Department of Meteorology

Data Assimilation for Multi-Scale Atmospheric Flow

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Introduction

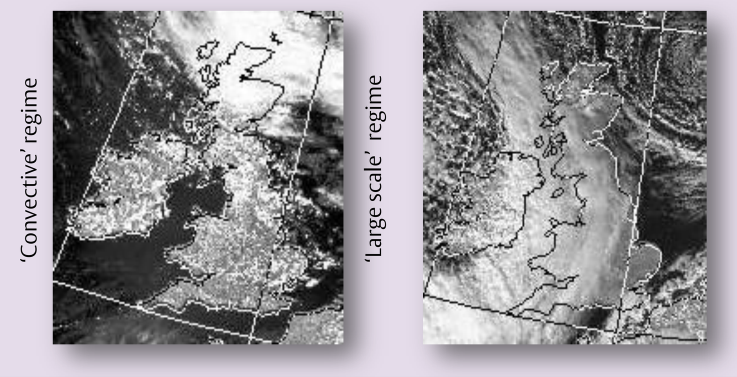
Data assimilation is needed to correct today's forecast by blending it with latest observations. Present day variational data assimilation systems are designed for large-scale flow characterised by:

- predominantly geostrophically balanced flow,
- perfectly hydrostatically balanced flow.

Both balances diminish as the scale of the flow reduces. What should be done if the flow includes small scale flow?

Questions:

- What are geostrophic and hydrostatic balances in the atmosphere?
- How do present day variational data assimilation systems impose these balances?
- What is the evidence that these balances are less effective at small scales?
- In multi-scale data assimilation:
  - How can geostrophic balance be relaxed at smaller scales?
  - How can hydrostatic balance be relaxed at smaller scales?



What are geostrophic and hydrostatic balances?

$$\frac{du}{dt} = fv - \frac{1}{\rho}\frac{\partial p}{\partial x} - D_x \quad \Rightarrow \quad \delta v = \frac{1}{f\rho}\frac{\partial p}{\partial x}$$

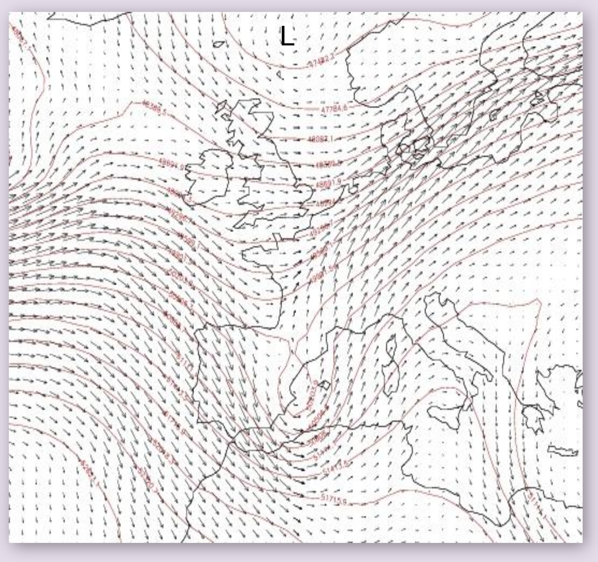
$$\frac{dv}{dt} = -fu - \frac{1}{\rho}\frac{\partial p}{\partial y} - D_y \quad \Rightarrow \quad \delta u = -\frac{1}{f\rho}\frac{\partial p}{\partial y}$$

$$\frac{dw}{dt} = -\frac{1}{\rho}\frac{\partial p}{\partial z} - g - D_z \quad \Rightarrow \quad \delta T \sim \left(\frac{\partial}{\partial z} - 1\right)\delta p$$

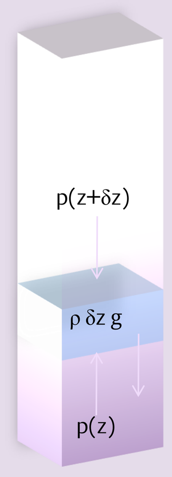
$$\frac{d}{dt} = \frac{\partial}{\partial t} + (\vec{u} \bullet \nabla) \qquad Ro = \frac{U}{f_0 L} = O(10^{-1})$$

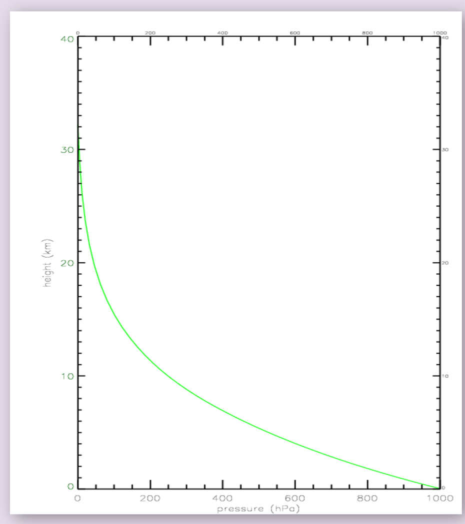
$$f = 2\Omega \sin(y/a) \qquad \frac{W}{U} = O(10^{-2})$$

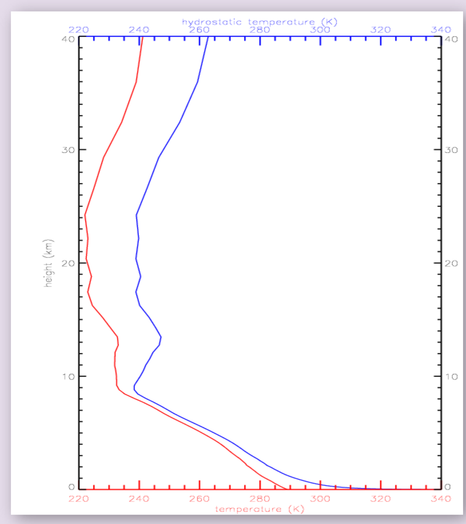
Geostrophic balance



Hydrostatic balance





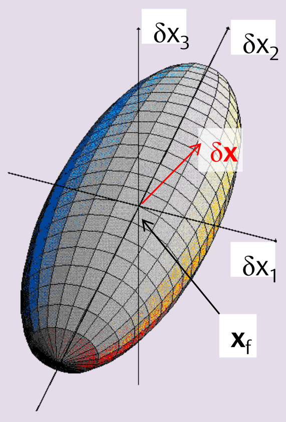


How do present day variational data assimilation systems impose these balances?

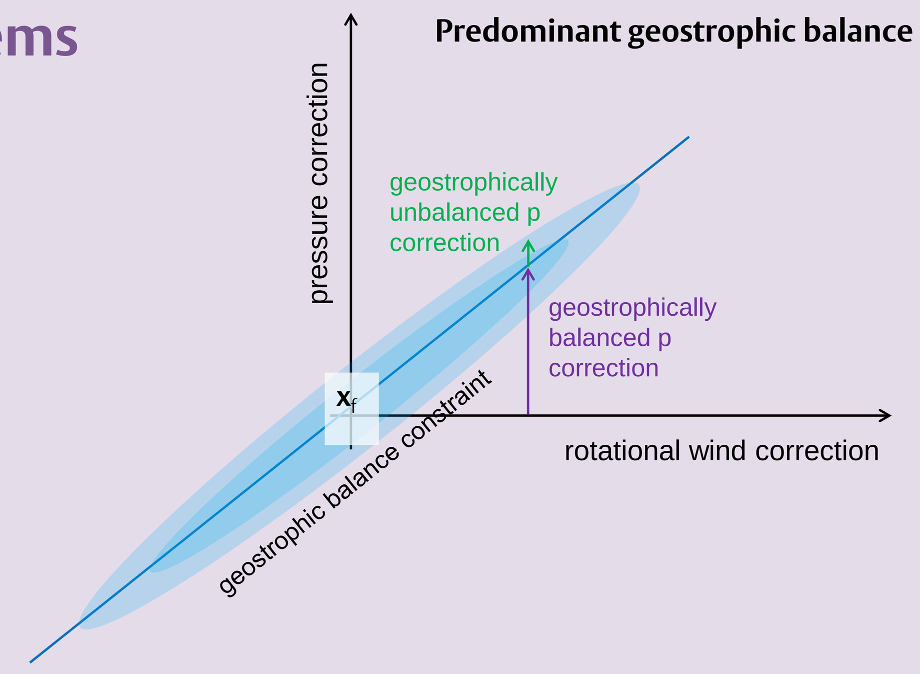
A variational data assimilation system makes corrections ($\delta\mathbf{x}$) to a forecast, $\mathbf{x}_f$ which is:

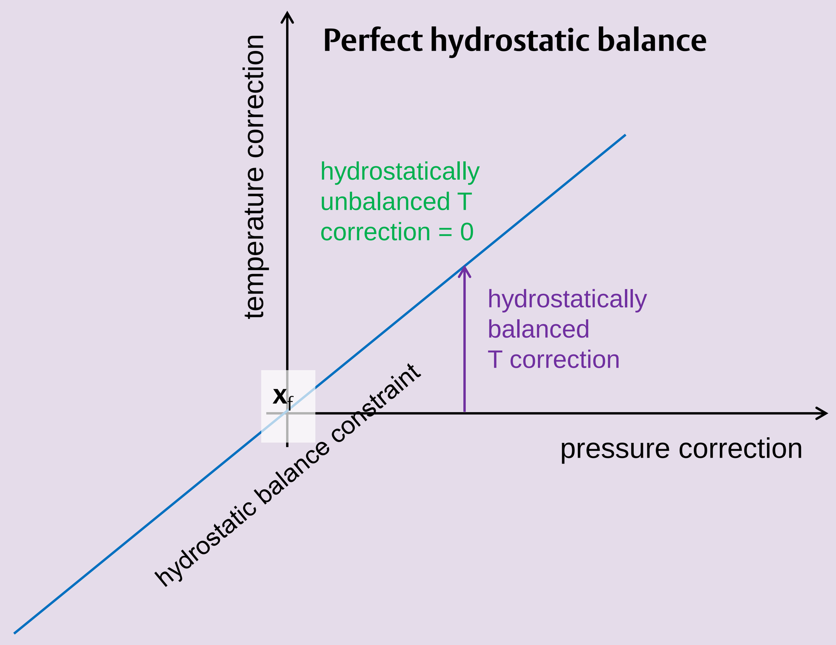
- consistent with the 'uncertainty bubble' associated with the forecast state.
- consistent with the latest observations,

Uncertainty bubble in model's phase space



The bubble's shape is difficult to determine, but can be modelled with dynamical balance relationships.

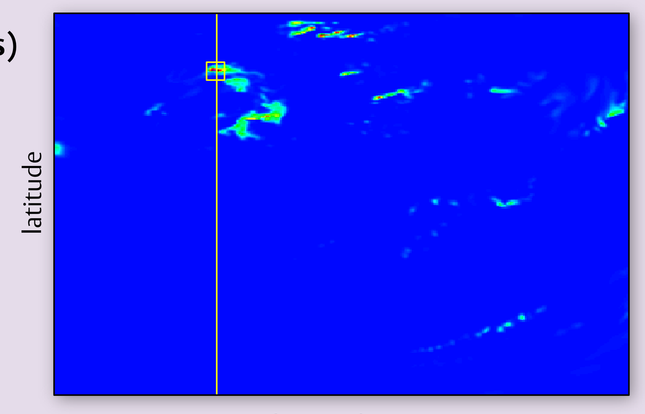




In the Met Office variational data assimilation scheme, the above are performed irrespective of scale.

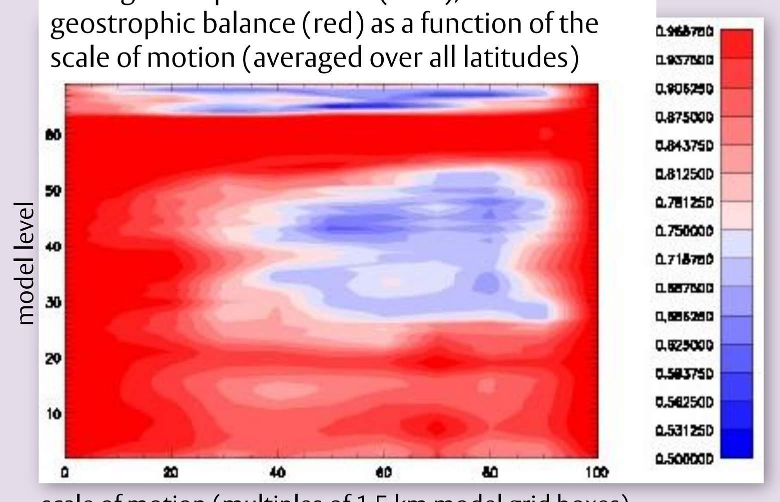
What is the evidence that these balances are less effective at small scales?

Rain rate (kg/m²/s)
18Z 26th July 2007



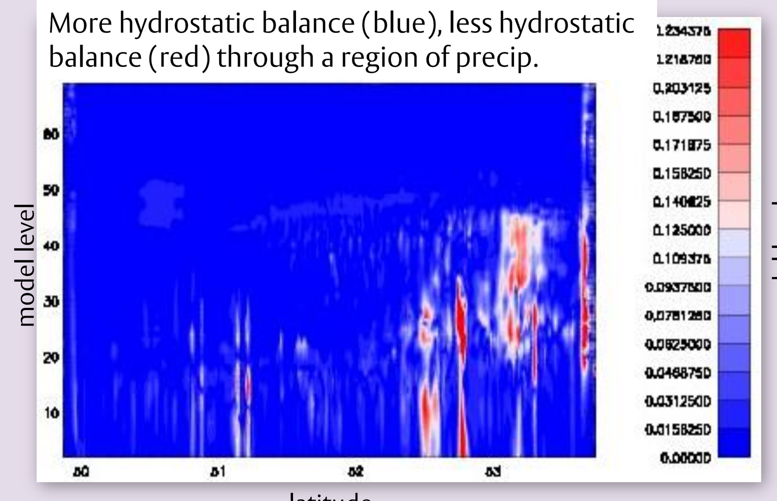
Geostrophic balance

More geostrophic balance (blue), less geostrophic balance (red) as a function of the scale of motion (averaged over all latitudes)

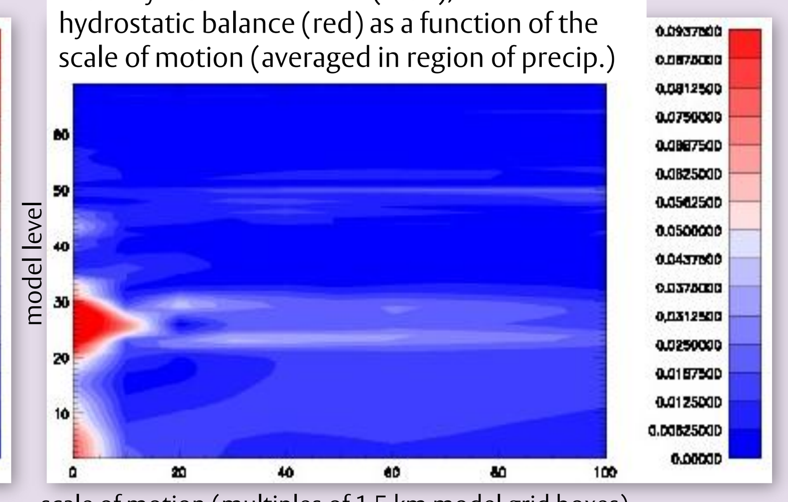


Hydrostatic balance

More hydrostatic balance (blue), less hydrostatic balance (red) through a region of precip.

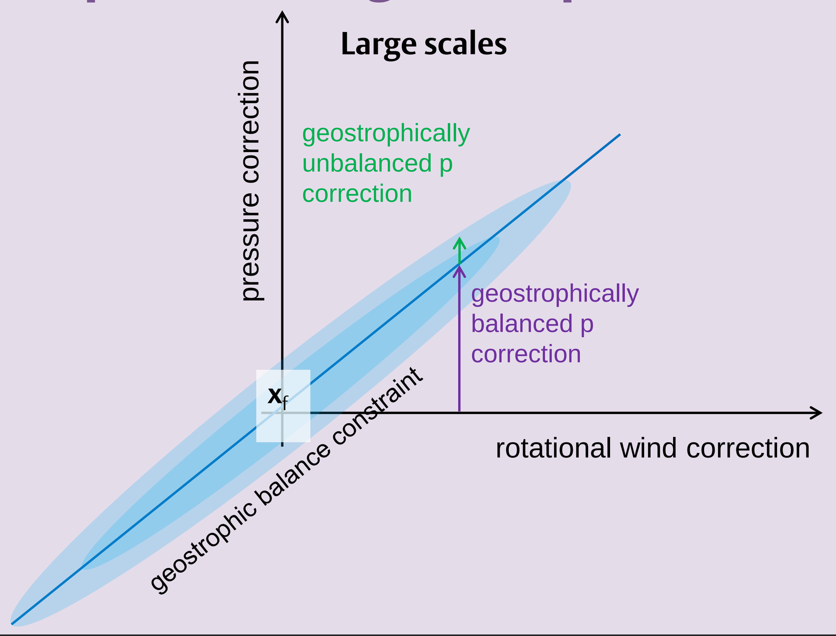


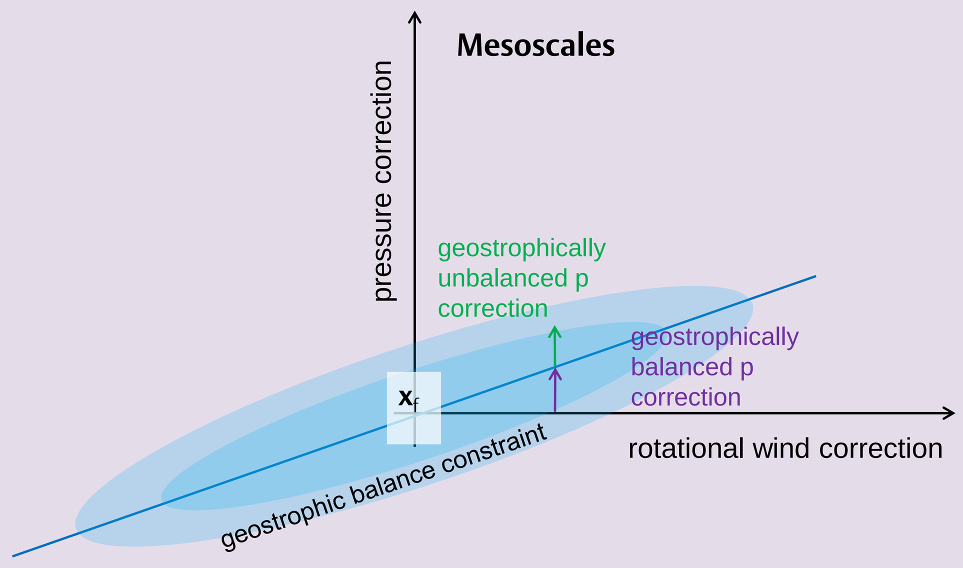
More hydrostatic balance (blue), less hydrostatic balance (red) as a function of the scale of motion (averaged in region of precip.)

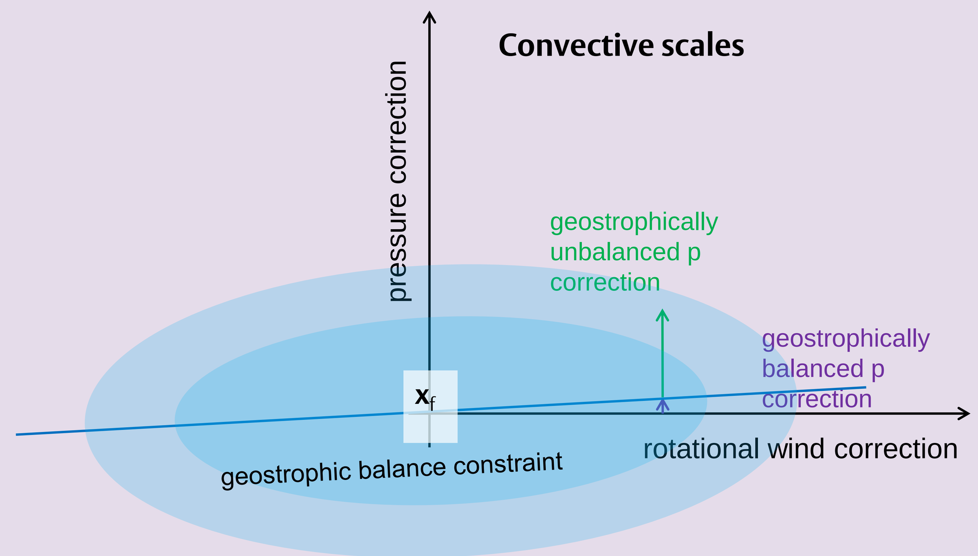


How can the imposition of geostrophic balance be relaxed at small scales for data assimilation?

The imposition of geostrophic balance may be made scale-dependent in a prescribed way.







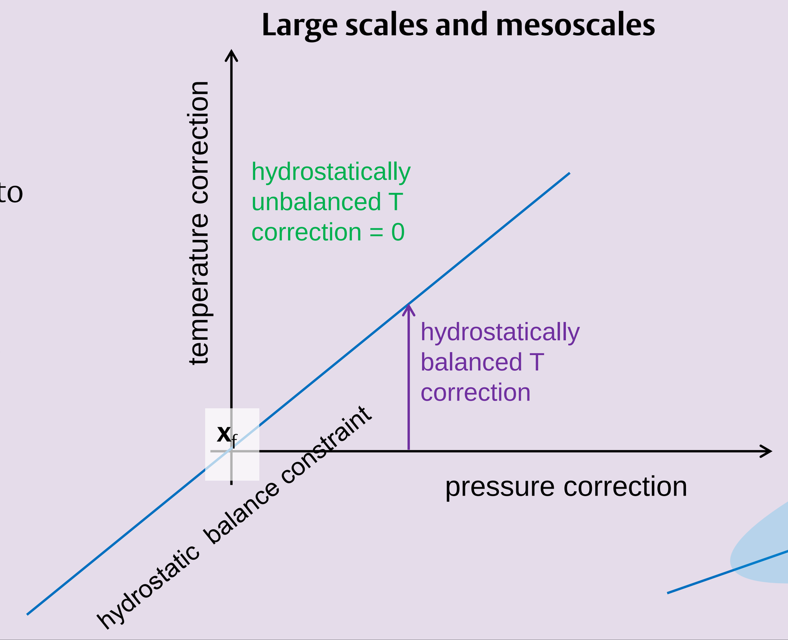
How can the imposition of hydrostatic balance be relaxed at small scales for data assimilation?

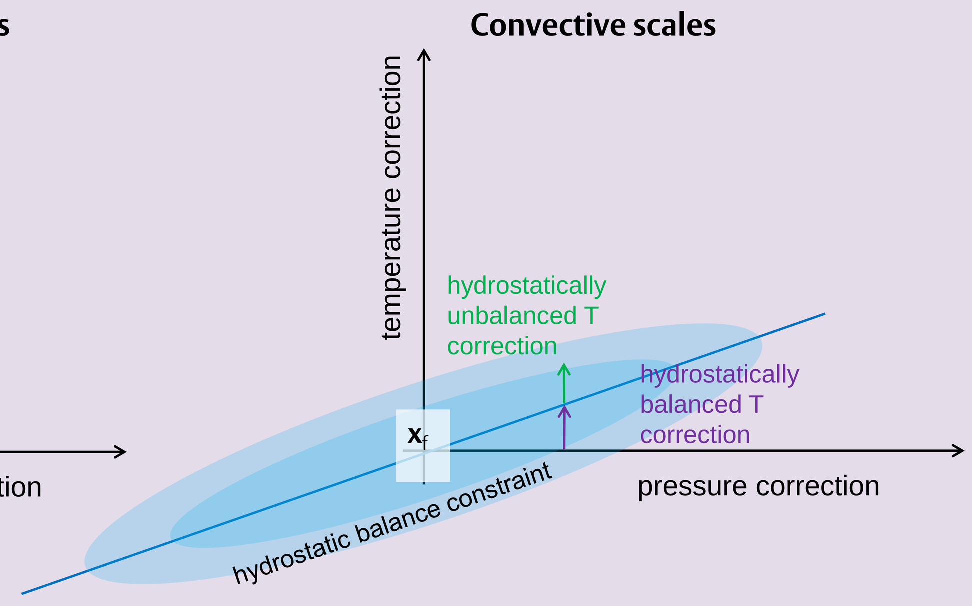
There are a number of ways that this could be done depending upon the approximations that one is willing to be made.

A. Assume that p is a hydrostatically balanced variable (i.e. that p can be used to calculate hydrostatic T with the hydrostatic balance relation), but allow for the possibility of a non-hydrostatic T component.

B. Allow for the possibility of non-hydrostatic T and non-hydrostatic p, but assume that another form of balance is appropriate (e.g. anelastic balance).

This is important for convective-scale data assimilation because hydrostatic balance is disturbed in regions of strong convection, such as inside a thunderstorm.





- For (A) the DA system has a hydrostatic T correction (computed using the hydrostatic balance relation from the p correction) and a non-hydrostatic T correction (left).
- For (B) the hydrostatic T correction is computed in the same way as in (A), but instead of applying the hydrostatic relation to the total p correction, it is applied only to the hydrostatic part of p. The non-hydrostatic p correction is found on theoretical grounds by assuming anelastic balance (3-D mass flux is divergence-free).

Summary

- The uncertainty of a forecast is extremely important in data assimilation:
  - Components of a forecast that are well-known (small error variance) are allowed to be modified only slightly.
  - Components of a forecast that are poorly-known (large error variance) all allowed to be modified significantly.
  - This information is represented pictorially as an 'error bubble' and needs to be carefully quantified in data assimilation.
- Most contemporary data assimilation systems model this error bubble by assuming that balance relations that are valid for large-scale flow (geostrophic and hydrostatic balance) are universal.
- Weather prediction models are now capable of dealing with fine-scale processes. In order for data assimilation to be useful for these models, these balance assumptions need to be relaxed.
- The DIAMET project and the NCEO are doing research to lay the foundation for such a data assimilation system.

Associated research questions

- How closely is anelastic balance obeyed at the convective scale?
- How are the balances affected by model error (it is often necessary to add model error to forecasts to represent the variability of forecast error)?
- How easily and efficiently can the above proposed schemes be implemented in an operational data assimilation system?