t), \\ \Delta q_{tj,i} =& B(w_{j,i}, T_{j,i}, q_{tj,i}, \Delta t), \\ \Delta w_{j,i} =& 0 \end{aligned} \quad (2)$$

where $\Delta T_{j,i}$, $\Delta q_{tj,i}$ and $\Delta w_{j,i}$ are changes (in time) of temperature, total water and vertical velocity respectively.

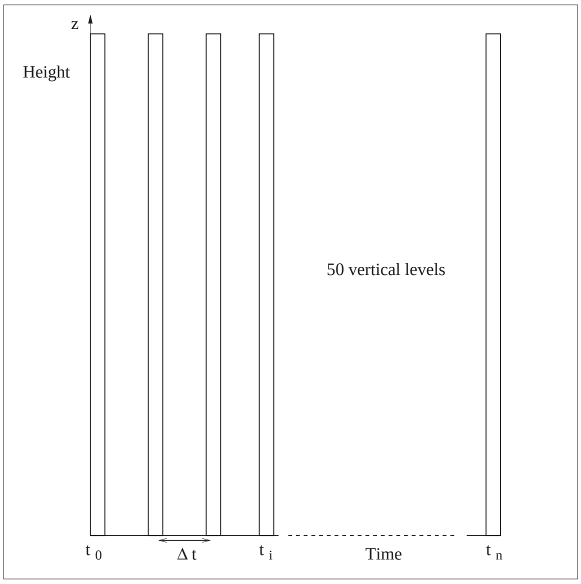


Figure 1: A schematic of the vertical and time 2D-Var system, with time on the x-axis and height on the z-axis. Each rectangle represents one vertical atmospheric column. Each column is for the same location, but at increasing timesteps. They contain information on the vertical velocity, temperature and total water profiles.

Details of the functions A(...) and B(...) have been developed during the research. The function A represents the first law of thermodynamics (section 4.2) and function B represents advection and moisture transport (section 4.1). Functions A and B define our forward model. The important details of which are contained in section (4.).

We have used a simple cloud scheme which links the fractional cloud cover ($f$) at level $j$, to the temperature and humidity at that level:

$$q_{satj,i} = D(T_{j,i}, p), \quad (3)$$

$$f_{j,i} = C(q_{tj,i}, q_{satj,i}), \quad (4)$$

where details of the functions C(...) and D(...) have been developed during the research. Function D relates the saturated specific humidity $q_{sat}$ to temperature and function C represents the fractional cloud cover, which is a function of $q_t$ and $q_{sat}$. Functions C and D define our cloud scheme which is outlined in section (4.3).

An essential component of a system for exploiting data from satellite sounding instruments is an accurate and fast radiative transfer scheme, which computes the radiance emitted at the top of the atmosphere. For this research a simple radiative transfer scheme was proposed for calculating upwelling brightness temperatures, equivalent to satellite radiances.

The RT model calculates TBs at each model level, $j = 1 \rightarrow N$,

$$TB_{j,i} = (1 - f_{j,i})TB_{j-1,i} + f_{j,i}T_{j,i}, \quad (5)$$

with a boundary condition for the surface level, $j = 1$:

$$TB_{1,i} = T_{1,i}. \quad (6)$$

The brightness temperature to space (as seen by a satellite) is simply the brightness temperature at the top level, $N$.

# 4. FORWARD MODEL

We have coded our single column model (SCM). It represents a single general circulation model (GCM) gridpoint atmospheric column, i.e. the values of various meteorological parameters at levels in a vertical column.

## 4.1 *Advection Scheme*

We have used a semi-Lagrangian (SL) advection scheme, which integrates the state vector (**x**) forward in time. Equivalent pressure values are needed in the cloud scheme for the calculation of $q_{sat}$ and are therefore diagnosed hydrostatically through an integration of the hydrostatic equation, this is done within the advection scheme code.

We assume a vertical velocity profile which is constant in time, therefore

$$\frac{\partial w}{\partial t} = 0. \quad (7)$$

In equation (8) we define the SL technique used to update total water ($q_t$) and temperature ($T_{SL}$):

$$q_t^{i+1} = (1 - \alpha)q^i_{tj-p} + \alpha q^i_{tj-p-1}, \quad (8)$$

$$T_{SL}^{i+1} = (1 - \alpha)T^i_{j-p} + \alpha T^i_{j-p-1}, \quad (9)$$

where p is the integer part of $w\frac{\Delta t}{\Delta z}$ and $\alpha = \frac{z_{j-p} - \tilde{z}^i_j}{\Delta z}$. The departure point of a trajectory originating at the time $t^i$ and arriving at $(z_j, t^{i+1})$ is denoted $\tilde{z}^i_j$.

## 4.2 *Thermodynamics*

It is unlikely that an entire column will be either fully saturated or fully unsaturated. We therefore require a combination of atmospheric lapse rates to

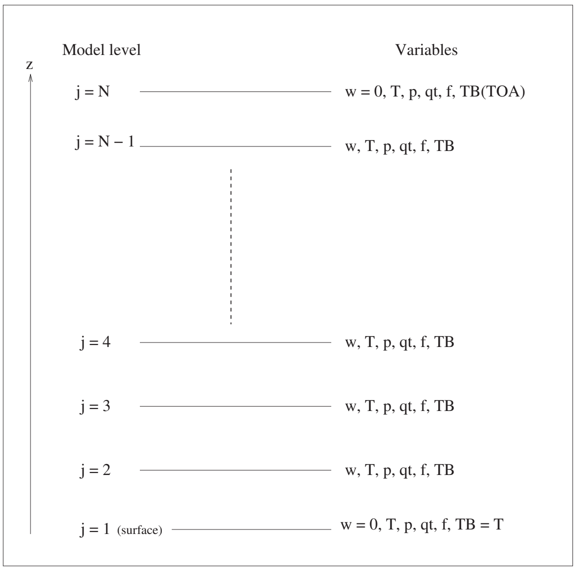


Figure 2: A schematic of the vertical structure of the model.

represent how the temperature profile of a parcel will change with height. We do this by considering the *dry adiabatic lapse rate* (DALR), which applies to the unsaturated part of the column, and the *saturated adiabatic lapse rate* (SALR), which applies to the saturated part. We use an appropriate average of the two.

Let $\Psi$ be the rate of change of the temperature profile of a parcel as it ascends. We compute $\Psi$ by weighting the DALR ($\Gamma_d$) and SALR ($\Gamma_s$) by the cloud field. With a cloud fraction of $f$, $\Psi$ is computed thus

$$\Psi_j = (1 - f_j)\Gamma_d + f_j\Gamma_s. \quad (10)$$

Equation (10) keeps the $\Psi$ profile consistent with our diagnosed cloud profile. The DALR is defined as

$$\frac{dT}{dz} = -\frac{g}{C_p} = -\Gamma_d, \quad (11)$$

(Houghton, 1986). $\Gamma_d \approx 10$ K $km^{-1}$. The SALR is defined as

$$\Gamma_s = 6.4 - 0.12T + 2.5E^{-5}T^3 + [-2.4 + 10^{-3}(T - 5)^2](1 - p/p_r) \quad (12)$$

where $p_r = 1000$mb and $T$ is the temperature (in °C) (Gill, 1982).

To calculate the updated temperature profile ($T_j^{i+1}$) we use

$$\frac{dT}{dt} = \frac{dT}{dz}\frac{dz}{dt}, \quad (13)$$

where

$$\frac{dT}{dz} = -\Psi \qquad \text{and} \qquad \frac{dz}{dt} = w. \tag{14}$$

Therefore

$$\frac{dT}{dt} = -\Psi w. \tag{15}$$

We then have that the change in the temperature ($\Delta T_j$) due to the advection by the vertical velocity profile;

$$\Delta T_j = -\Psi_j w_j \Delta t. \tag{16}$$

Equation (16) is then added to the semi-Lagrangian temperature $T_{SL}$ (9) to get the temperature at time $t = i + 1$,

$$T_j^{i+1} = T_{jSL}^{i+1} + \Delta T_j^{i+1}, \tag{17}$$

where $T_{jSL}^{i+1}$ is the SL updated T at time $t = i + 1$.

### 4.3 *Cloud Scheme*

The cloud scheme inputs are temperature, total water and pressure profiles, and it outputs the cloud profile. We calculate $q_{sat}$ from

$$q_{sat}(T, p) = \frac{\epsilon e_s(T)}{p}, \tag{18}$$

and liquid water content from

$$q_{cl} = q_t - q_{sat}(T, p). \tag{19}$$

The fractional cloud cover is defined by

$$f = \frac{1}{2}\left[1 + tanh\left(\frac{2q_{cl}}{q_{sat}(T, p)(1 - RH_{crit})}\right)\right], \tag{20}$$

where $e_s$ is the saturation vapour pressure, $f$ is the liquid cloud fraction and $RH_{crit}$ is the critical relative humidity for cloud formation. All variables evaluated at time $t = i$.

### 4.4 *Radiative Transfer Scheme*

The RT scheme takes information on the cloud profile and calculates brightness temperatures:

$$TB_j = (1 - f_j)TB_{j-1} + f_j T_j, \tag{21}$$

$$TB_1 = T_1, \tag{22}$$

where the variables are all evaluated at the same time level, $t = i$. The brightness temperature to space is simply the brightness temperature at the top level $j = N$.

We have made several assumptions in relation to the RT scheme, they will be outlined here. It is important to note that all of them would need to be re-examined when applied to real data, but they are adequate in the context of this idealised study. The first assumption is that we assume random overlap between clouds at adjacent levels in the vertical. Secondly, we assume that radiance and temperature are linearly related, this is a significant approximation in the infra-red. Thirdly, we assume that the surface skin temperature is equal to the air temperature at level $j = 1$, $TB_1 = T_1$ and finally, we assume that the top level of our model is the top of the atmosphere for radiative transfer purposes, $TB(TOA) = TB_N$.

## 5. FUTURE WORK

Work is currently underway coding the tangent linear and adjoint of the forward model and observation operators for use in the minimisation scheme. We plan to try the CONMIN minimisation algorithm, which is a quasi-Newton scheme (Shanno and Phua, 2003). Once the VAR system is coded we will test it with simulated observations (identical twin experiments) to see if we can recover the profiles of $w$, $T$ and $q_t$.

In parallel with this idealised study, work is proceeding to implement these ideas within the full 4D-Var scheme of the Met Office (Li and Pullen, 2005).

## References


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