# Ideas for adding flow-dependence to the Met Office VAR system.

ECMWF Seminar, June 2007

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*Meteorological R & D*
*Exeter, UK*

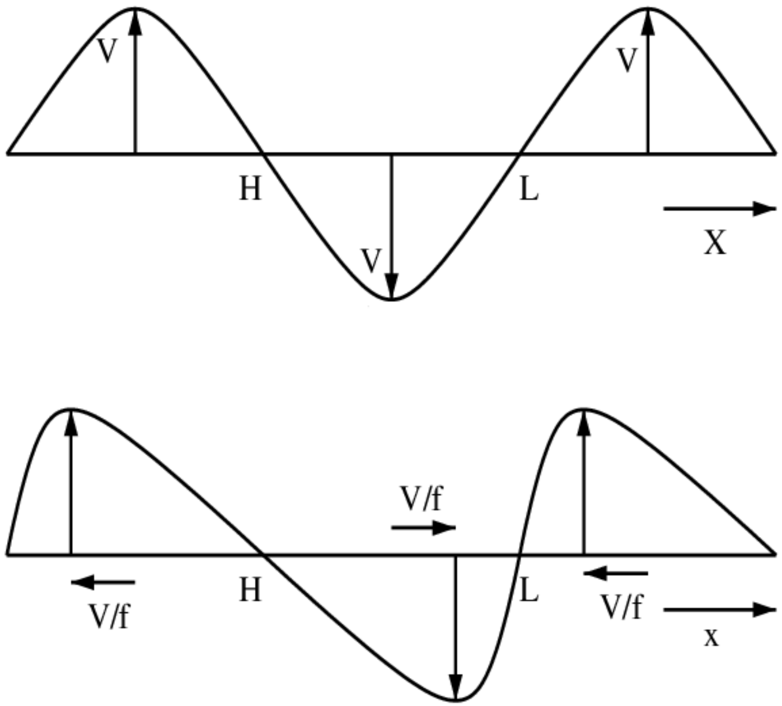
# Outline

- Ideas tried during development of VAR system (1993 start, 1999 3D-Var, 2004 4D-Var):
  - Geostrophic Coordinate transform.
  - Error Modes Of The Day.
  - 4D-Var.
  - Assimilation of layer clouds.
- Comments.
- Plans.

# Geostrophic Coordinate transform

$$x_G = x_R + \frac{1}{f} v_g$$

$$y_G = y_R - \frac{1}{f} u_g$$




Mark Dubal

Desroziers, Gerard 1997: "A coordinate change for data assimilation in spherical geometry of frontal structures" *Mon. Wea. Rev.*, **125**, 3030-3039.

# GC transform – Met Office implementation

- **U** (=$\mathbf{U}_p\mathbf{U}_g\mathbf{U}_v\mathbf{U}_h$) converts ***v*** to ***w'***.
- $\mathbf{U}_g$ operates on $\chi'$, $\psi'$, $Ap'$, and $\mu'$ along global model layers (no LAM version).
- Uses smoothed LS rotational wind instead of geostrophic.
- Displacement is like semi-lagrangian advection, with departure point calculation and interpolation.

*Mark Dubal*

- After trials, development was suspended in favour of EOTD modes (next).

# Error Modes Of The Day

- Idea is to use EOTD modes to fit observations, as well as standard control variables:

$$J(\mathbf{w}',\boldsymbol{\alpha}) = \tfrac{1}{2}\mathbf{w}'^T\,\mathbf{B}^{-1}\mathbf{w}' + \tfrac{1}{2}\boldsymbol{\alpha}^T\mathbf{C}^{-1}\boldsymbol{\alpha} + \tfrac{1}{2}\left(\mathbf{y}-\mathbf{y}^o\right)^T\mathbf{R}^{-1}\left(\mathbf{y}-\mathbf{y}^o\right)$$

$$\mathbf{y} = H\left(\mathbf{x}^g + \mu_1\mathbf{w}' + \mu_2\mathbf{X}^f \circ \boldsymbol{\alpha}\right)$$

- If $\mathbf{X}^f$ are ensemble perturbations, then variational determination of **α** is equivalent to mean analysis in localised ensemble Kalman filter (Lorenc 2003, Wang et al. 2007).

# Variational use of EnKF covariance (1)

## Basic EnKF

$$\mathbf{P}_e^f = \mathbf{X}^f \mathbf{X}^{fT} .$$

Define transform from $\boldsymbol{\alpha}$ : $\mathbf{x} = \overline{\mathbf{x}^f} + \mathbf{X}^f \boldsymbol{\alpha}$ .

Let covariance $\mathbf{B}_{(\alpha)} = \langle \boldsymbol{\alpha}\boldsymbol{\alpha}^T \rangle = \mathbf{I}$ .

Then $\left\langle \left(\mathbf{x} - \overline{\mathbf{x}^f}\right)\left(\mathbf{x} - \overline{\mathbf{x}^f}\right)^T \right\rangle = \mathbf{P}_e^f$ .

So the variational analysis for the transformed variable $\boldsymbol{\alpha}$ is obtained by minimising

$$J(\alpha) = \tfrac{1}{2}\alpha^T\alpha + \tfrac{1}{2}\left(\mathbf{y} - \mathbf{y}^o\right)^T \mathbf{R}^{-1}\left(\mathbf{y} - \mathbf{y}^o\right)$$

$$\mathbf{y} = H\left(\overline{\mathbf{x}^f} + \mathbf{X}^f \boldsymbol{\alpha}\right)$$

(2)

Similarly, VAR can use ensemble covariances modified by a Schur product:

## *EnKF with Schur product*

Use as control variable a vector $\boldsymbol{\alpha}$ of $N$ 2D fields $\boldsymbol{\alpha}_i$, each with covariance C.
The variational problem is then to minimise

$$J(\alpha)=\tfrac{1}{2}\alpha^T\begin{pmatrix}\mathbf{C} & & 0\\ & \ddots & \\ 0 & & \mathbf{C}\end{pmatrix}^{-1}\alpha+\tfrac{1}{2}\left(\mathbf{y}-\mathbf{y}^o\right)^T\mathbf{R}^{-1}\left(\mathbf{y}-\mathbf{y}^o\right)$$

$$\mathbf{y}=H\left(\overline{\mathbf{x}^f}+\left(\mathbf{X}^f\circ\boldsymbol{\alpha}\right)\begin{pmatrix}1\\ \vdots\\ 1\end{pmatrix}\right)$$

As in standard 3D-Var methods, the inversion of the block diagonal matrix is avoided by a further horizontal transform of each field $\boldsymbol{\alpha}_i$ into spectral space.

(3)

VAR can use the ensemble to augment the “traditional” covariance model with some *Errors Of The Day*.

## *Hybrid Var-EnKF with Schur product*

Use the traditional variation control variable v supplemented by α , so that we minimise

$$J(\mathbf{v},\boldsymbol{\alpha}) = \tfrac{1}{2}\mathbf{v}^T\mathbf{v} + \tfrac{1}{2}\boldsymbol{\alpha}^T \begin{pmatrix} \mathbf{C} & & 0 \\ & \ddots & \\ 0 & & \mathbf{C} \end{pmatrix}^{-1} \boldsymbol{\alpha}$$

$$+\tfrac{1}{2}(\mathbf{y}-\mathbf{y}^o)^T \mathbf{R}^{-1} (\mathbf{y}-\mathbf{y}^o)$$

$$\mathbf{y} = H\left( \mathbf{x}^g + \mathbf{U}\mathbf{v} + (\mathbf{X}^f \circ \boldsymbol{\alpha}) \begin{pmatrix} 1 \\ \vdots \\ 1 \end{pmatrix} \right)$$

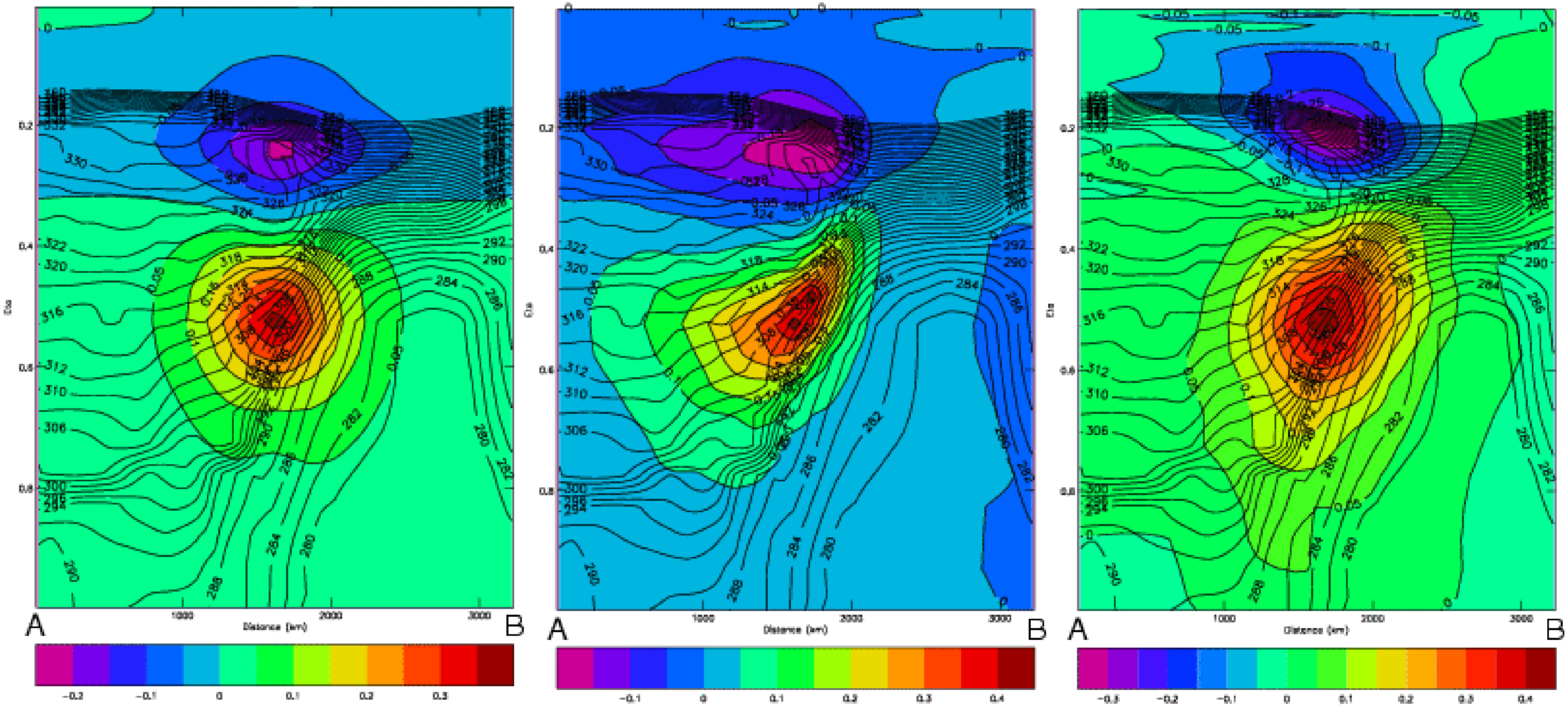
Should reduce “traditional” error covariances to compensate for those represented by the ensemble.

# Met Office implementation of EOTD modes

- Uses 2D **α** (no vertical localisation) on *χ´*, *ψ´*, *Ap´*, and *μ´*
- Tested with single mode from an error breeding system, in global system. (Code should work with more modes, and in LAM).
- Results encouraging in case studies, but no significant overall impact.
- Preconditioning and tuning needed.
- Because of small impact using 1 mode, and effort needed to develop and run EBS, testing was suspended in 2004 until MOGREPS is available in 2007.
- *Done by Dale Barker, who has continued at NCAR.*

# Response to a single T ob

Contours - UM analysis, thetal




Dale Barker EOTD expts.
Mark Dubal GCT expts.
Adrian Semple, 2001: A Meteorological Assessment of the Geostrophic Co-ordinate Transform and Error Breeding System When used in 3D Variational Data Assimilation. NWP Tech Rep 357.

# Why should 4D-Var beat 3D-Var?

*Met Office pre-operational trials showed a significant improvement for 4D-Var over similar 3D-Var.*

*This might be because 4D-Var uses:*

- more accurate times of observations;
- evolved covariances, giving dynamically consistent structure functions;
- ✗ time-tendency information from more frequent observations;
- ✗ observations of precipitation etc.

*Not in the experiments reported here.*

# Incremental VAR schemes used

- Basic 3D-Var

- 3D-Var with FGAT

  Uses First-Guess at Appropriate Time.

  Operational at Met Office before Oct 2004.

- "Synoptic" 4D-Var

  Treats obs times like 3D-Var with FGAT.

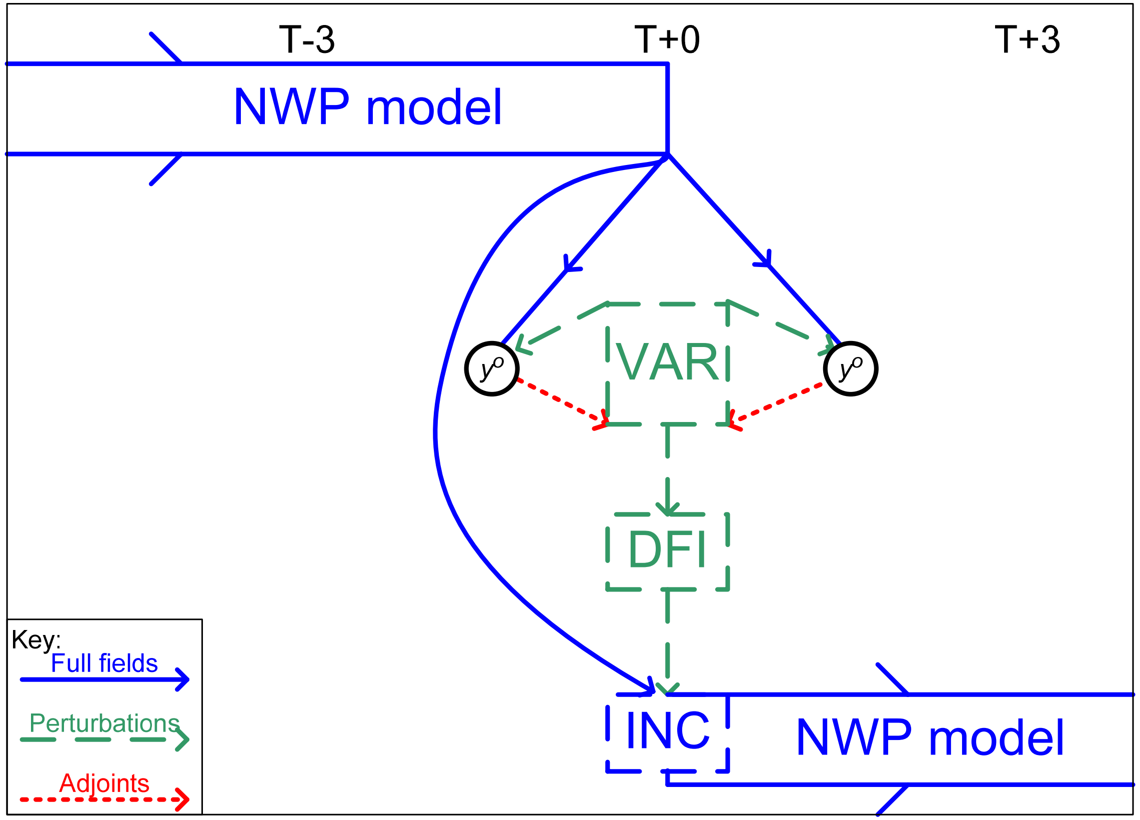
  Has evolved covariances like basic 4D-Var.

- Basic 4D-Var

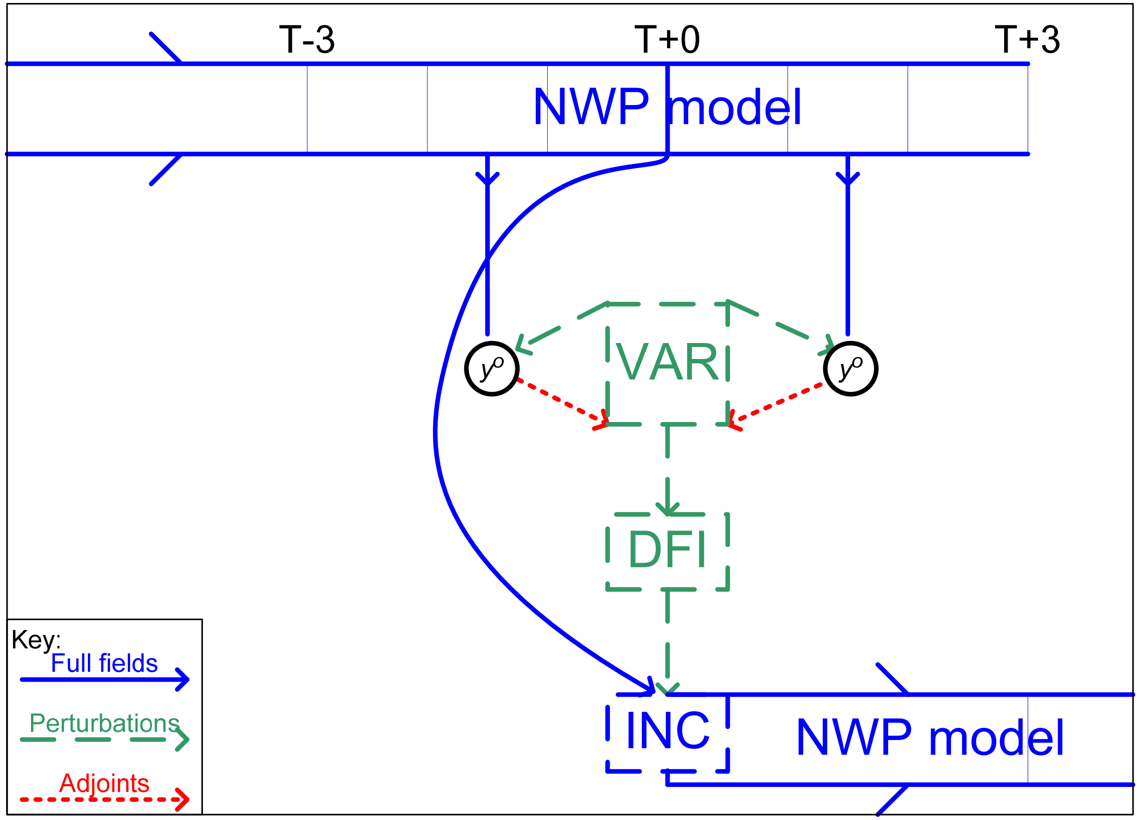
  No outer-loop iteration.  Very simple physics.

  Operational at Met Office after Oct 2004.

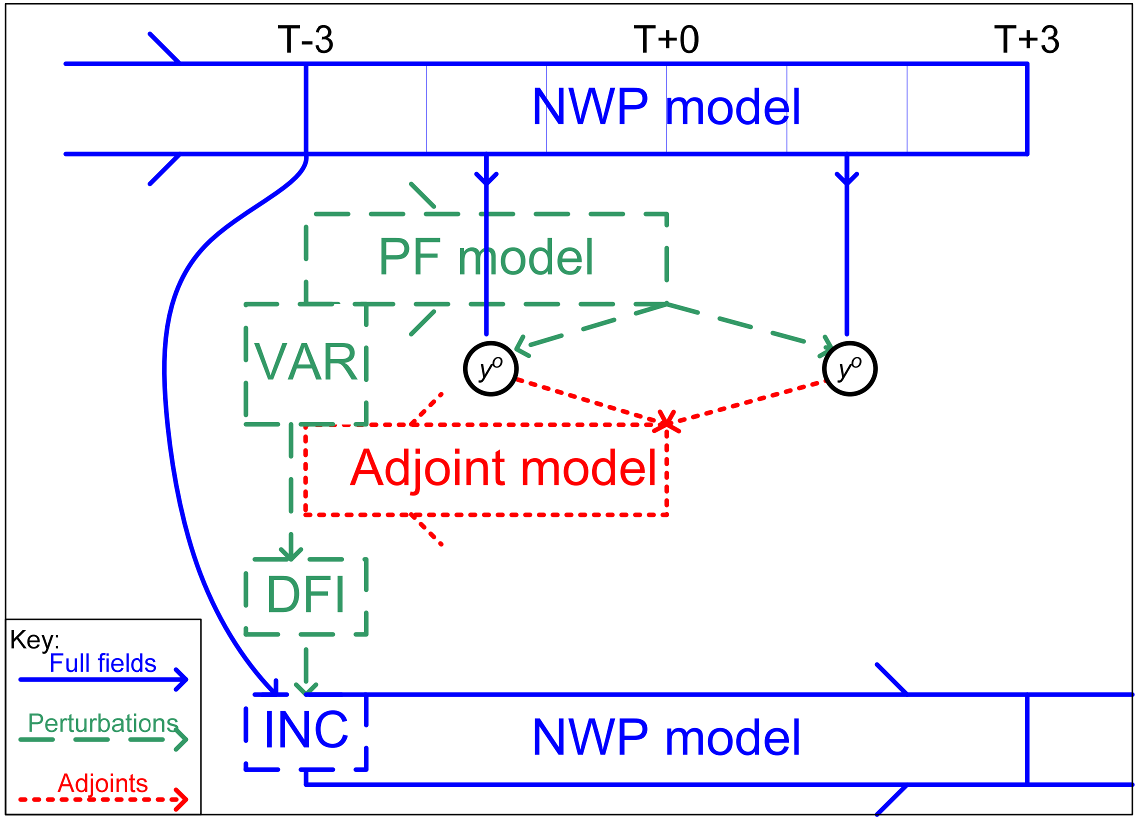
# Basic 3D-Var


T-3
T+0
T+3
NWP model
VAR
DFI
INC
NWP model
Key:
Full fields
Perturbations
Adjoints

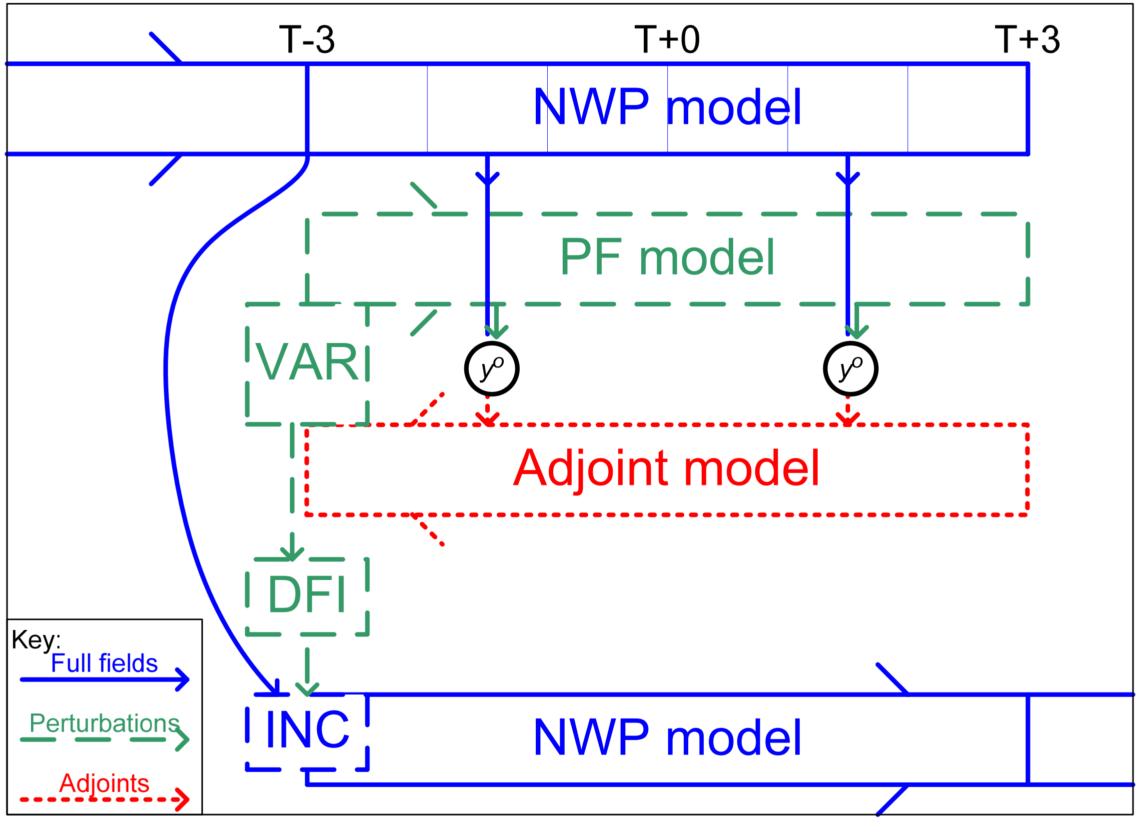
# 3D-Var with FGAT



# Synoptic 4D-Var



# Basic 4D-Var



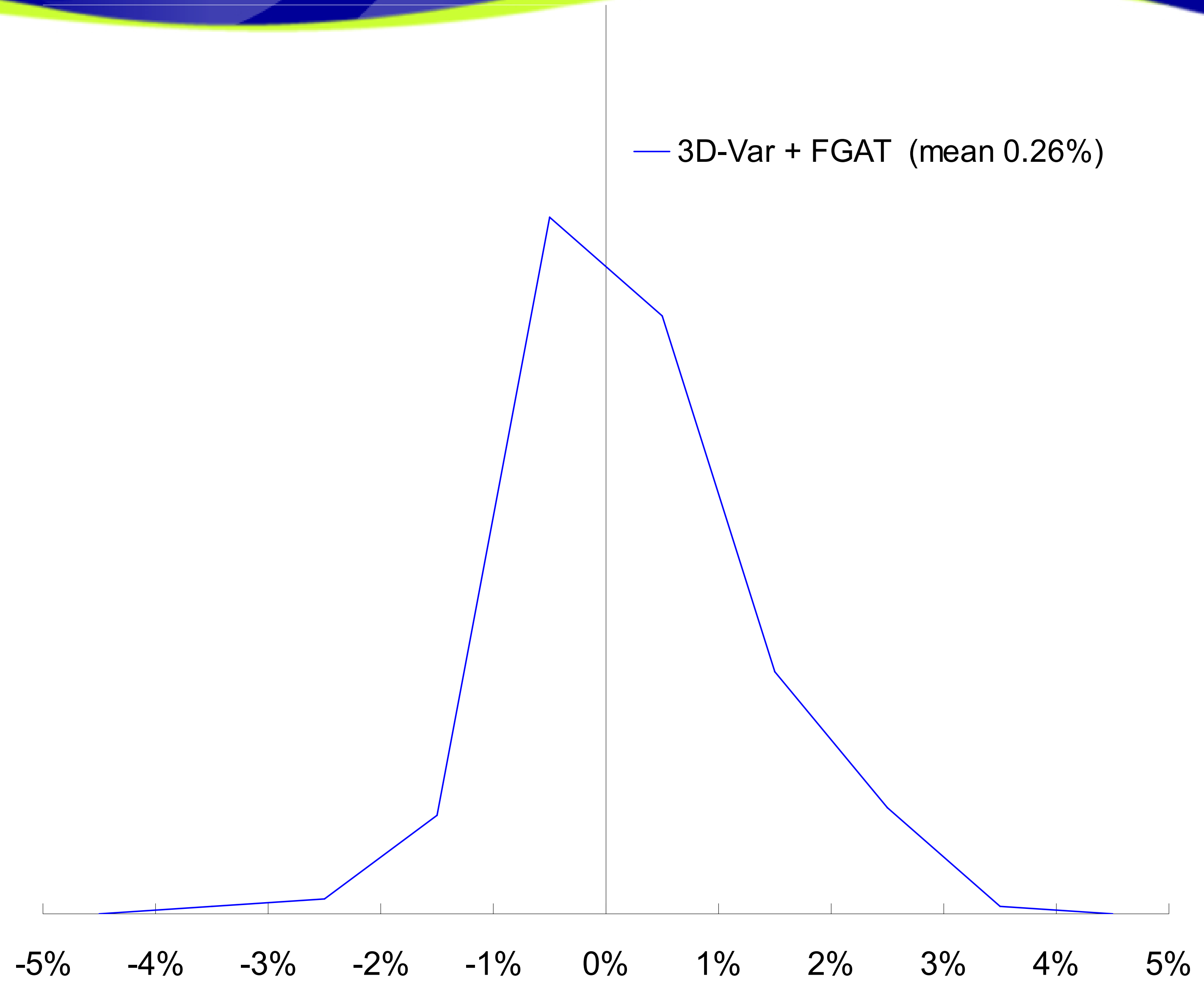
T-3
T+0
T+3
NWP model
PF model
VAR
$y^o$
$y^o$
Adjoint model
DFI
INC
NWP model
Key:
Full fields
Perturbations
Adjoints

# Experimental design

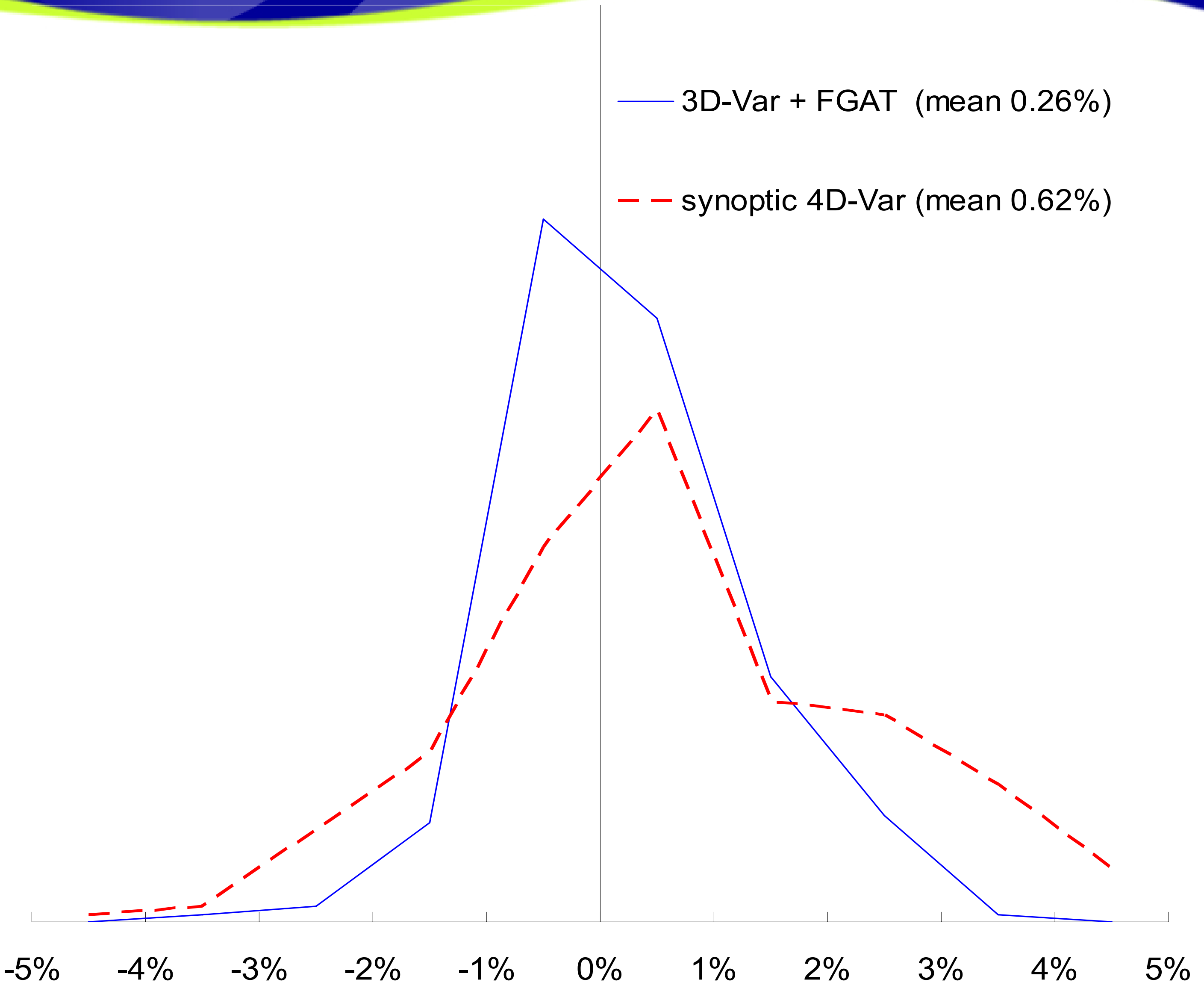
- Parallel trials for July 2003.
- 6hr cycle with a 6day forecast each 12Z.
- Much lower resolution (N48) than operational.
- Observation selection tuned for 3D-Var.
- 234 forecast fields verified:

| | | |
|---|---|---|
| 3 areas: | Tropics and northern and southern extratropics. | |
| 6 times: | Forecast days 1 to 6. | |
| 13 fields: | 3 variables: | geopotential height, temperature and vector wind. |
| | at 4 levels: | 850, 700, 500 and 250 hPa. |
| | Pressure at mean sea-level. | |

# Reductions in RMS verification v obs compared to Basic 3D-Var



# Reductions in RMS verification v obs compared to Basic 3D-Var



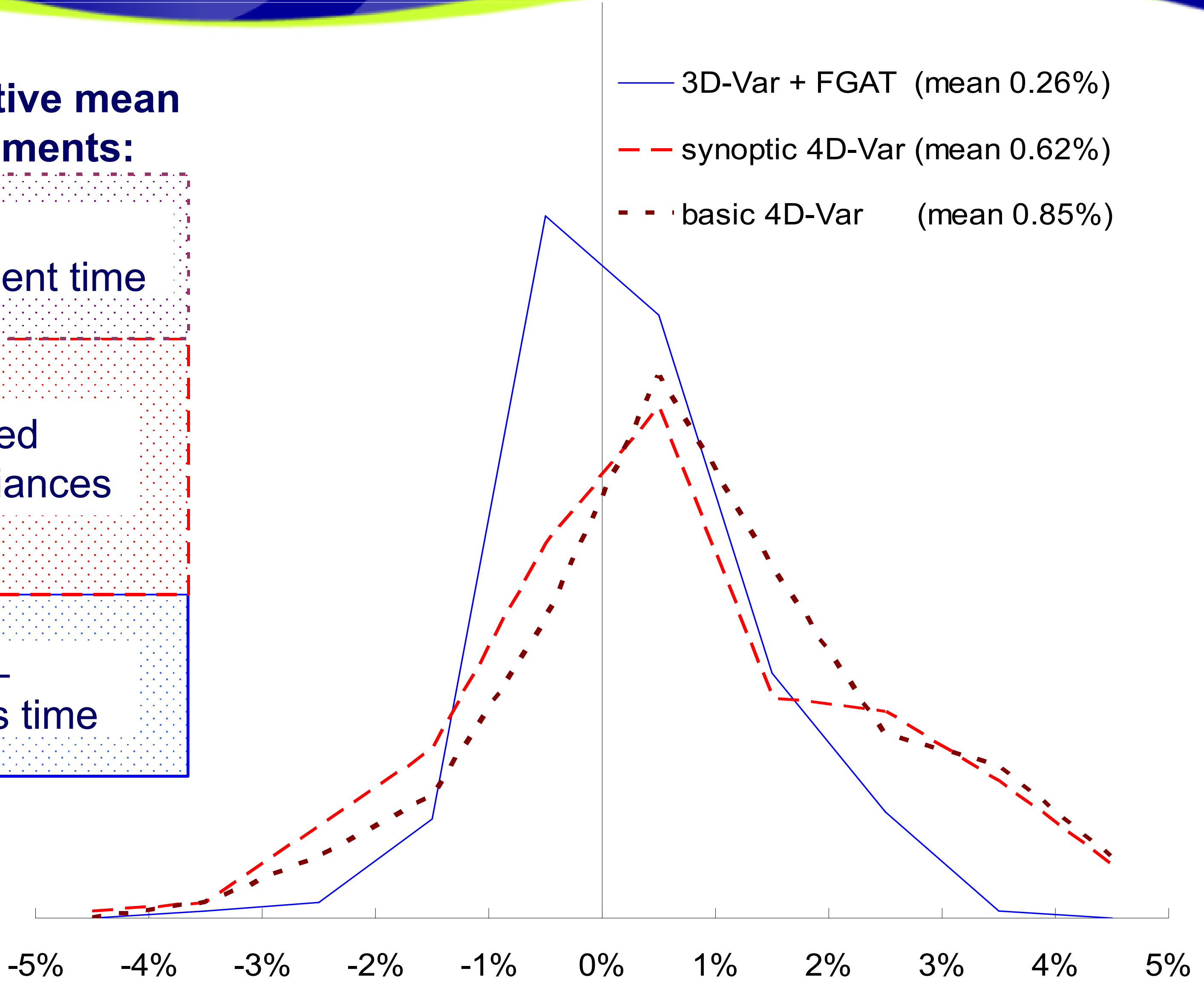
# Reductions in RMS verification v obs compared to Basic 3D-Var

**Cumulative mean improvements:**

Obs - increment time

Evolved covariances

Obs – guess time



# Cloud-topped Inversions

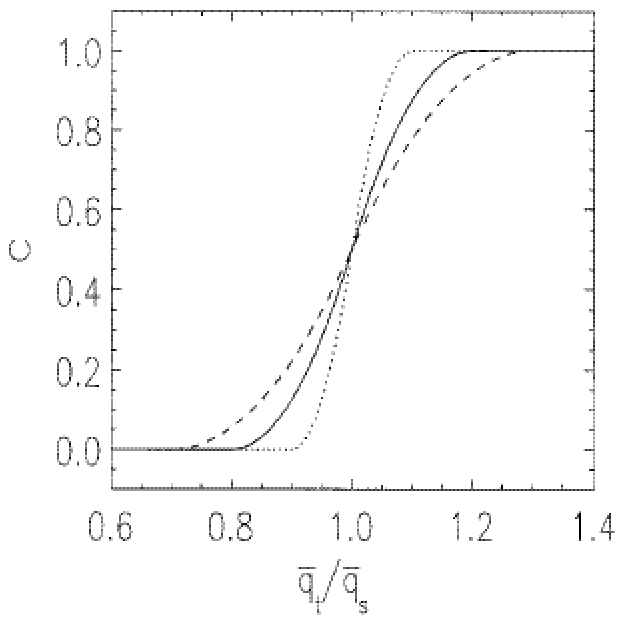
- Probably the commonest cause of forecast error in the UK is the misrepresentation of inversions and strato-cumulus layers.
- For many years we have had some success using MOPS (Macpherson et al. 1996):
  - Pre-process to give 3D cloud analysis for UK;
  - Nudge model RH towards fitting the cloud.
- It is awkward to combine MOPS nudging with 4D-Var, but direct assimilation of MOPS cloud in VAR has not done as well.
- This is because VAR's vertical correlations of RH across the inversion are too large.

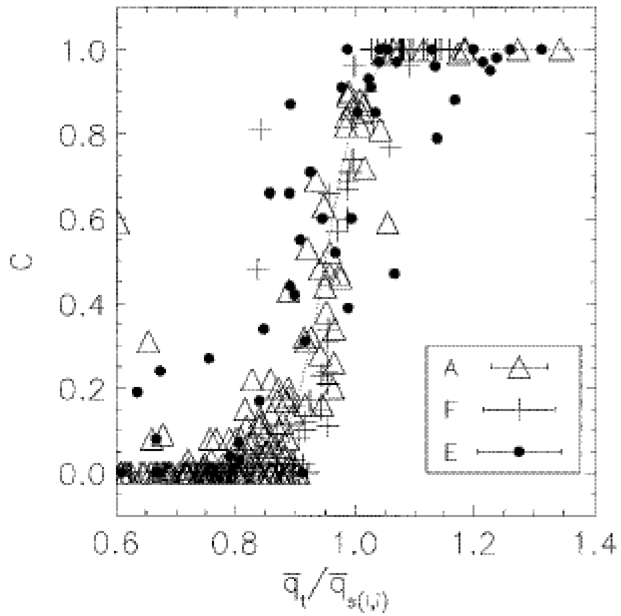
# High impact weather!




1000 flights were cancelled just before Christmas 2006

# Cloud-RH diagnostic




Smith scheme

QJRMS 1990

aircraft data

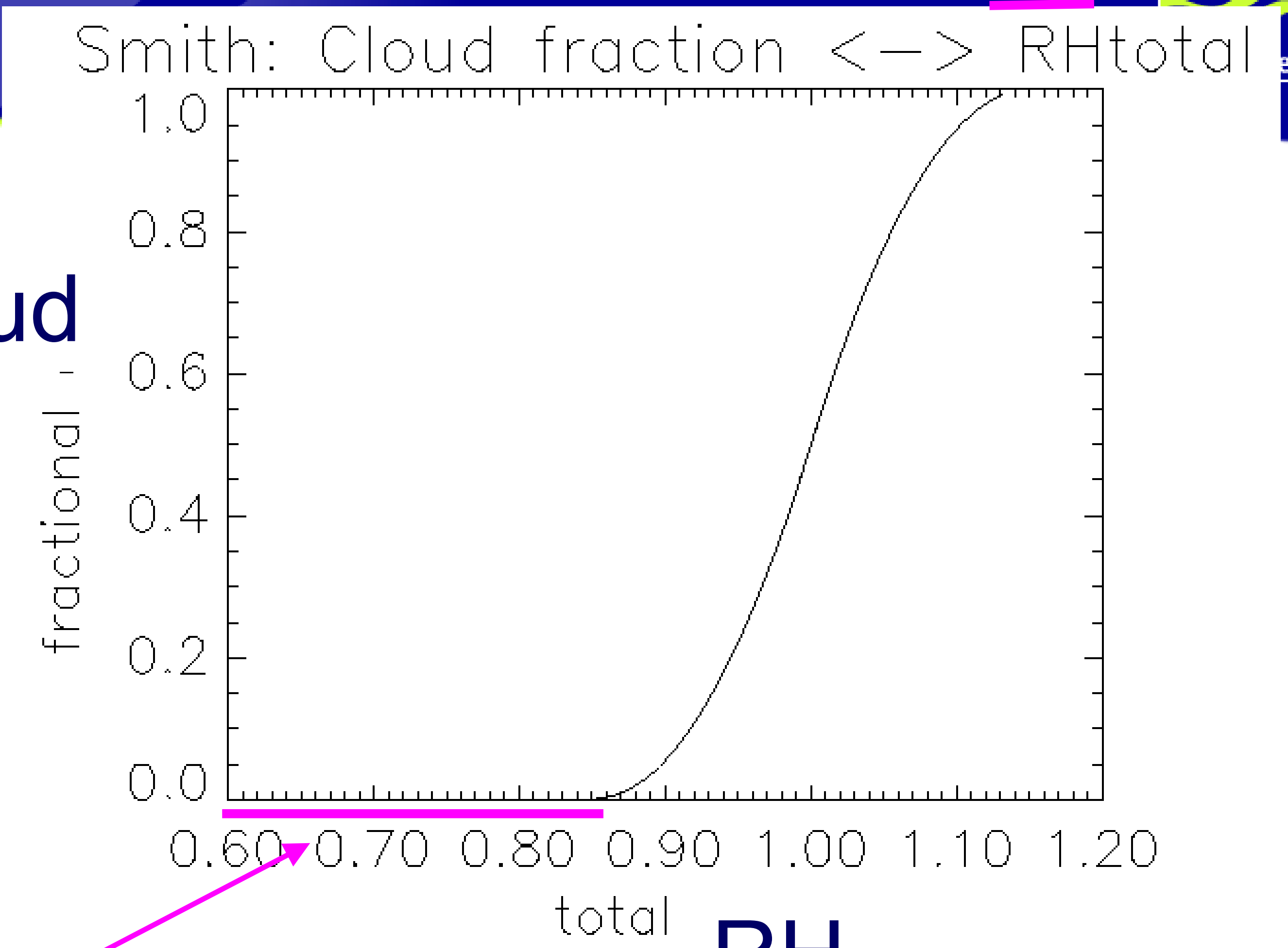
Rob Wood, JAS 2000

# observation penalty function

$$J_o = ½(y(x) - y_{ob})^2 / σ^2$$

$$\frac{\partial J_o}{\partial x} = \frac{\partial y}{\partial x}(y(x) - y_{ob}) / σ^2$$

*Richard Renshaw*




cloud

RH

d[cloud] / d[RH] = 0

*Richard Renshaw*

# observation cost function

$$J_o = \tfrac{1}{2}(x - f^{-1}(y_{ob}))^2 / \sigma^2$$

$$\frac{\partial J_o}{\partial x} = (x - f^{-1}(y_{ob})) / \sigma^2$$

$x$ = analysis RH

$f^{-1}(y_{ob})$ = "observed RH"

*Richard Renshaw*

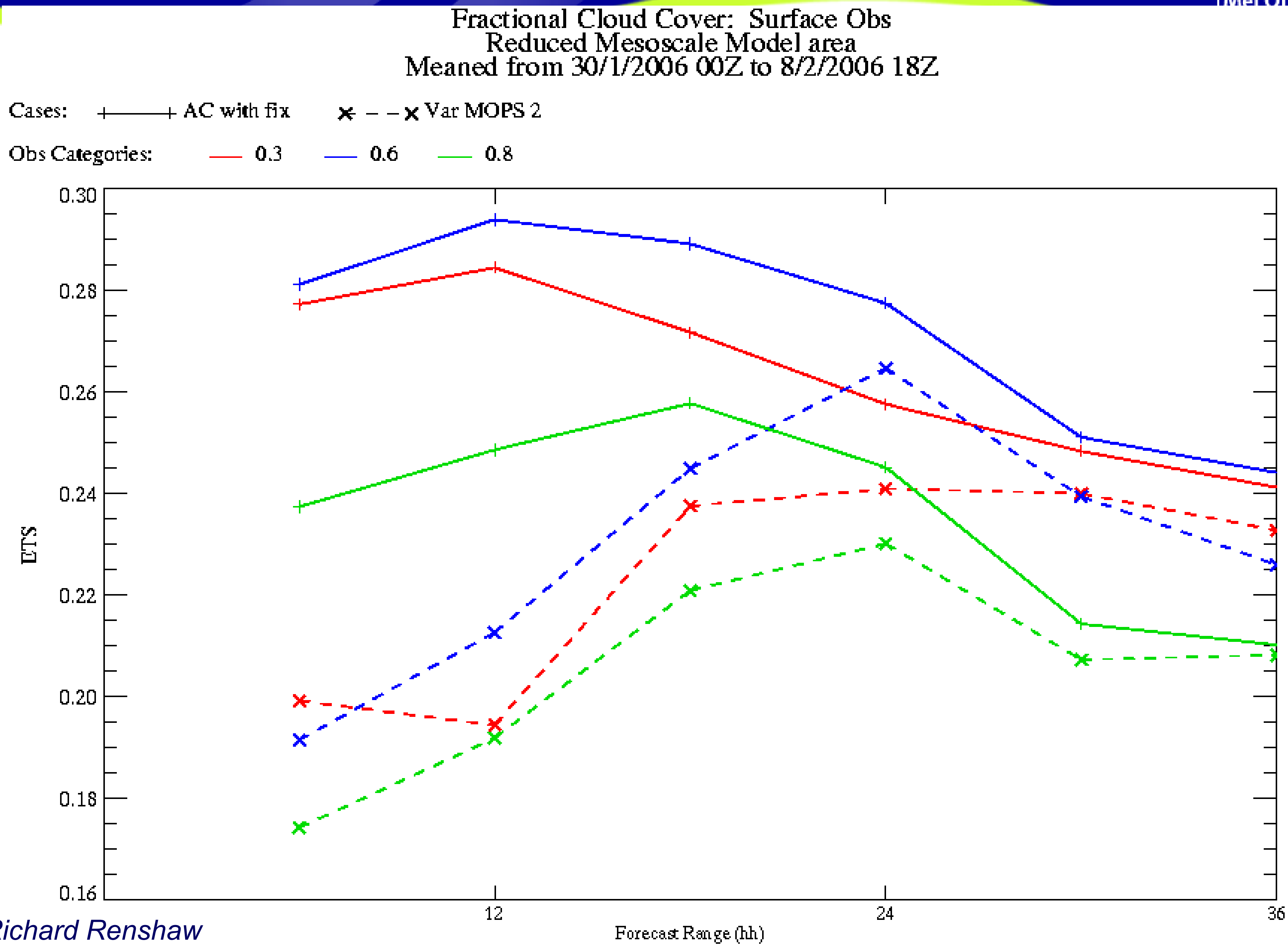
# Modification when Ob = 0 and Model Cloud = 0

$$J_o = ½ ( x – RH_{crit} )^2 /\sigma^2$$

Instead set $J_o = 0$

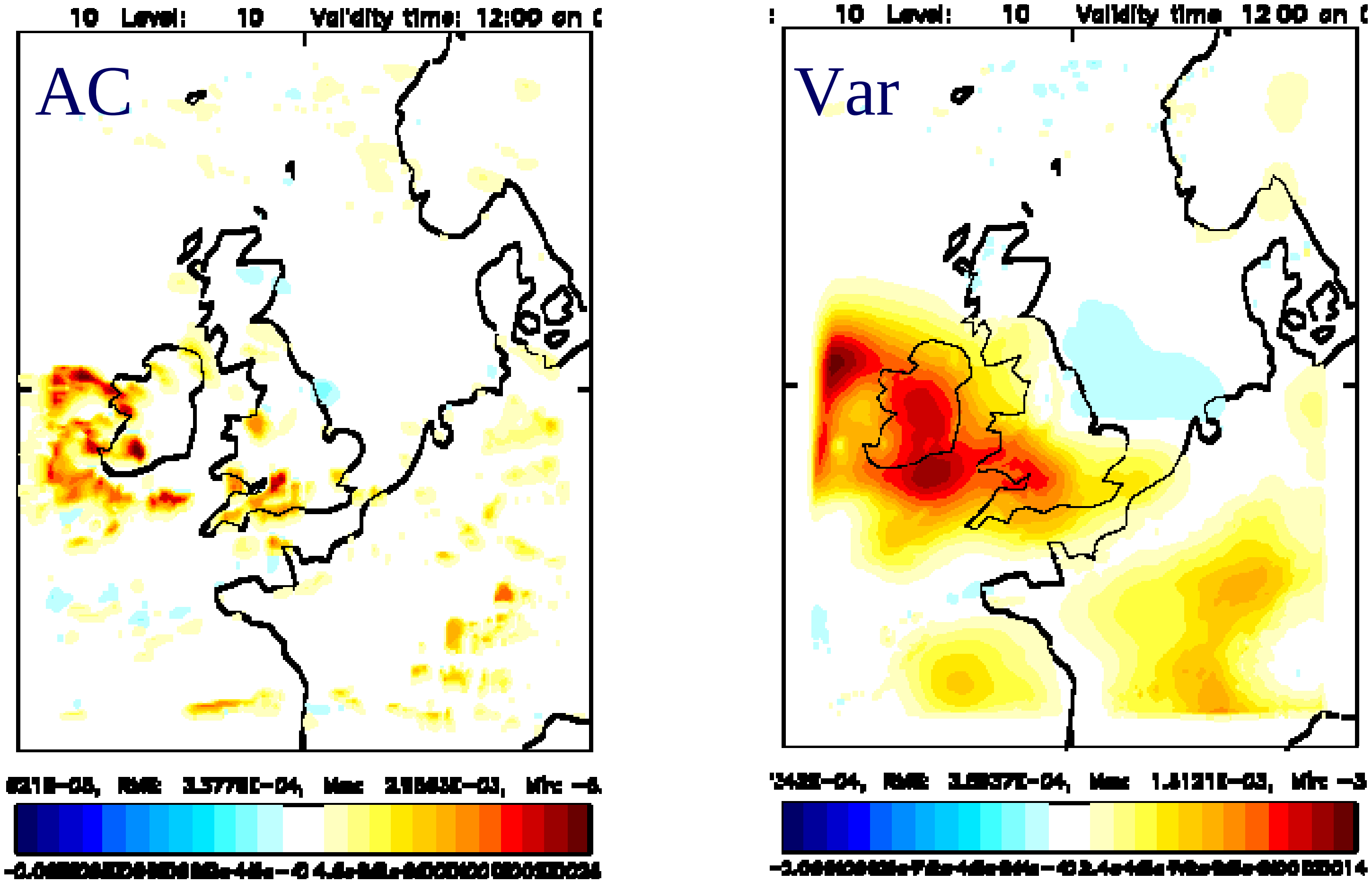
*Richard Renshaw*

# Var Cloud performance, Feb 2006 trial



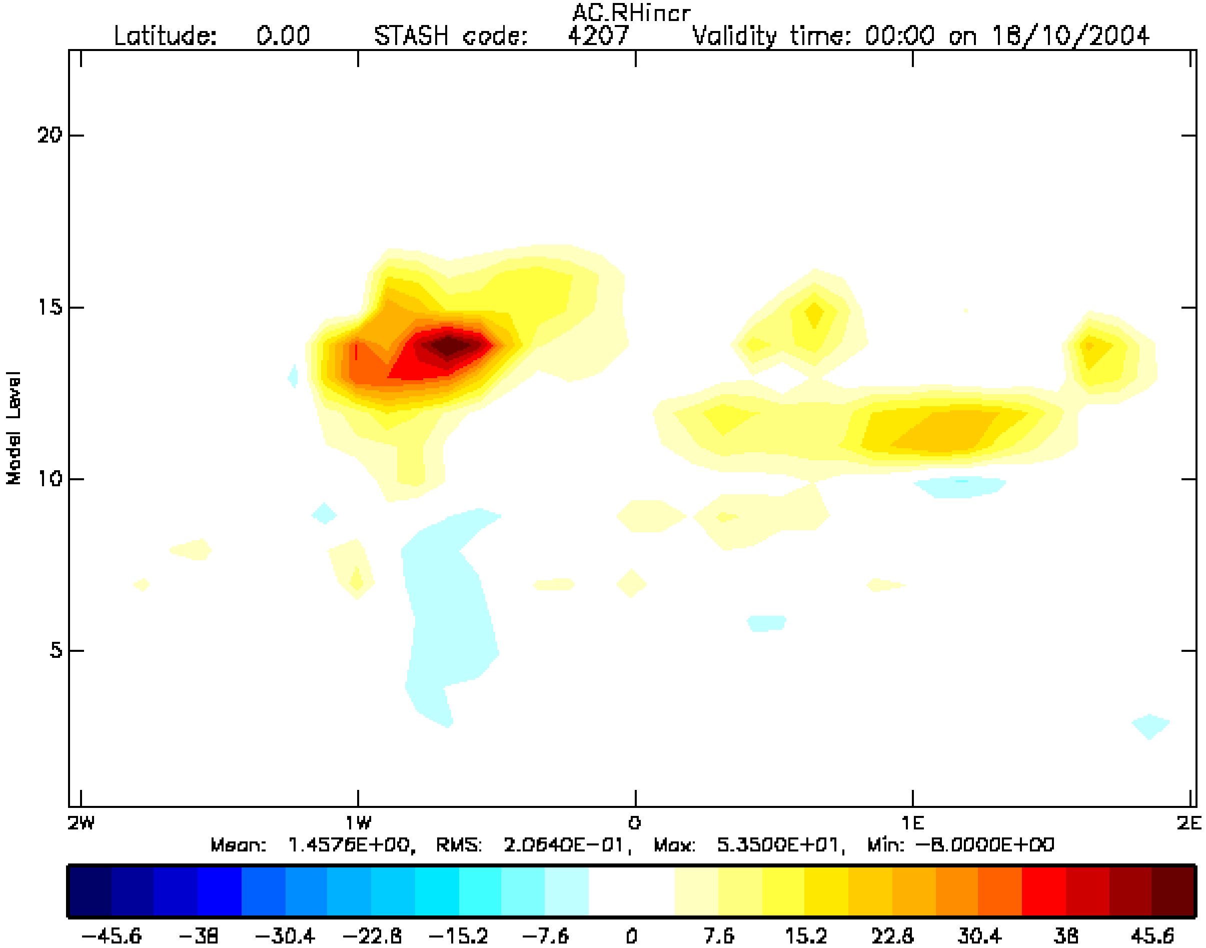

*Richard Renshaw*

# Increments to q, model level 10

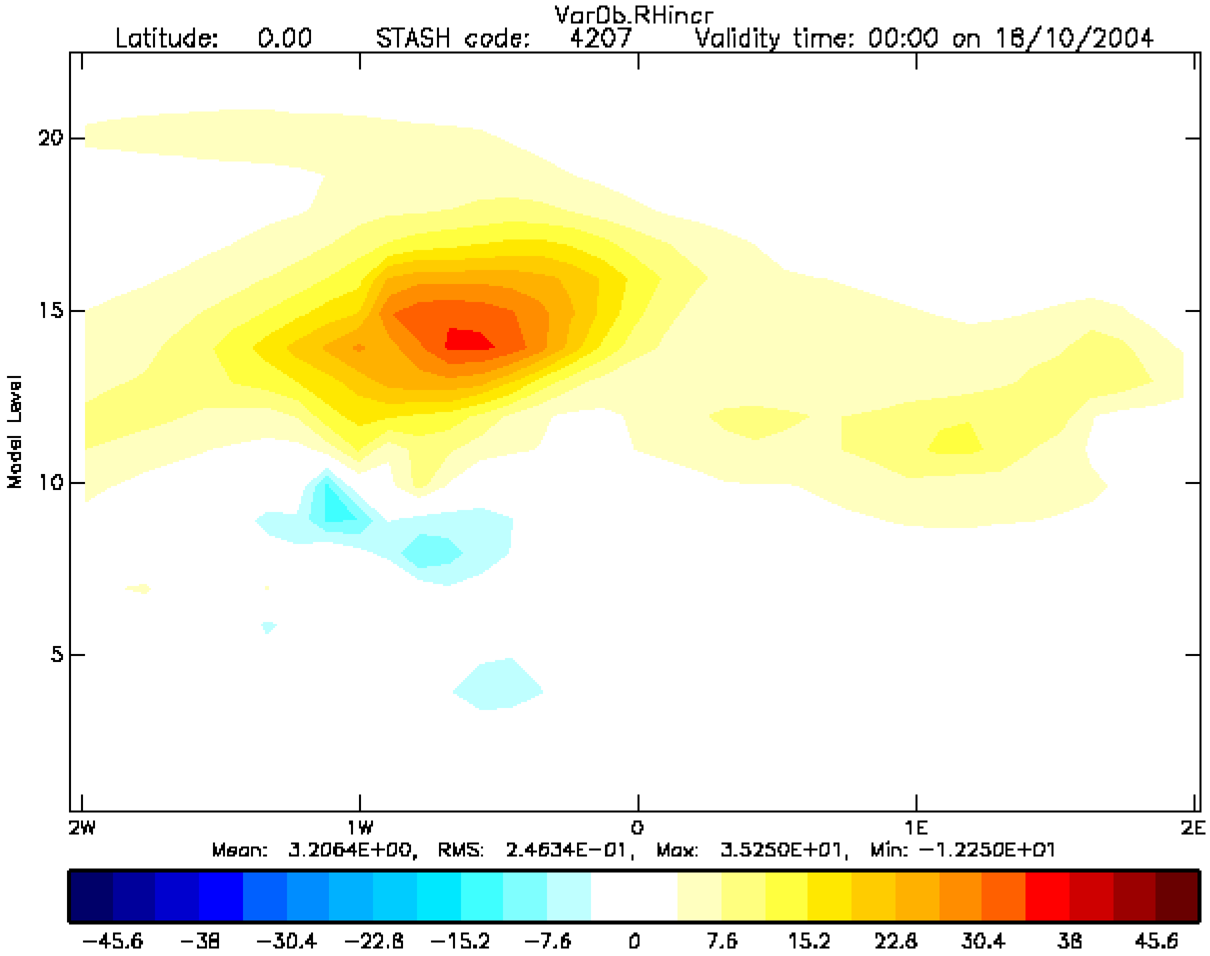



*Richard Renshaw*

# RH increments from AC

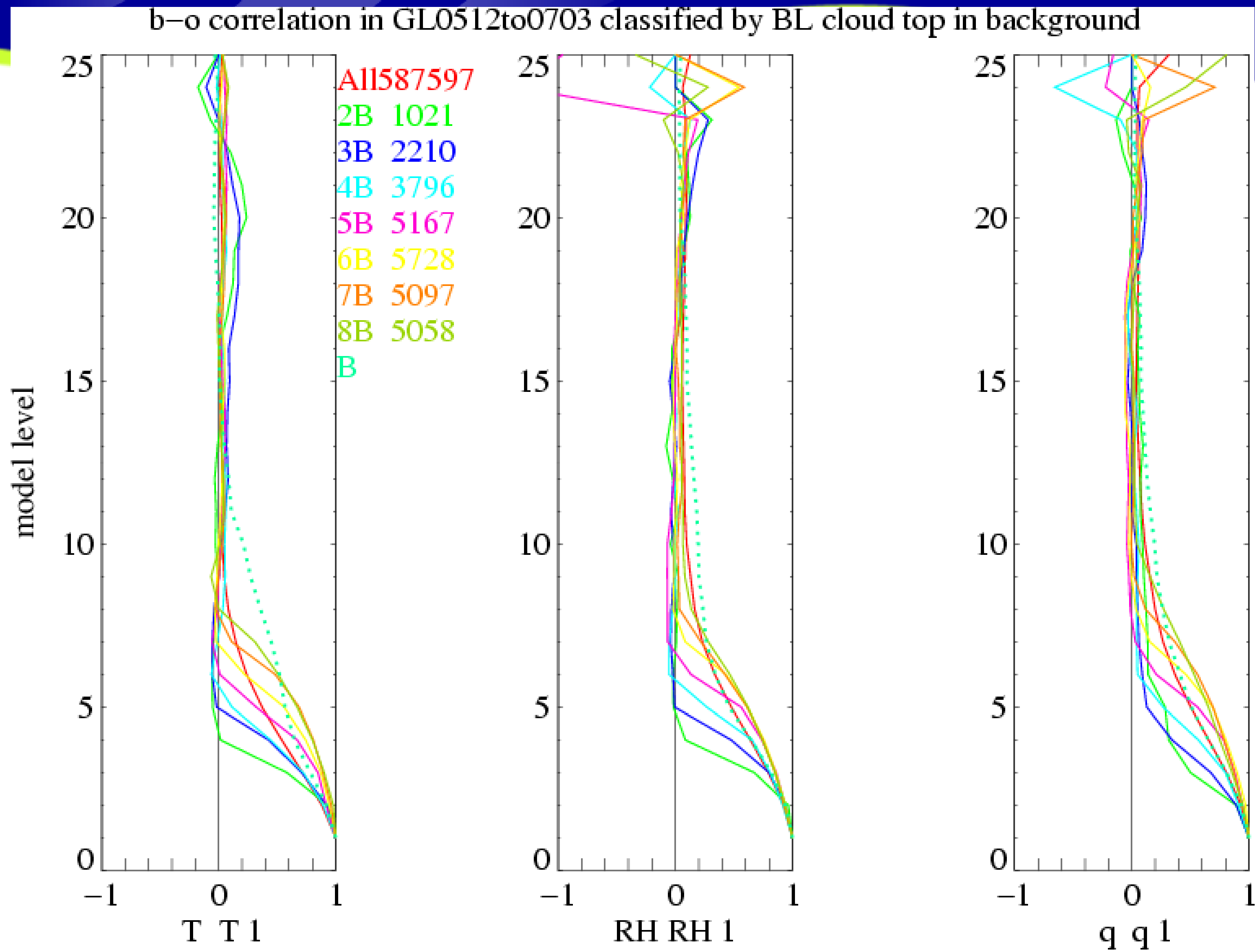


# RH increments from Var

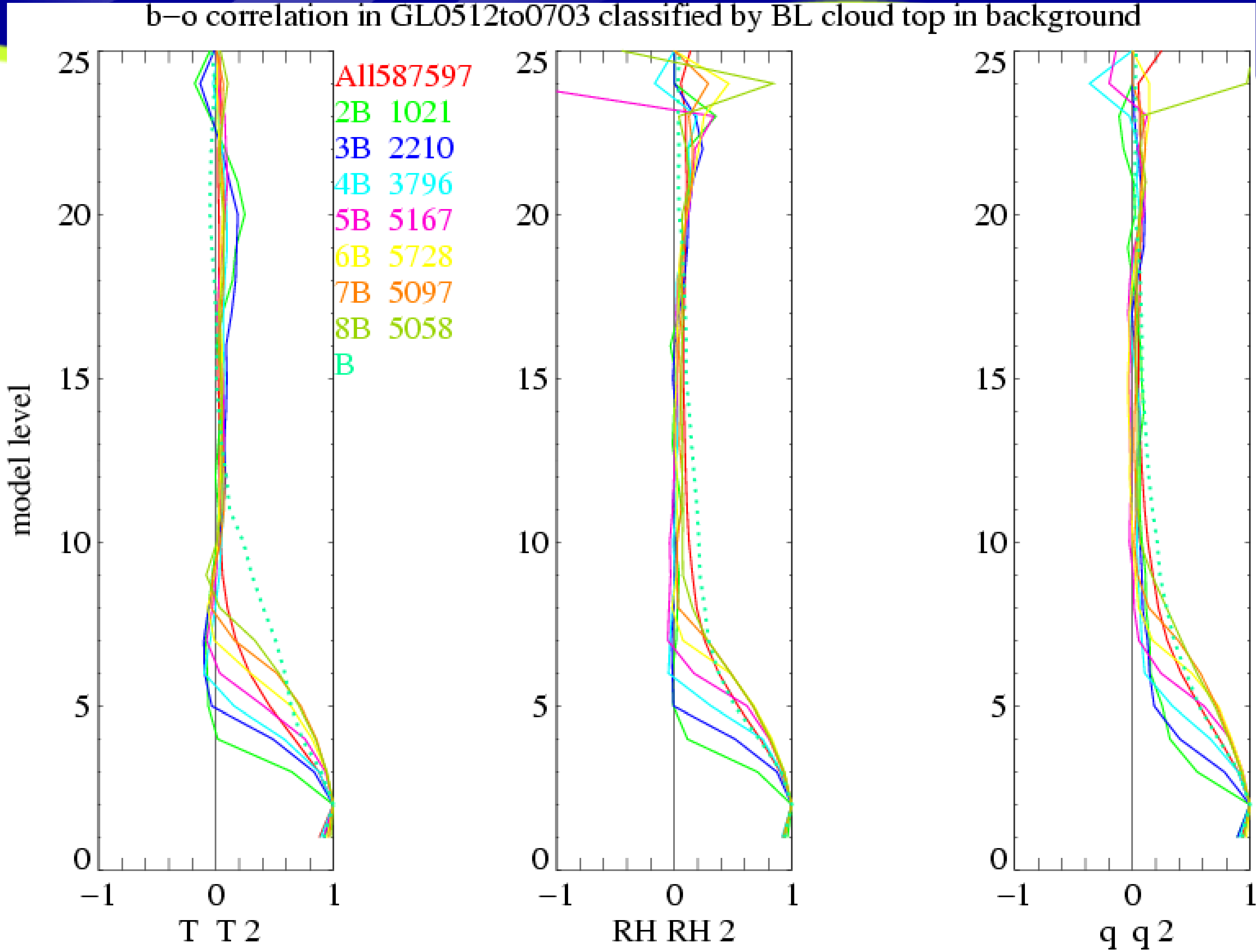



*Richard Renshaw*

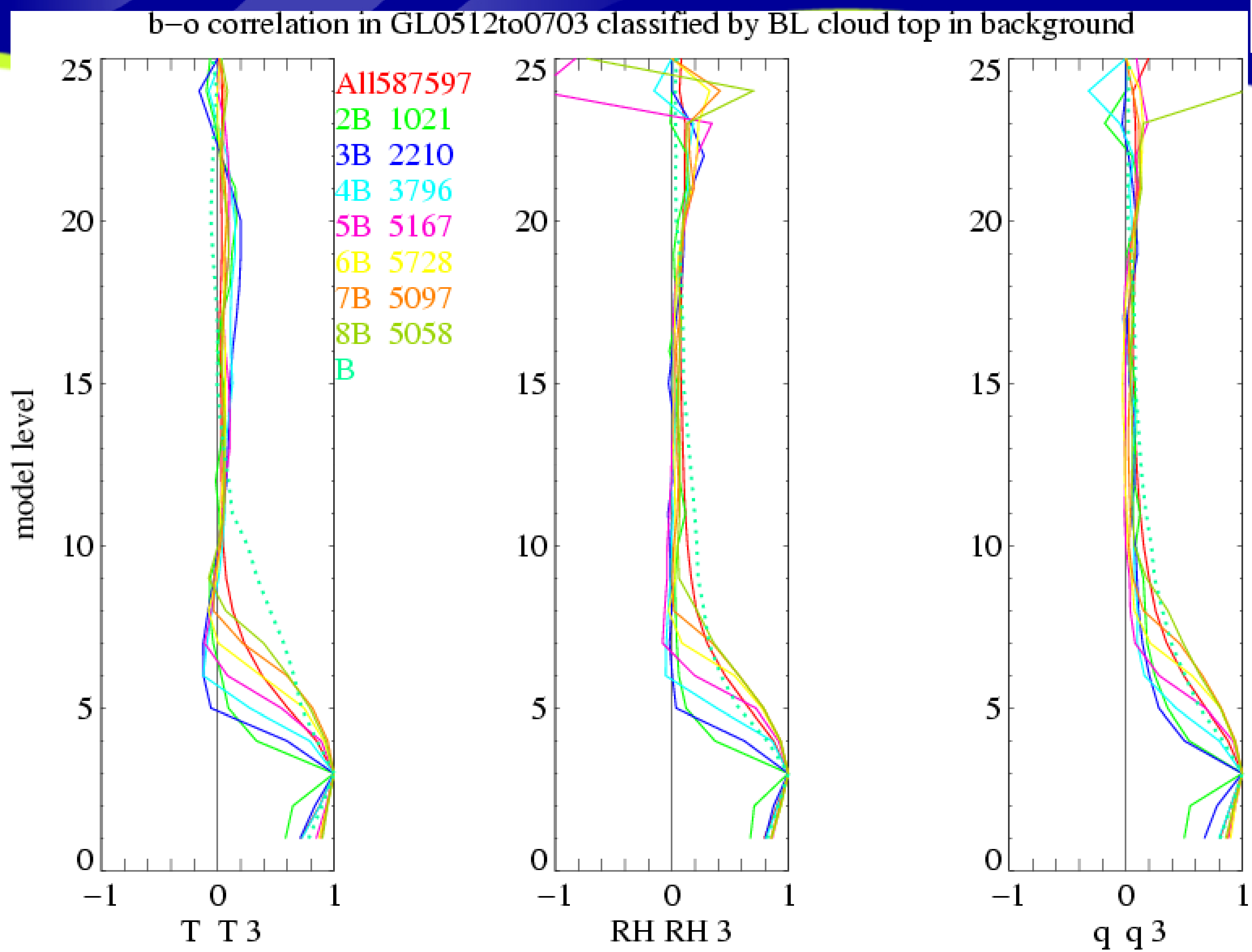
# Background-sonde correlations with model level 1



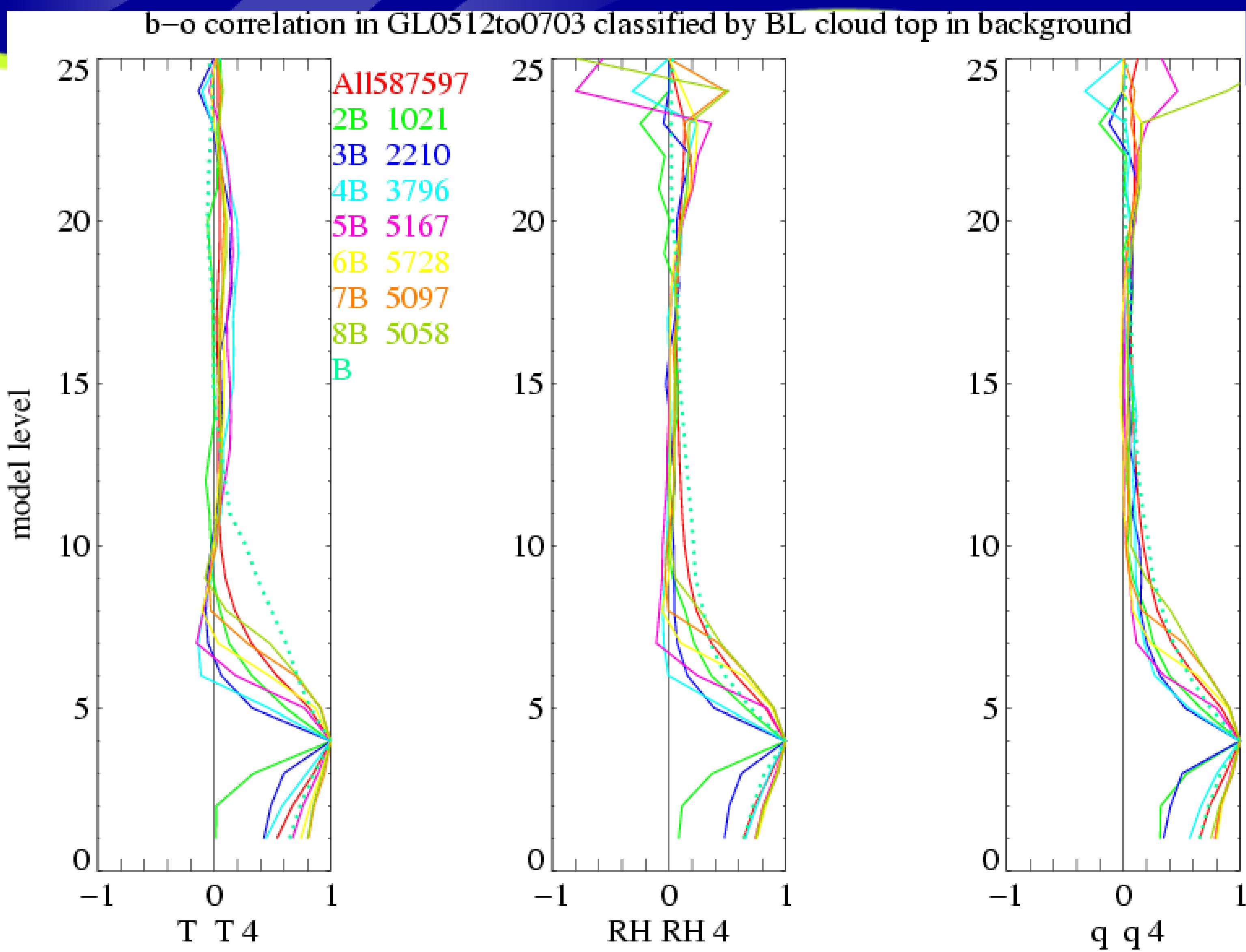
# Background-sonde correlations with model level 2



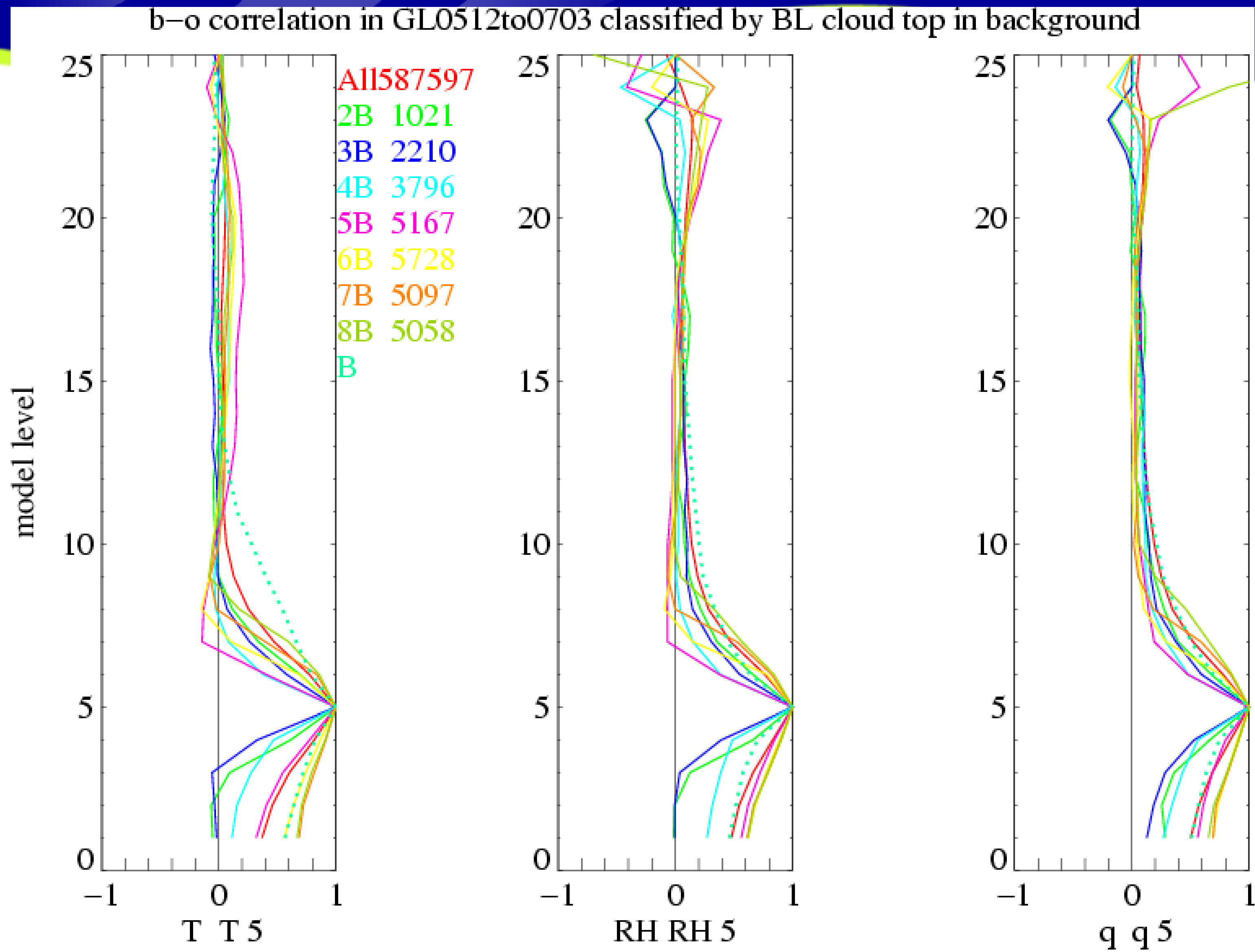
# Background-sonde correlations with model level 3



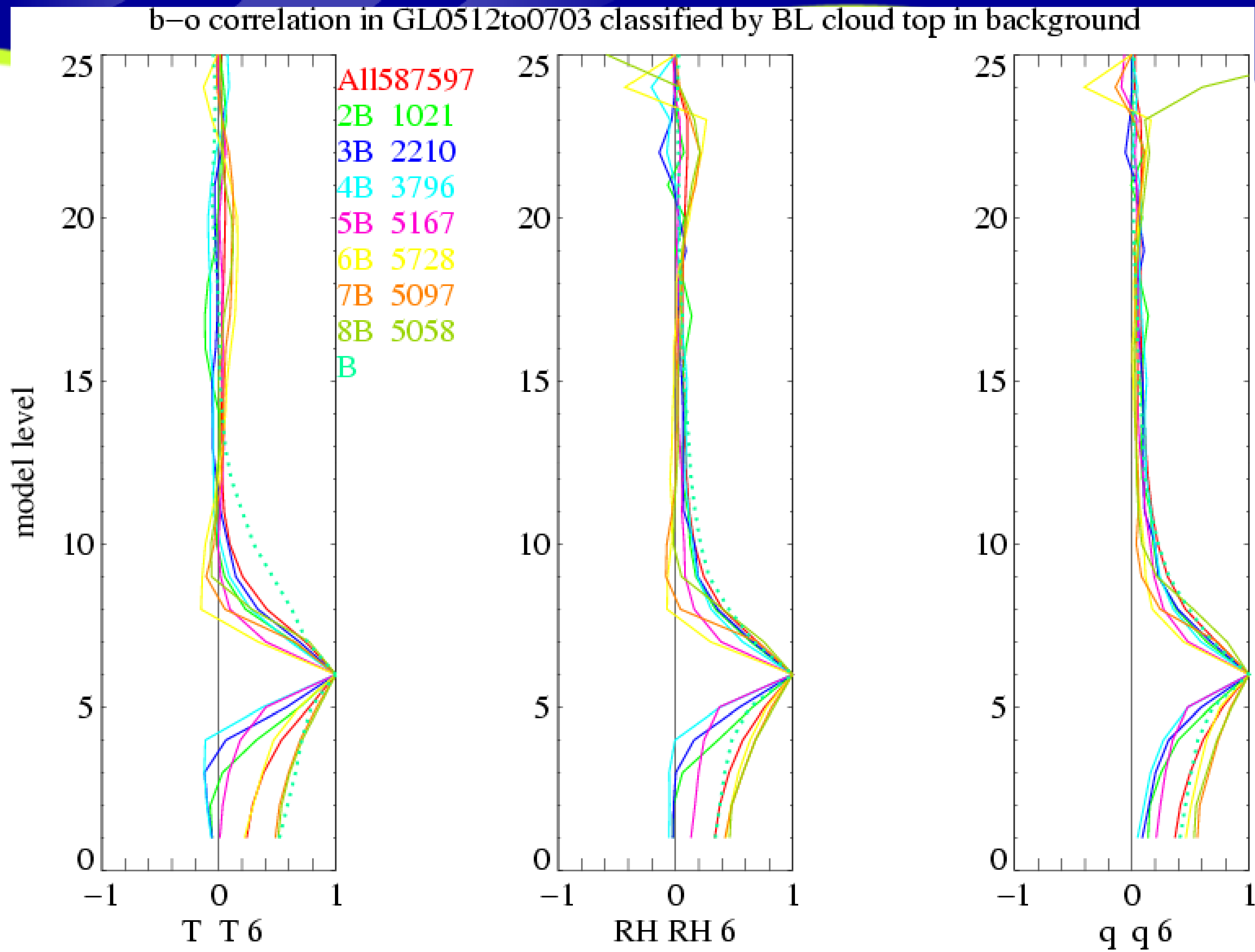
# Background-sonde correlations with model level 4



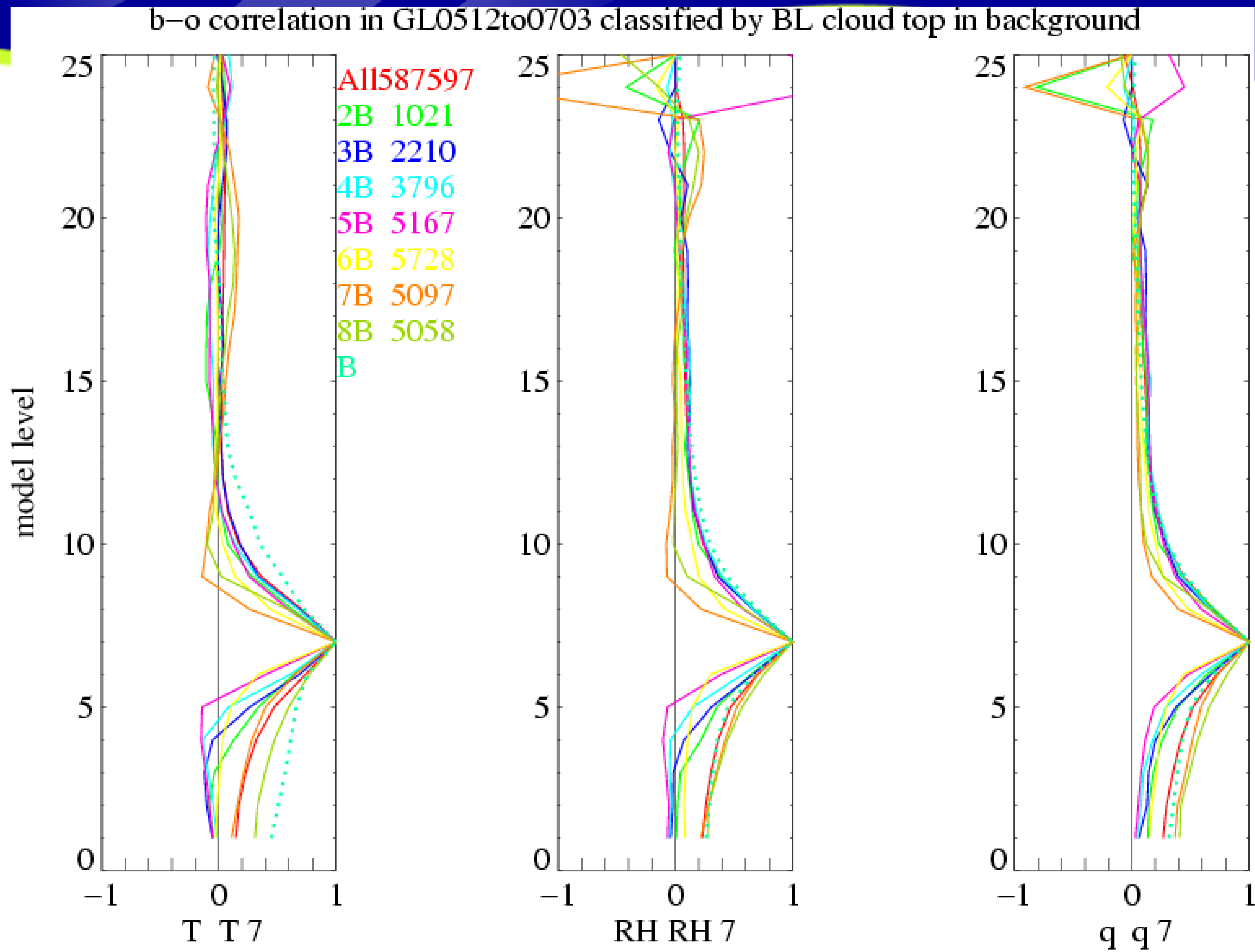
# Background-sonde correlations with model level 5



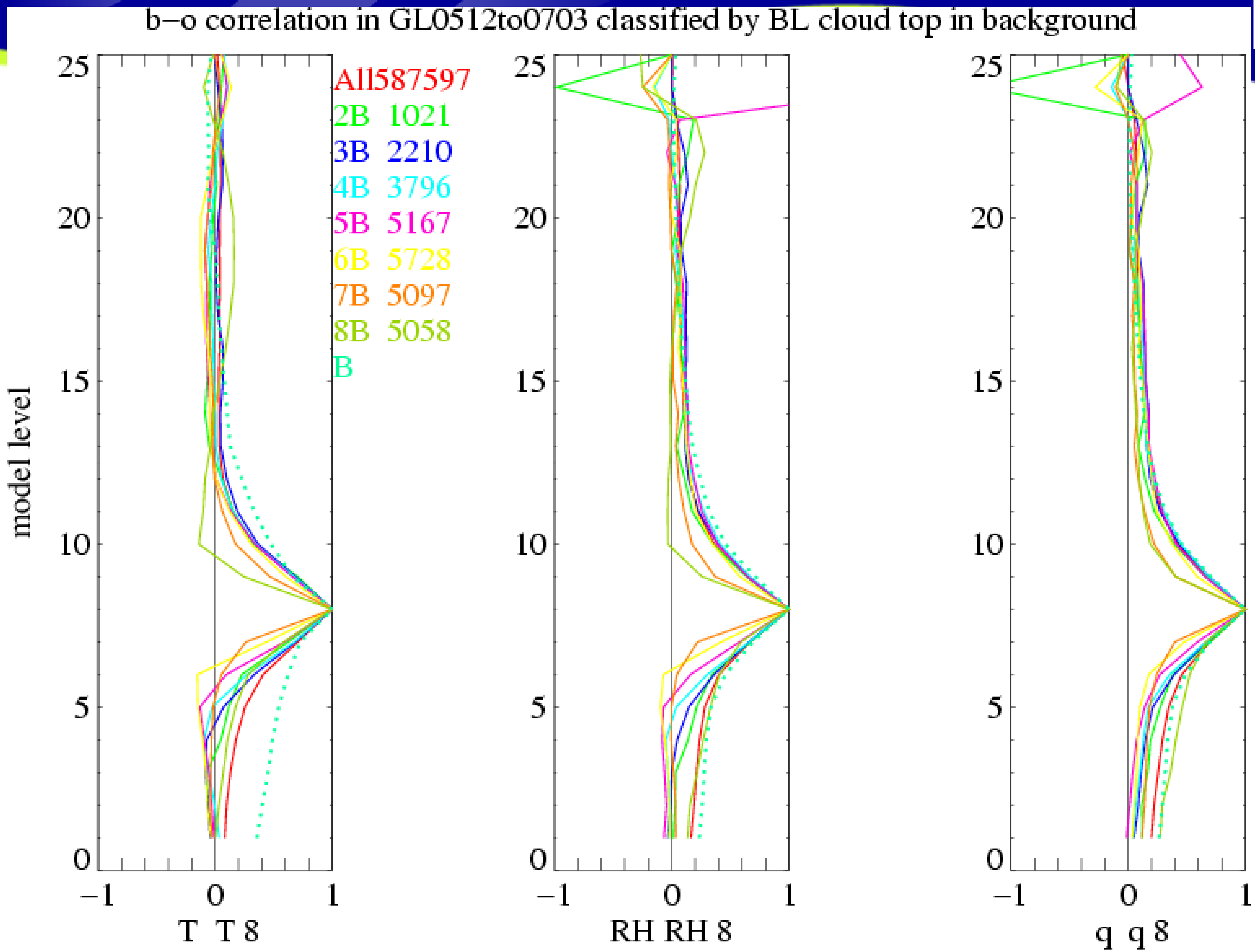
# Background-sonde correlations with model level 6



# Background-sonde correlations with model level 7



# Background-sonde correlations with model level 8

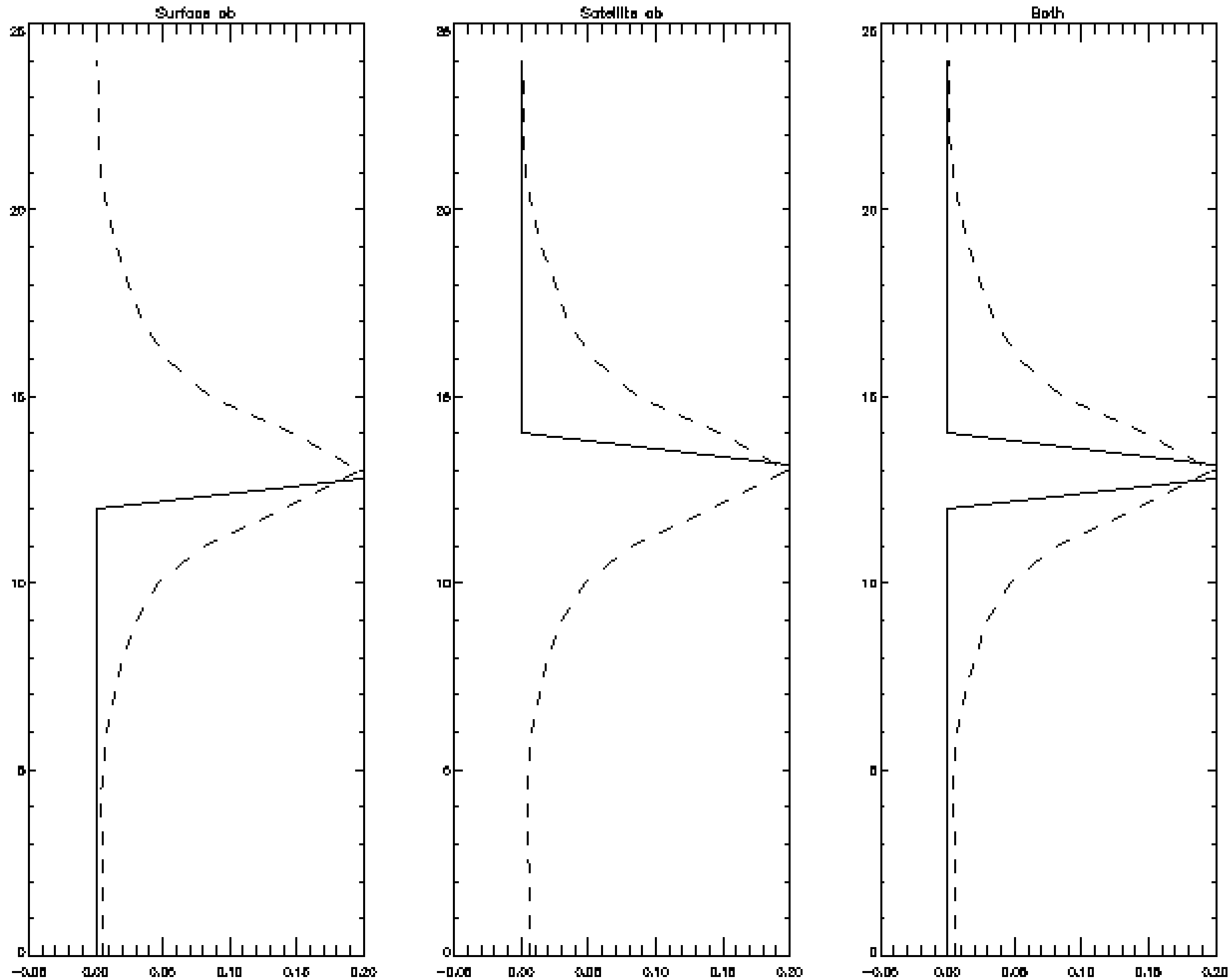


# Simple Var RH operator

MOPS cloud

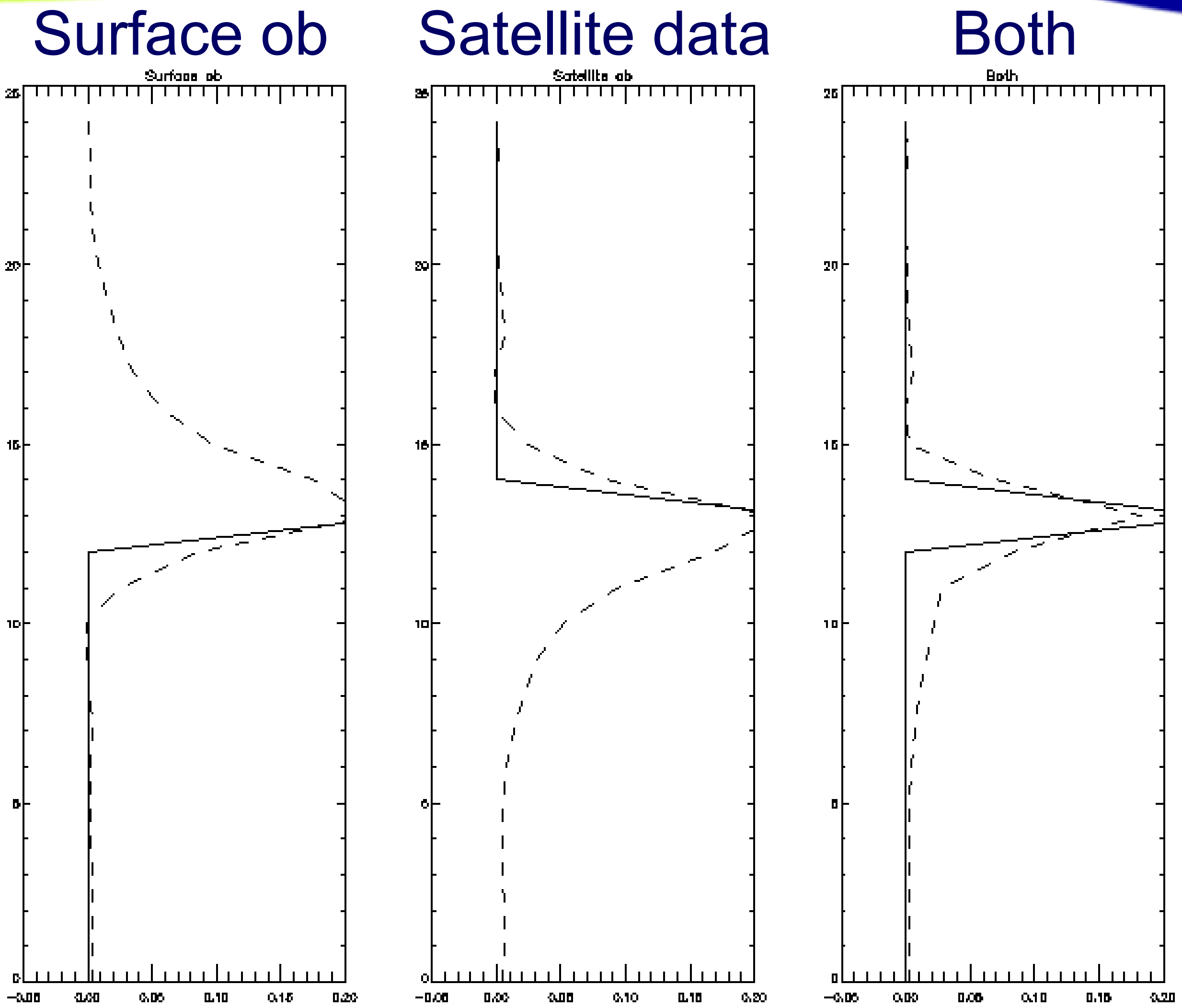
RH increment

Surface ob | Satellite data | Both




*Richard Renshaw*

# Redesigned operator

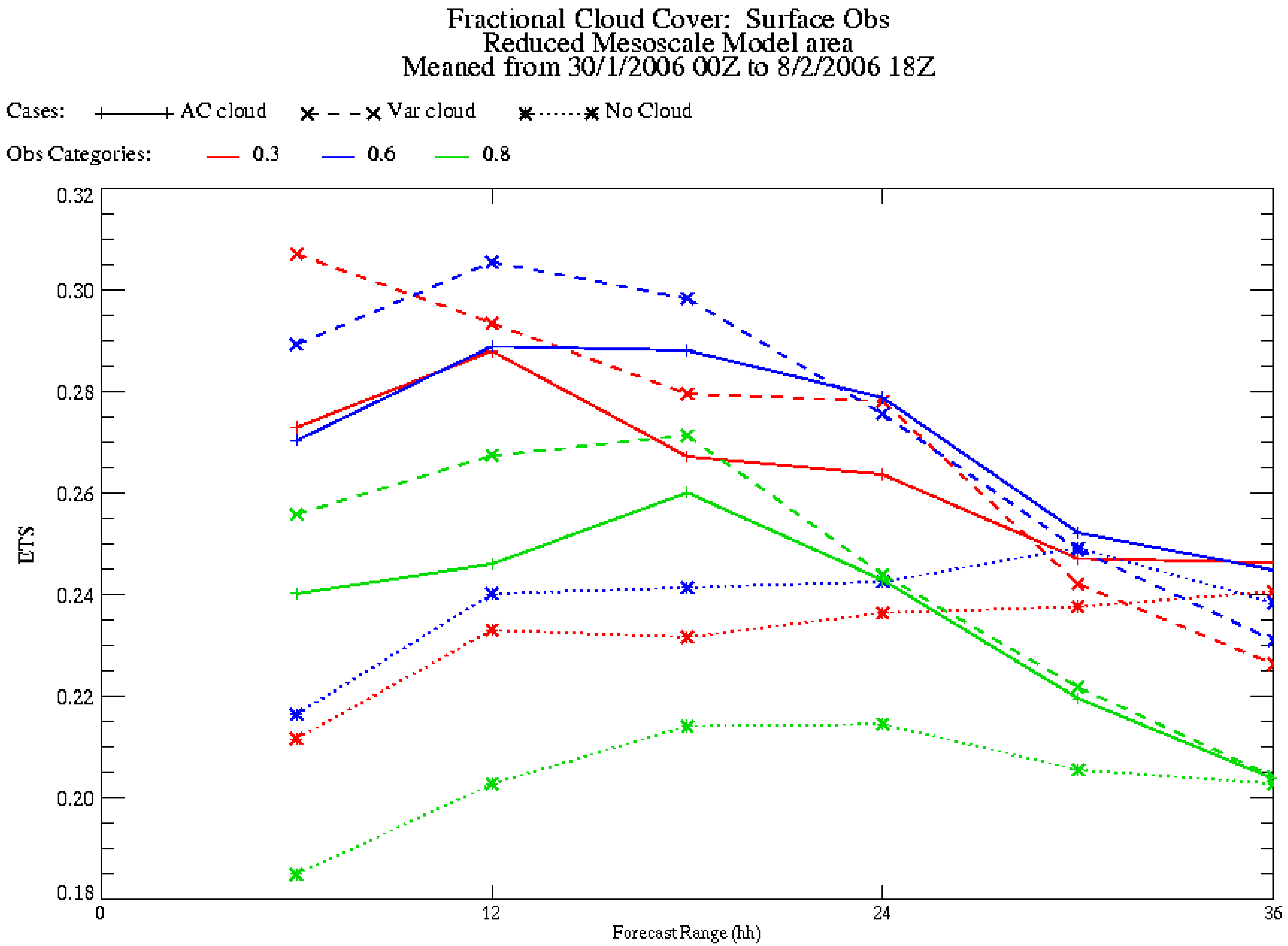



MOPS cloud ————————

RH increment - - - - - - - - - - - - - - -

*Richard Renshaw*

# Var cloud performance, 3D-Var mes trial




And

# 4D-Var NAE trial of Var cloud

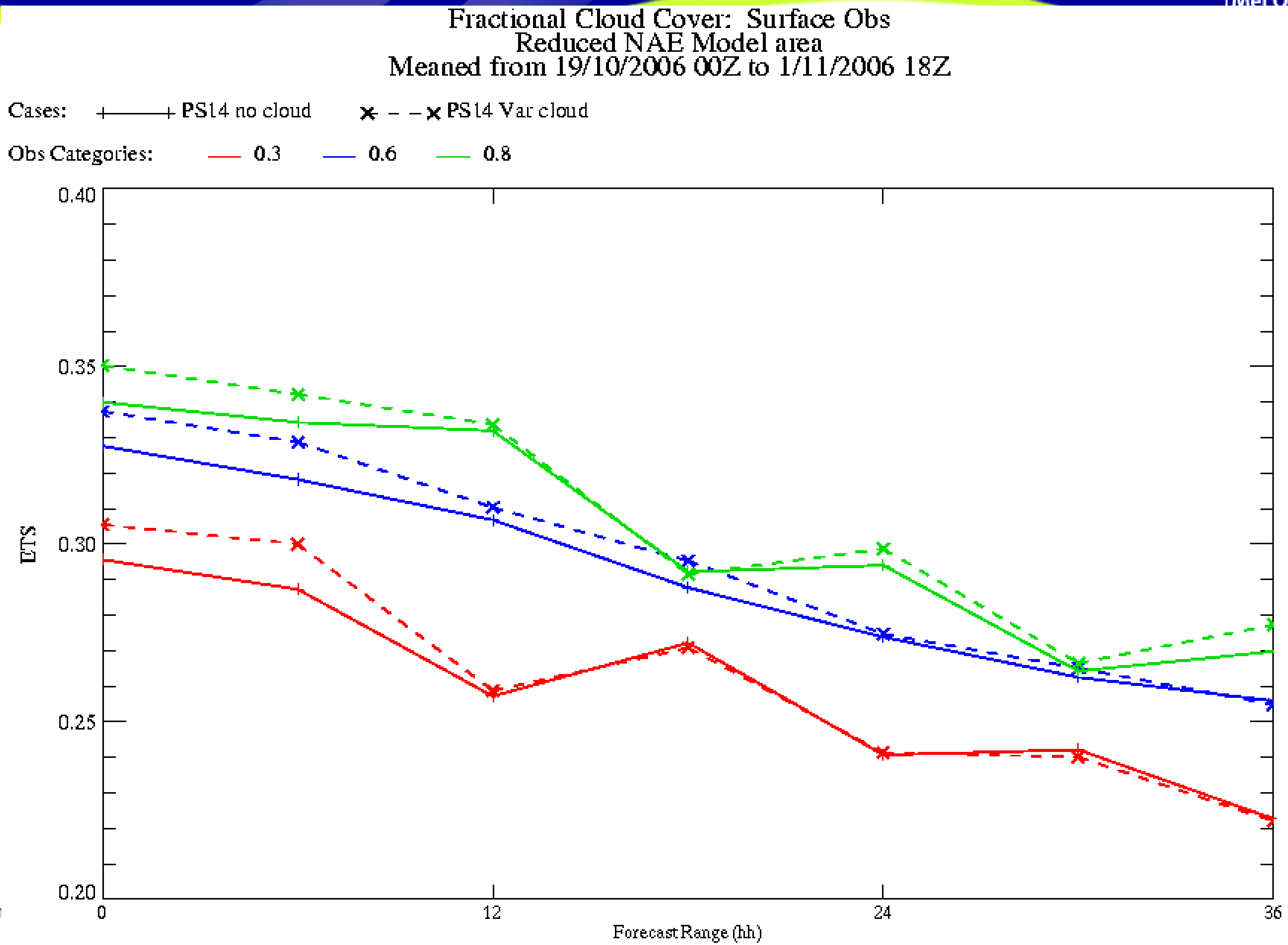
19/10/2006 - 10/11/2006

- 1st half mobile flow
  depressions, wind, rain

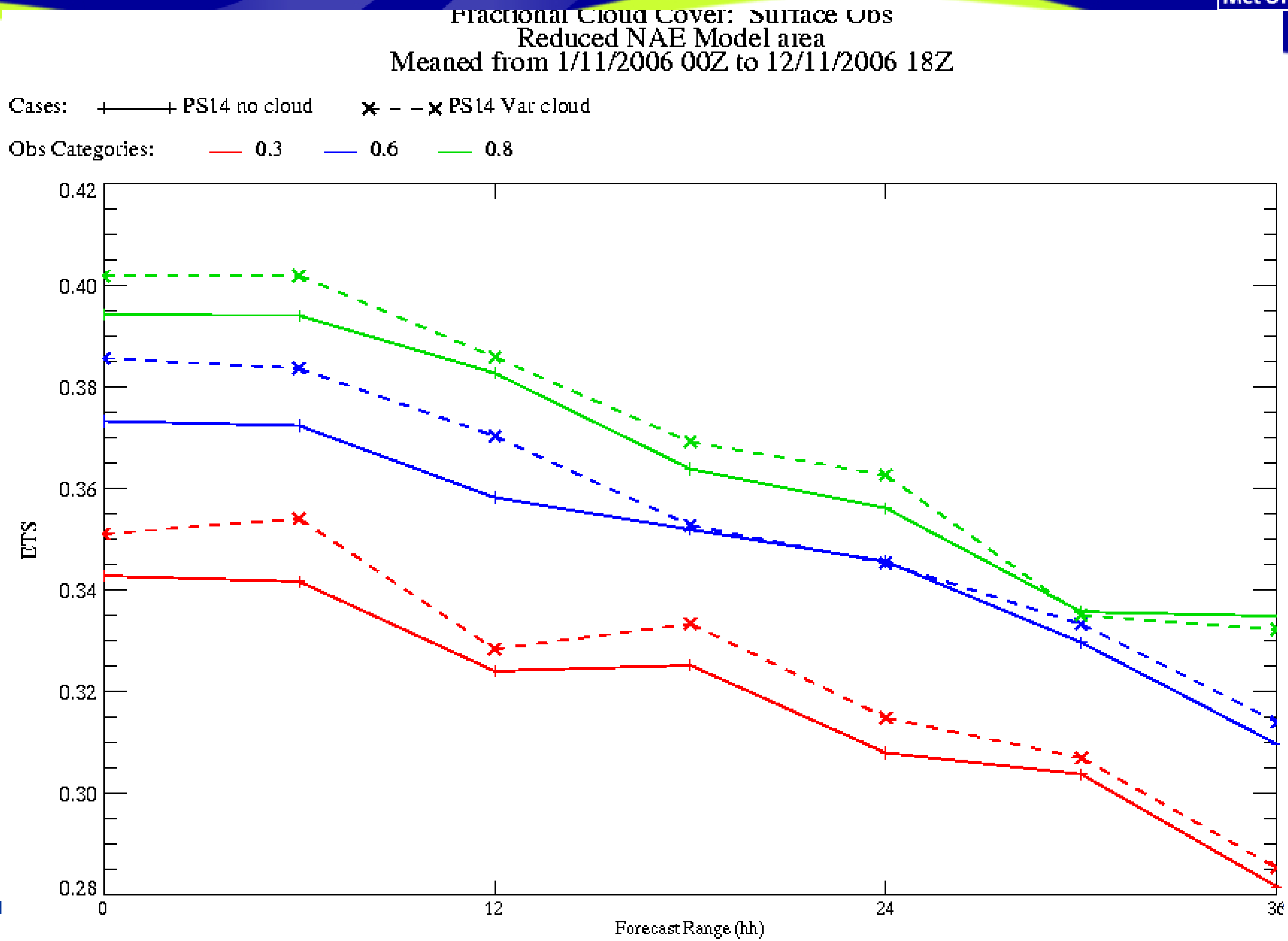
- 2nd half anti-cyclonic
  frost + fog

*Richard Renshaw*

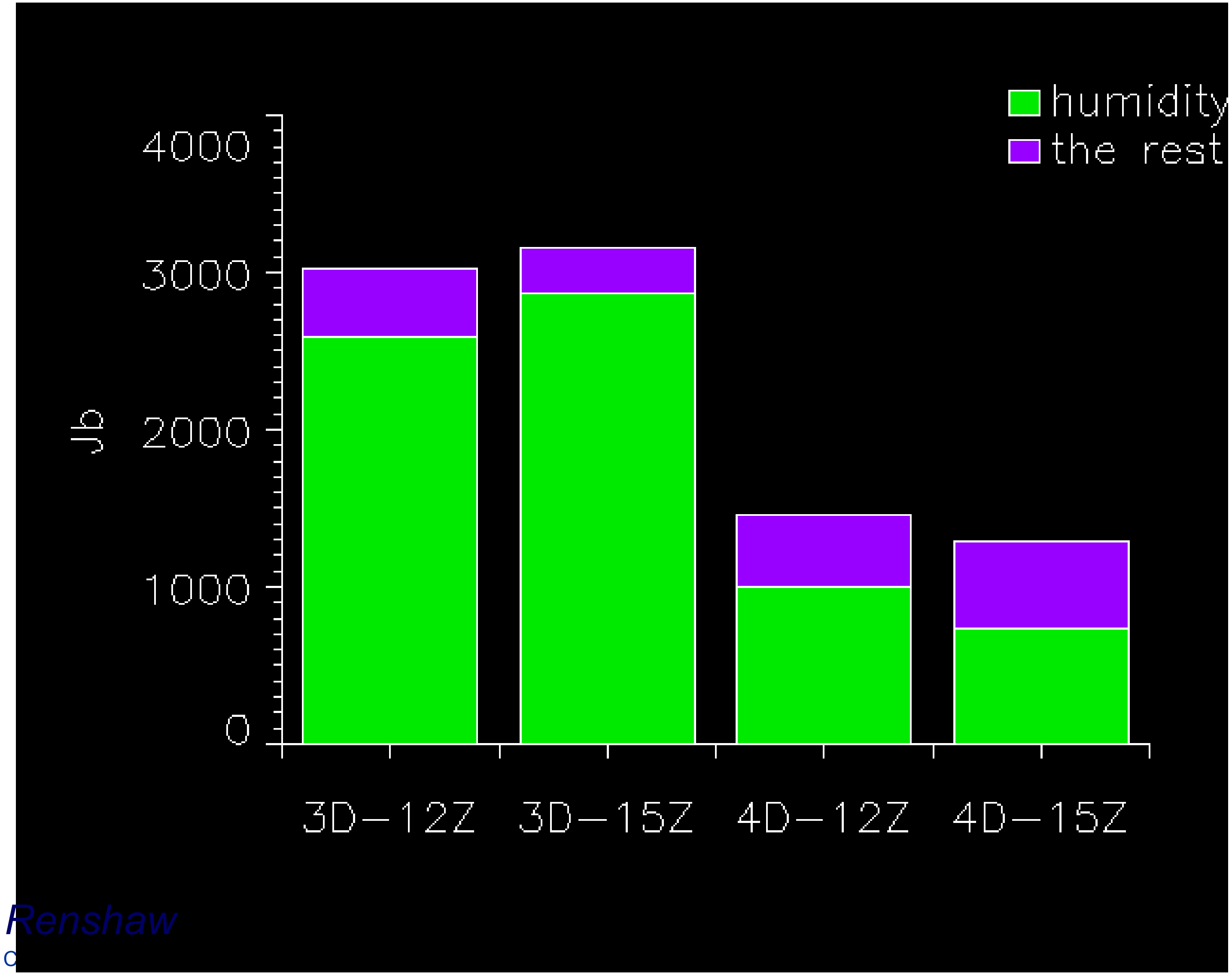
# Var vs No Cloud , 4D-Var NAE Period 1



# Var vs No Cloud , 4D-Var NAE Period 2

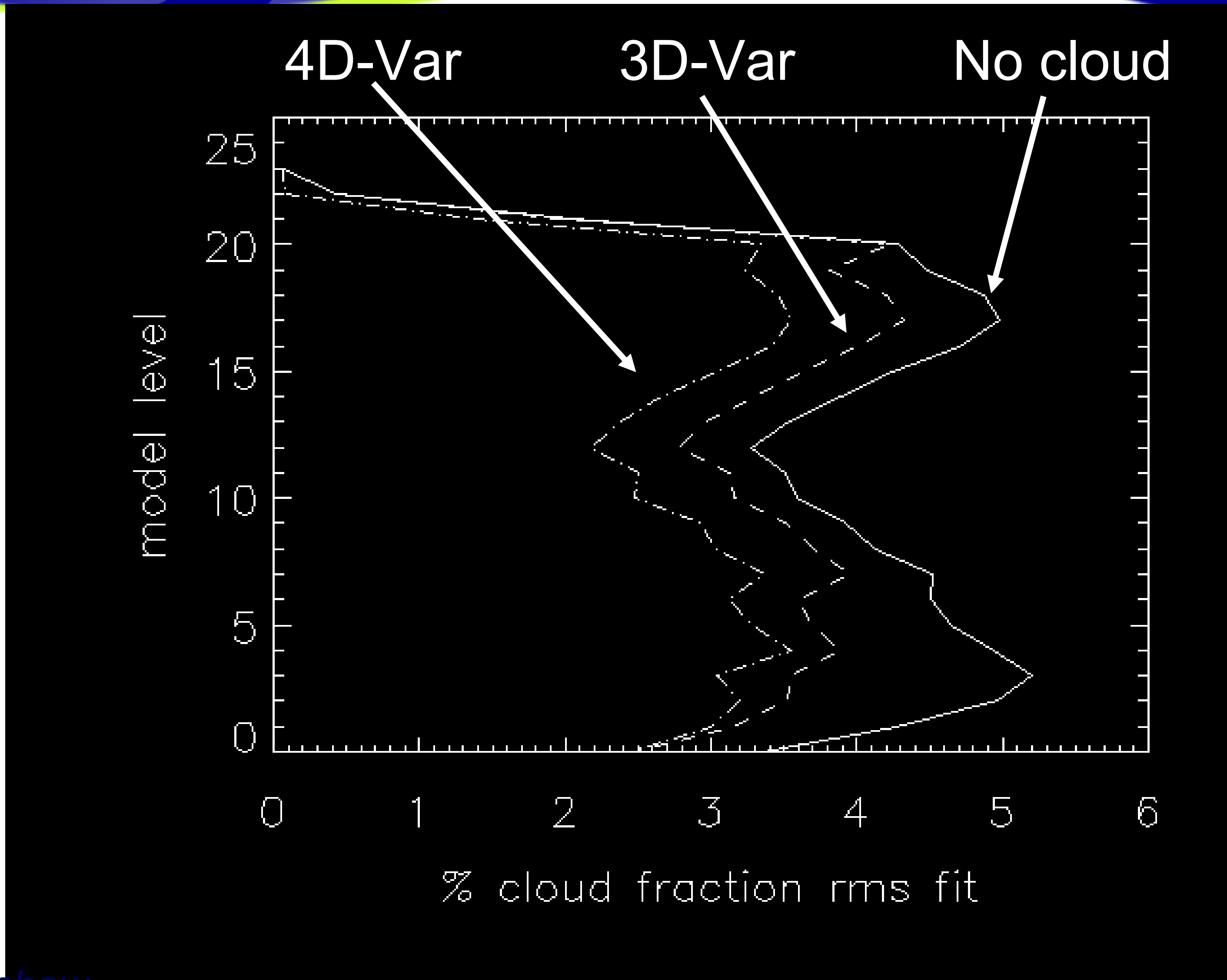


# Breakdown of the increments - Jb




*Richard Renshaw*

# T+3 fit to NIMROD cloud




*Richard Renshaw*

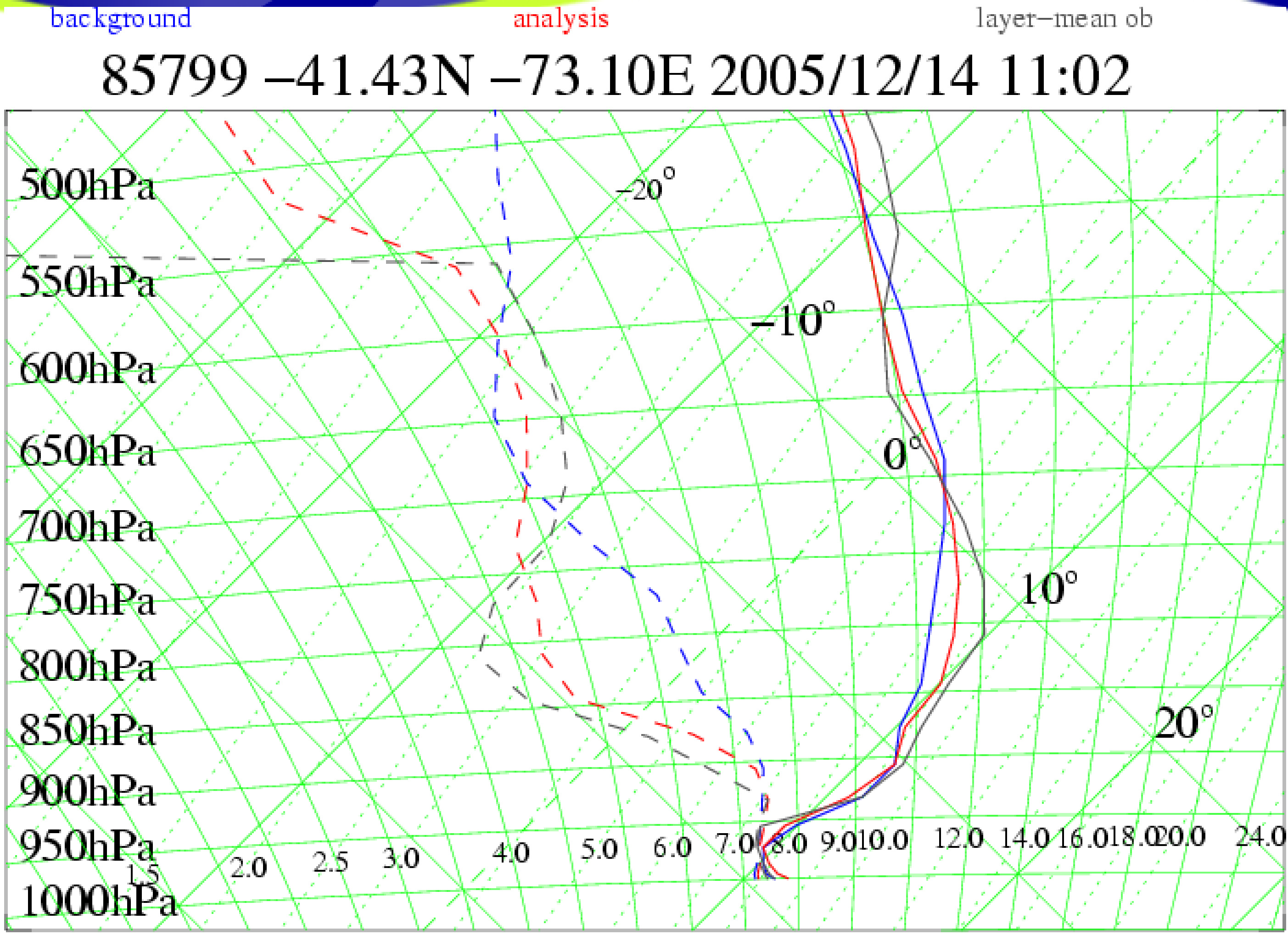
# Summary

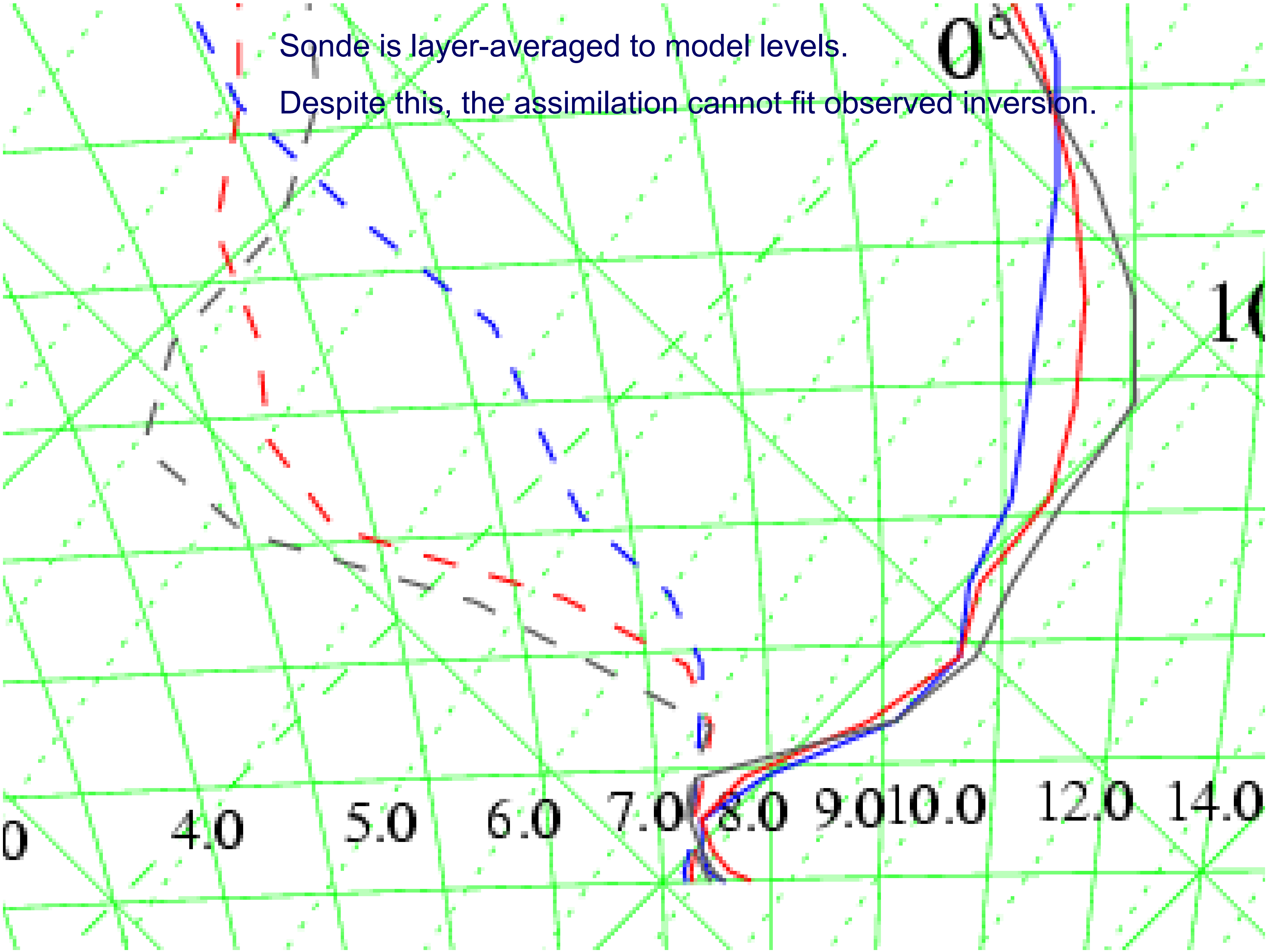
- GC transform works, but impact small and difficult to do LAM – dropped.
- EOTD modes, using **α**, equivalent to localised Ensemble KF. Impacts small from 1 mode – suspended pending MOGREPS.
- Evolved covariances in 4D-Var as important as treating obs at correct time.
- Assimilation of layer cloud not useful with average vertical covariances. Can be made useful by reducing vertical spreading.

# Some comments for workshop

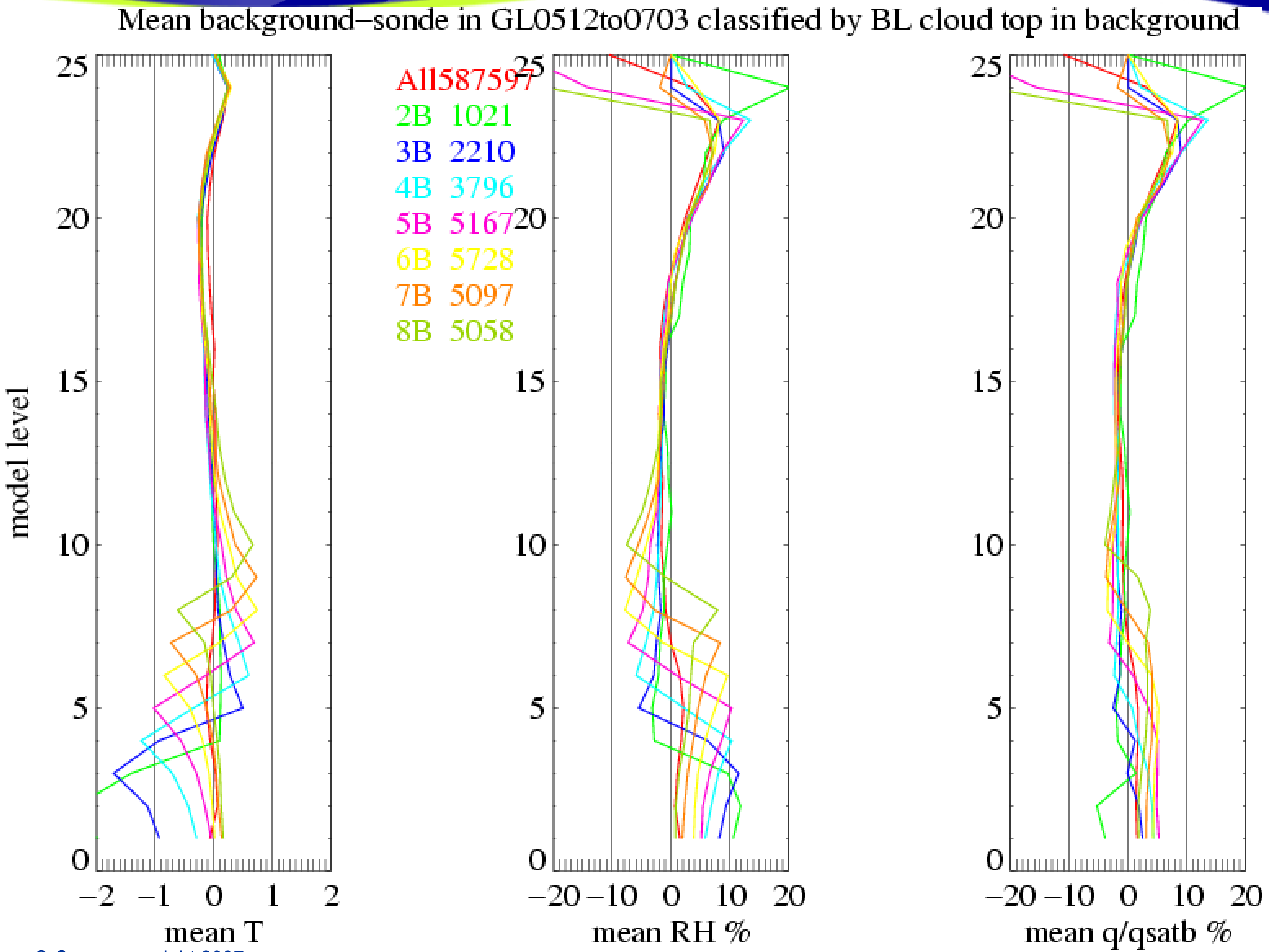
- ***Get the basics right first.*** VAR results are still sensitive to changes in the covariance model smaller than believed inaccuracies.
- ***Model variability determines analysis resolution.*** VAR schemes which generate their covariances from the NMC method, or ensemble perturbations, can only fit structures which are common in the learning set, i.e. which the model can spontaneously generate.
- ***Non-Gaussian PDF means even perfect covariances are not sufficient.*** Coherent structures (inversions, fronts, cyclones, convective cells) which have position errors lead to non-Gaussian PDFs. VAR theory (least squares best fit, using covariances to characterise errors) breaks down!

# Tephigram showing 4D-Var fit to sonde

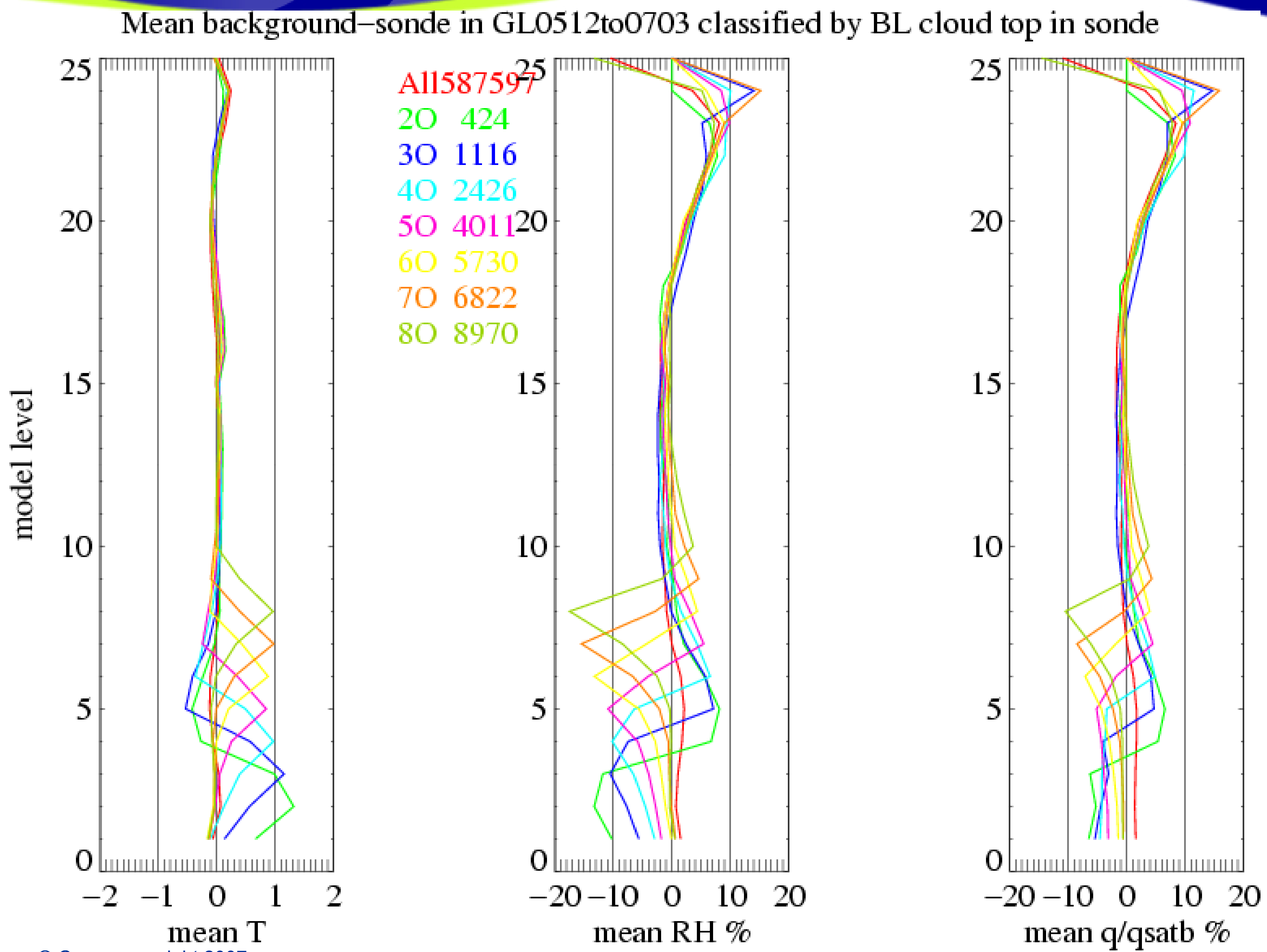



Sonde is layer-averaged to model levels.
Despite this, the assimilation cannot fit observed inversion.
0°
10
0
4.0
5.0
6.0
7.0
8.0
9.0
10.0
12.0
14.0

# Non-Gaussian PDF: skewed distribution has biased mean which is smoother than background



# Compositing by observed cloud top reverses the bias



# Met Office Plans

*Most effort into getting basics right first – improved covariance and PF models.*

- Evaluate MOGREPS T+6 perturbations as a sample of errors.
- If necessary improve the localised ETKF and stochastic perturbations to model.
- Generate improved covariances.
- Then go on to restart EOTD modes work.

- Implement “MOPS in VAR” in operation regional 4D-Var and UK 3D-Var.
- Extend to 1D-Var cloud retrievals from IR sounders, over a wider area.

# Met Office *possible* plans

- o Revise covariance model to allow more flexible horizontal variation (wavelet-based).
- o Use the spread of the MOGREPS ensemble to modulate local variances.

- ❑ Institute a vertical transform as well as, or instead of, the GC transform. The grid to be chosen to keep same domain but seek to equalise spacing in isentropic coordinates.