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The Met Office hourly 4D-Var system, status and plans

ISDA

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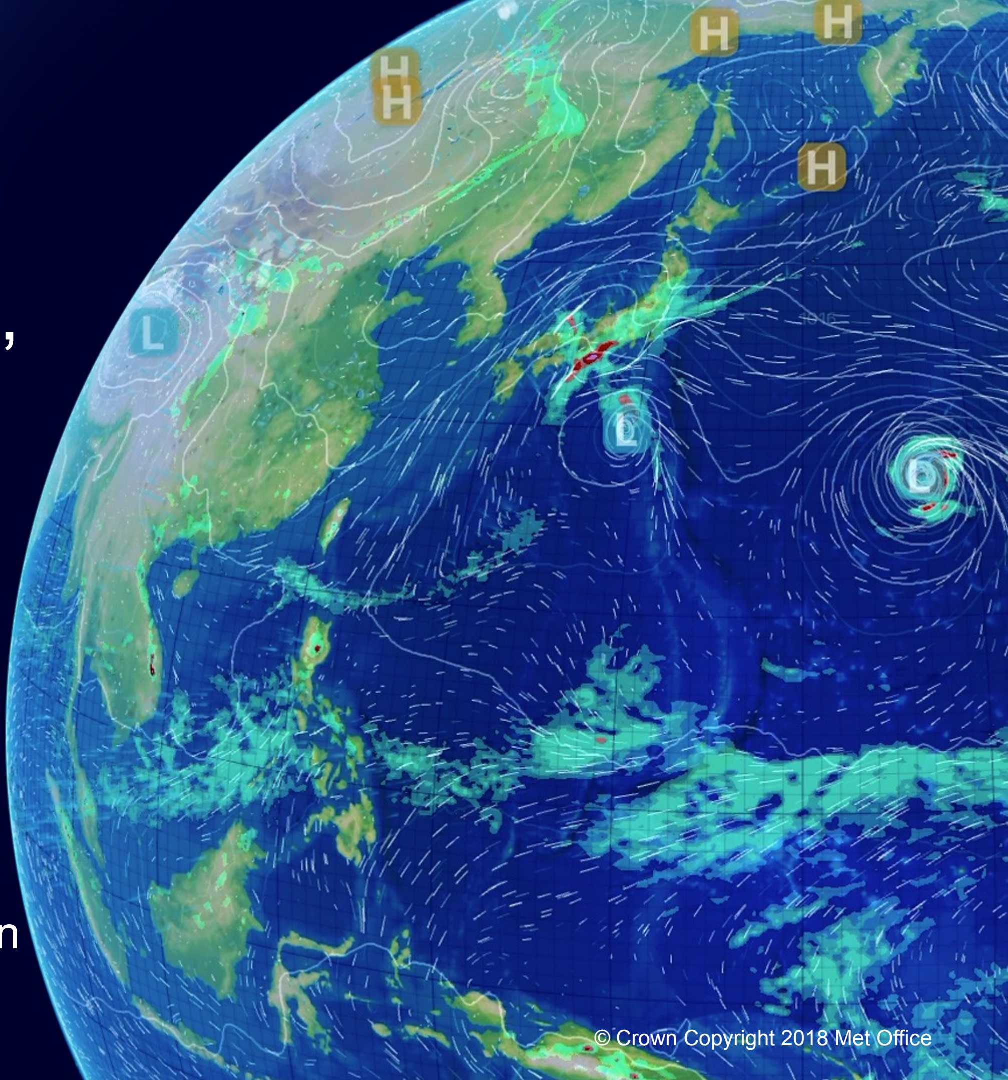
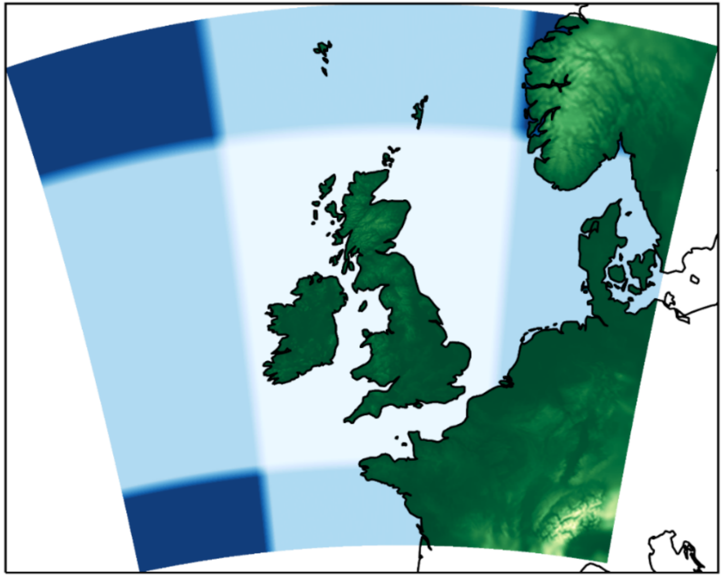


OVERVIEW

- Hourly UKV 4D-Var.
- Observations used.
- Cut-off time and reduction of observations.
- Value of the observations (FSOI).
- Issues in the definition of a background error covariance matrix and possible solutions.
- Possible different approach to hourly cycling.

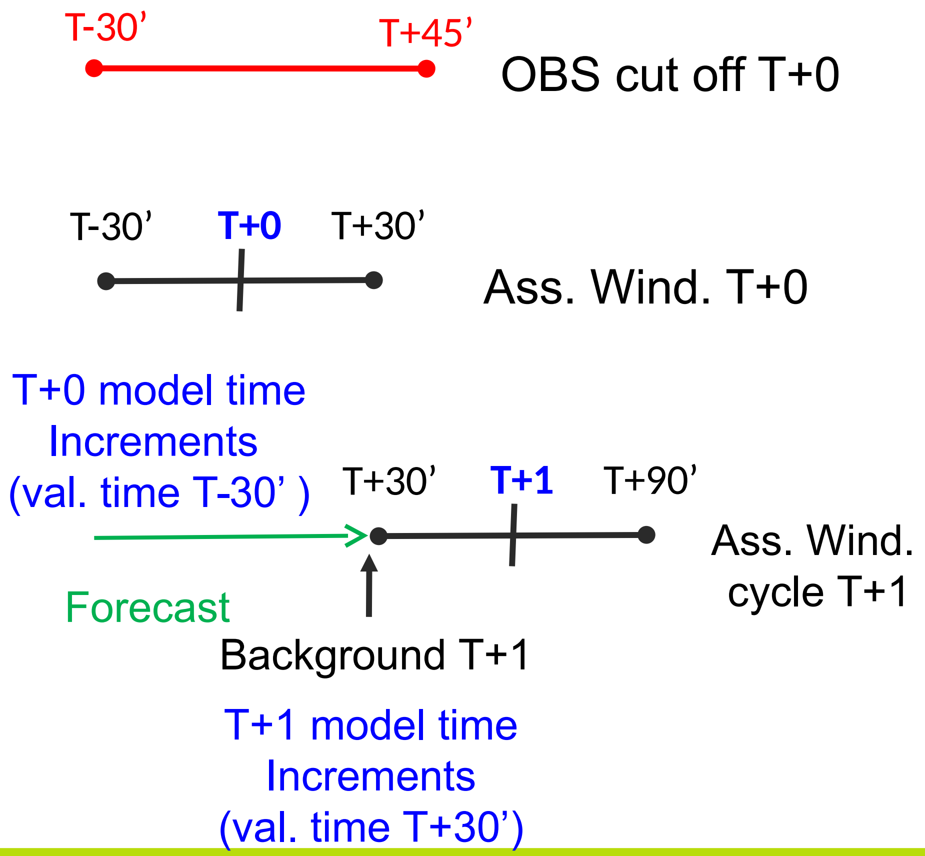
UKV model

UKV Domain



- Hourly 4D-Var assimilation method, operational since July 2017.
- Linear Perturbation Forecast (PF) model and DA, 4.5 km resolution (constant on the whole domain).
- UM model resolution in UK region 1.5km. Resolution 1.5×4 km resolution along the edges and 4×4 km at the corners.
- Global boundary conditions 10 km resolution.
- LBC from 00, 06, 12, 18 UTC runs of 10km Global model
  - 'Age' of LBC runs lies in range hh-3hr→hh-8hr
- Observation cut-off 45 mins.
- Apply varbc to satellite radiances.

Hourly UKV-4DVar cycle



- Cycle for T+0 (e.g. 01 UTC)
  - Assimilation window starts at T-30’ and finishes at T+30’ (e.g. between 00:30 UTC and 01:30 UTC) .
  - Cut off time until T+45’ (e.g. 01:45).
  - Operationally, the forecasts are mostly available at T+75’ (e.g. 02:15); for longer forecasts T+140’.

UKV - extra observations not assimilated in global model

4D-Var:

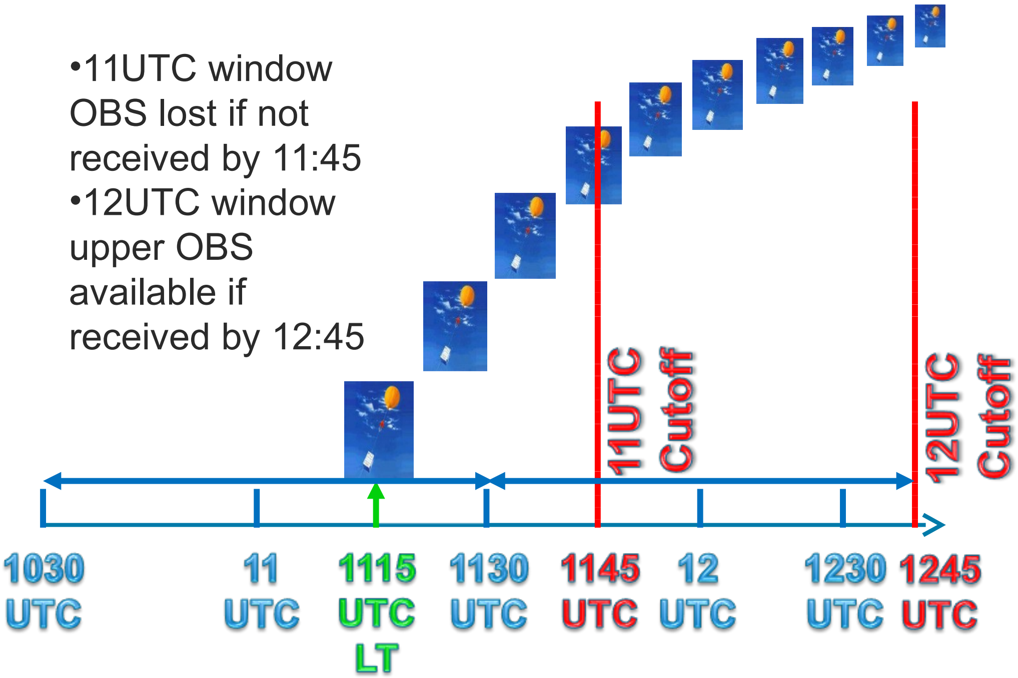
- GeoCloud cloud fraction profiles (hourly, 12km thinning, assumes cloudy box if mixed cloud and clear sky).
- Cloud fraction profiles from SYNOPs (hourly).
- Visibility from SYNOPs and METARs (hourly).
- T2m & RH2m from ~600 roadside sensors (hourly).
- Doppler radial winds from ~12 UK radars (10min).
- AMVs from NWC SAF (hourly) .
- Plans to add radar reflectivity in 2019. Radar refractivity later on.

After 4D-Var:

- radar-derived surface rain rate (15min, 5km resolution), via LHN.

OBSERVATION

- 11UTC window OBS lost if not received by 11:45
- 12UTC window upper OBS available if received by 12:45



Previous system, 3hourly 3D-Var:

- 3 hourly cycle. Assimilation window from T-1h30’ to T+1h30’
- 3D-Var. IAU applied increments over 1 hour.
- Lots of information per cycle.

Hourly 4D-Var:

- 1 Hourly cycle, less information per cycle. 45’ cut-off time
- Better analysis fit to the observation.
- Loss of some observations, e.g. lower part of UK sounding for 11 and 23 cycles.

Forecast Sensitivity Observation Impact (FSOI)

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- Adjoint derived (single outer loop) observation impact.
- Use data assimilation system to assess the impact of all OBS simultaneously. Impact of each OBS to forecast.
- Don't require a data-denial experiment (OSE) for each separate observation type.

Observation innovations δy^o

↓ (data assimilation)

Analysis increment w_o

↓ (forecast model) w^f

Forecast in OBS space y^f

↓

Difference in the quadratic forecast error measure (using OBS as truth) δe^f

→

(Adjoint PF states to OBS)

↑

Forecast error sensitivities(Sensitivity based on quadratic norm) $\left(\frac{\partial \delta e^f}{\partial \delta w^f}\right)^T$

↑ (Adjoint forecast model)

Analysis sensitivities $\left(\frac{\partial \delta e^f}{\partial \delta w_o}\right)^T$

↑ (Adjoint data assimilation)

OBS sensitivities $\left(\frac{\partial \delta e^f}{\partial \delta y^o}\right)^T$

↑ (use OBS innovation)

Observation impact $\left(\frac{\partial \delta e^f}{\partial \delta y^o}\right)^T \delta y^o$

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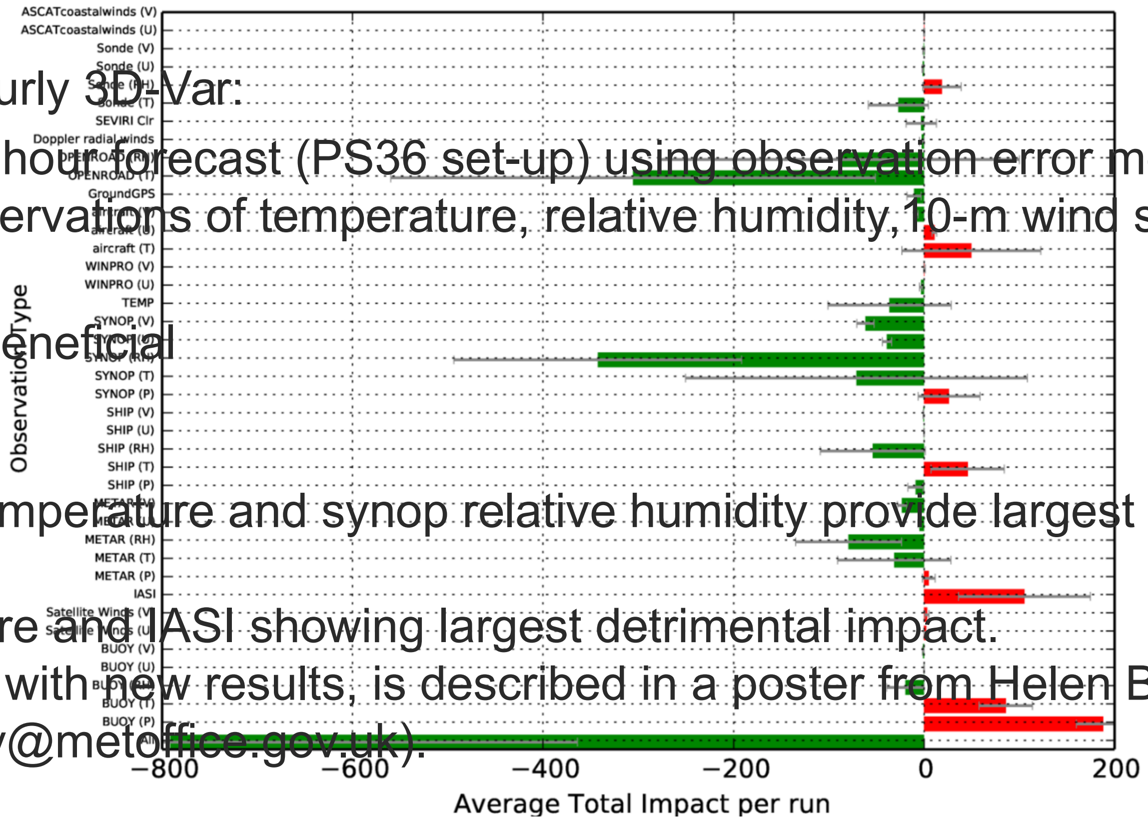
Some results



Previous 3hourly 3D-Var:

- Assessing 3 hour forecast (PS36 set-up) using observation error metric based on synop observations of temperature, relative humidity,10-m wind speed and log visibility.
- Negative = beneficial

In this setup:

- Openroad temperature and synop relative humidity provide largest beneficial impact
- Buoy pressure and IASI showing largest detrimental impact.
- This project, with new results, is described in a poster from Helen Buttery (helen.buttery@metoffice.gov.uk).

Background error covariance matrix: Tests using NMC method

- Forecast differences at same validity time (T+m)-(T+n)=Tmn
- Control run uses forecast differences from **3 hourly UKV-3DVar** T63
- First tests using T21 and T63 based on **hourly UKV-4DVar** data and T63+J_b scaling (variances as T21), gave discouraging results. Lesson learnt:
  - Error structure depends on the different forecast lead times used
- Start different tests using a larger sample (4 months):
  - T43, 1 hour time lag avoiding spin up problems
  - T63
  - T31, compromise between long and short time lag
  - T31, using data where the forecast starts at 00, 06, 12, 18. To have more information from OBS and large differences between forecasts

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Background error covariance matrix: Tests using NMC method

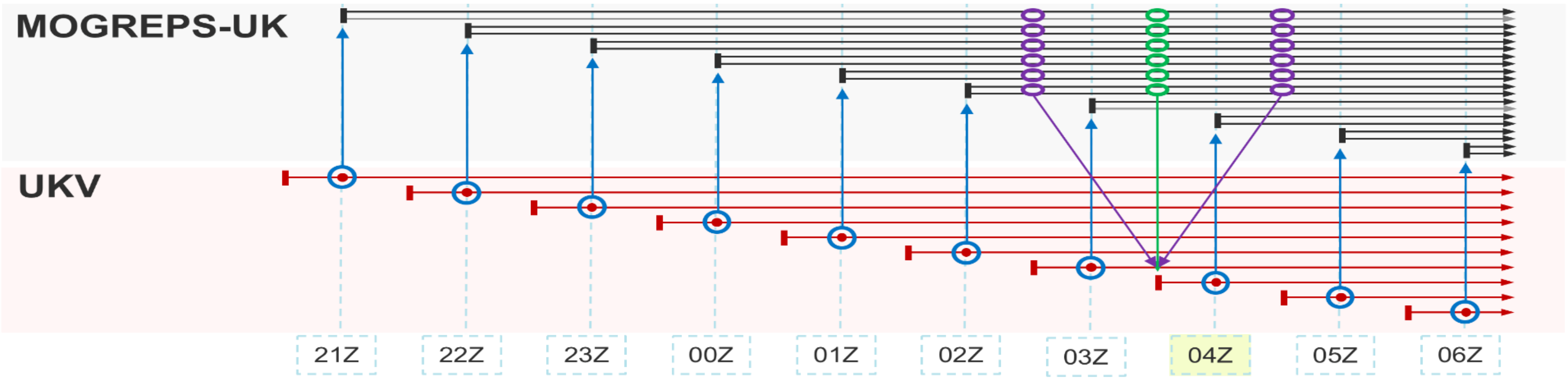
- Tests using T63 gave neutral/slightly positive results.
    - Better surface skills.
    - The improvements are not sufficiently positive for operational implementation.
- All other approaches deteriorate the forecast skill.
- We assume that the error coming from the boundary can be neglected.
    - Very strong approximation.
    - A new approach considering error correlation between local and synoptic scales could be beneficial.

Development of hybrid-4DVar

- Combine standard covariance $\mathbf{B}_c$ with a localised $(\mathbf{L})$ ensemble covariance $\mathbf{P}_e^f$:

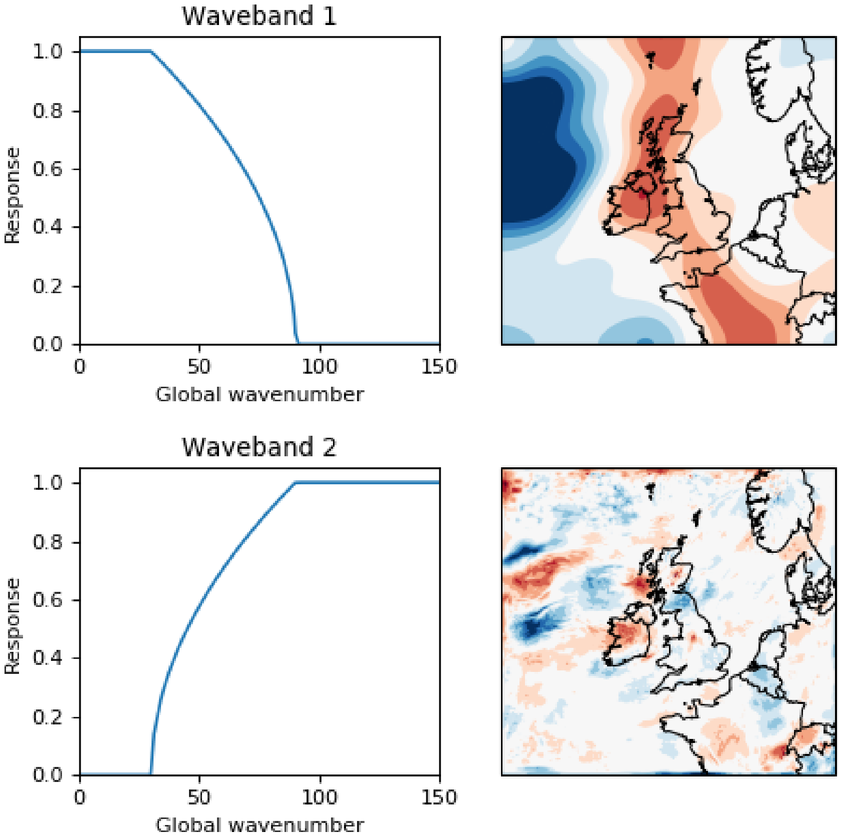
$$\mathbf{B} = \beta_c^2 \mathbf{B}_c + \beta_e^2 \mathbf{L} \circ \mathbf{P}_e^f$$

- Ensemble forecasts from 3-members-per-hour "MOGREPS-UK" ensemble.
- Considering options to increase the ensemble size:
  a. Run extra (short-range) members.
  b. Include global ensemble members (for larger scales).
  c. Use **time-lagging** and **time-shifting**. For example:



Development of hybrid-4DVar

- Treatment of large and smaller scales in perturbations likely to be important.
- Can remove large scales entirely, or separate perturbations into wavebands and localise them separately with different localisation scales.
- Target for trialled hybrid-4DVar system: **March 2019**.



New cycling

Re-capturing lost sonde observations is a priority in UKV-4DVar.

•Main method:

- Extend the cut-off on 2 key cycles (11UTC & 23UTC) from 45 minutes to 80 minutes (operational since Friday 23rd February 2018).

•Alternative (under development) method:

- Use the forecast from T-2 as background (instead from T-1) for T+0.
- The T+0 cycle has 2 hours available to provide the background state to the T+2 cycle (currently is 1 hour). thus we can enhance the cut-off time.
- T+2 forecast fields are better spun-up as the time from the initialization is longer. Thus it could been better adjusted to the initialization shock.
- The new background will be based on older observation. The background could be less representative of the actual state.

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Conclusions

- Achievements:
  - Operational hourly 4D-Var, useful for Nowcasting.
  - Larger domain at high resolution, take into account more synoptic inflow.
  - New types of OBS, e.g. roadside, can have large value for the forecast.
- Nobody's perfect:
  - Hourly cycles lose the assimilation of some OBS.
  - Static background error covariances generated using NMC method at high resolution are not performing well enough.
- Future plans:
  - Find a way to assimilate more conventional OBS.
  - Regularly apply FSOI to know the value of the OBS.
  - New background error covariance matrix using Hybrid approach.

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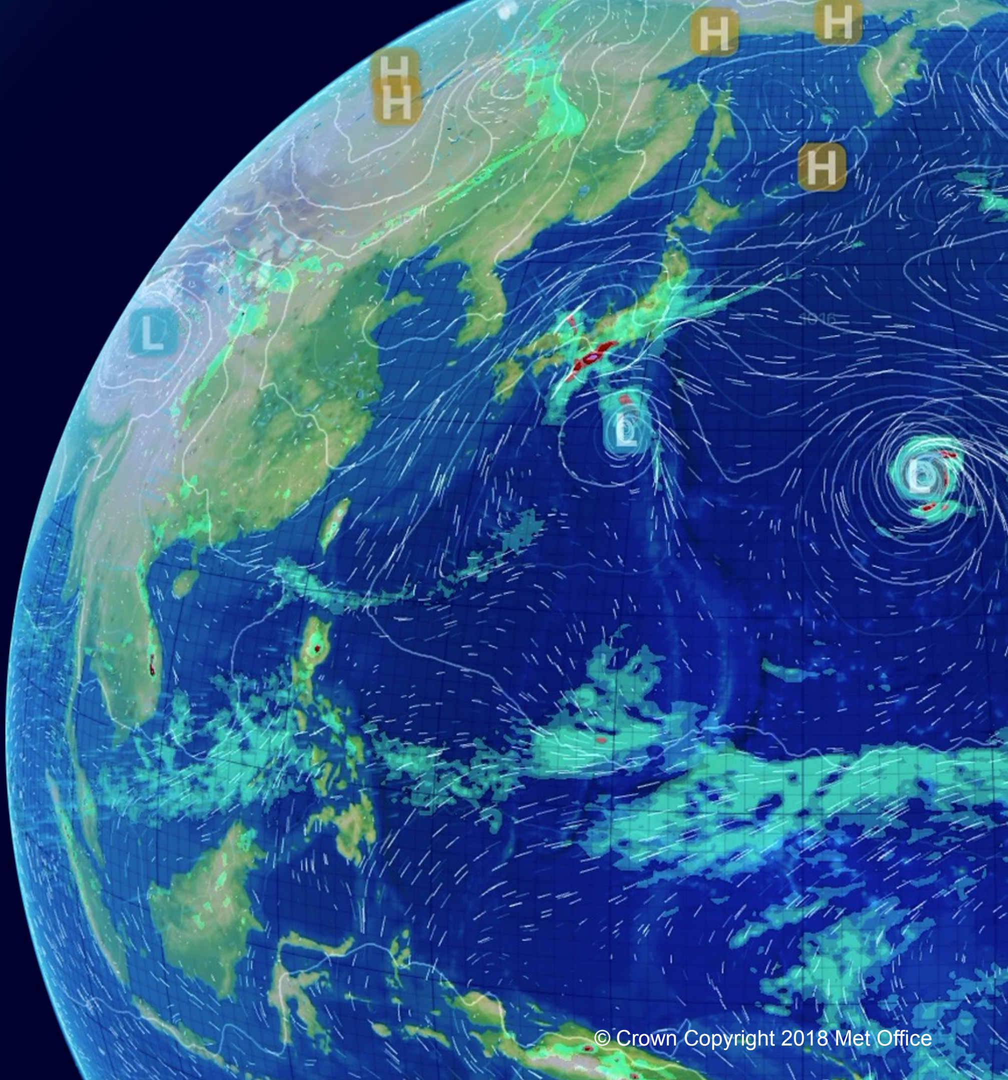
Thank you very much

Questions?



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References

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- Andrew C. Lorenc and Richard T. Marriott(2014). A Forecast sensitivity to observations in the Met Office Global numerical weather prediction. QJR Met Soc 140, 209-224
- Parrish, D. and J. C. Derber (1992). The National Meteorological Center's Spectral Statistical Inter-polation analysis system. Mon. Wea. Rev. 120, 1747–1763.

Questions

- Incremental 4D-Var
- Observation thinning
- The NMC method assumptions and limits
- Introduction to FSOI
- Idea for new cycle
- Time lagging/time shifting

Incremental 4D-VAR

- Based on the formulation of Rawlins et al. 2007

$$
\begin{aligned}
\mathbf{x}^a &= \mathbf{x}^g + \delta\mathbf{x} \\
\delta\mathbf{w} &= S(\mathbf{x}^g + \delta\mathbf{x}) - S(\mathbf{x}^g) \simeq \mathbf{S}\delta\mathbf{x} \\
\delta\mathbf{w}^b &= S(\mathbf{x}^b) - S(\mathbf{x}^g)
\end{aligned}
$$

- g, first guess; a, analysis; b, background; o observations
- *S* is a non-linear simplification operator with tangent linear approximation **S**
- 4DVAR Cost function, using the simplified increments (notation avoids sums)

$$
J(\delta\mathbf{w}) = \frac{1}{2}(\delta\mathbf{w} - \delta\mathbf{w}^b)^T\mathbf{B}^{-1}(\delta\mathbf{w} - \delta\mathbf{w}^b) + \frac{1}{2}(\underline{\mathbf{y}} - \underline{\mathbf{y}^o})^T\underline{\mathbf{R}^{-1}}(\underline{\mathbf{y}} - \underline{\mathbf{y}^o})
$$

(A strategy for operational implementation of 4D-Var, using an incremental approach. Courtier et al., 1994. doi: 10.1002/qj.49712051912)

Incremental 4D-VAR

- In the minimization a CVT (Control Variable Transform) is used.
- The **B** become an Identity
- New variable using CVT (swapped order):

$$\delta \mathbf{w} = \mathbf{U}\mathbf{v} = \mathbf{U}_p \mathbf{U}_a \mathbf{U}_v \mathbf{U}_h \mathbf{v}$$

$$J_b = \frac{1}{2}(\mathbf{v} - \mathbf{v}^b)^T (\mathbf{v} - \mathbf{v}^b)$$

$$J_o = \frac{1}{2}(\underline{\mathbf{y}} - H(\mathbf{x}^g) - \mathbf{H}\mathbf{U}\underline{\mathbf{v}})^T \underline{\mathbf{R}^{-1}}(\underline{\mathbf{y}} - H(\mathbf{x}^g) - \mathbf{H}\mathbf{U}\underline{\mathbf{v}})$$

- $\mathbf{U}_a$, is the vertically adaptive grid transform (AG; Piccolo and Cullen, 2011).

Observation thinning

- The spatial correlation between observations is used to defined the usefulness of the observations.
- The larger are the number of the observations the higher are the computational costs during the assimilation.
- We reduce the number of observations used taking out the less useful ones.

The NMC method assumptions and limits

- When the differences between the forecasts are small the NMC method underestimates variances. The analysis will be less influenced by the observations.
- The forecasts used to compute the differences are assumed uncorrelated.
- Leads to a climatological approximation of the covariances. The error due to the synoptic case is not taken into account.
- Large scale atmospheric states evolve with LBC.
- For LAM to reduce the influence due to LBC, forecast differences are based on forecast using the same LBC.

Introduction to the FSOI

Observation based forecast error norm:

$$e^f = \left(\mathbf{y}^f - \mathbf{y}^O\right)^T \mathbf{R}^{-1}\left(\mathbf{y}^f - \mathbf{y}^O\right)$$

$\mathbf{y}^O$ Vector of observations

$\mathbf{y}^f$ Vector of predicted observations

Difference in the error between background forecast and analysis forecast:

$$\delta e^f = \left[\left(\mathbf{y}^{fa} - \mathbf{y}^O\right)^T \mathbf{R}^{-1}\left(\mathbf{y}^{fa} - \mathbf{y}^O\right)\right] - \left[\left(\mathbf{y}^{fb} - \mathbf{y}^O\right)^T \mathbf{R}^{-1}\left(\mathbf{y}^{fb} - \mathbf{y}^O\right)\right]$$

Forecast error (verified against OBS):

$$\widetilde{\mathbf{w}_t^f} = \mathbf{y}^f - \mathbf{y}^O = H\left(\mathbf{c}_x\right) + \mathbf{H}\left[\mathbf{S}^{-I}\mathbf{L}\left(\mathbf{w}_t^f - \mathbf{w}_t^b\right)\right] - \mathbf{y}^O$$

Forecast error sensitivity:

$$\left(\frac{\partial \delta e^f}{\partial \delta \mathbf{w}_t^f}\right)^T_{\widetilde{\mathbf{w}_t^{fa}} + \widetilde{\mathbf{w}_t^{fb}}} = \mathbf{L}^T\mathbf{S}^{-I}\mathbf{H}^T\mathbf{R}^{-1}\left[\widetilde{\mathbf{w}_t^{fa}} + \widetilde{\mathbf{w}_t^{fb}}\right]$$

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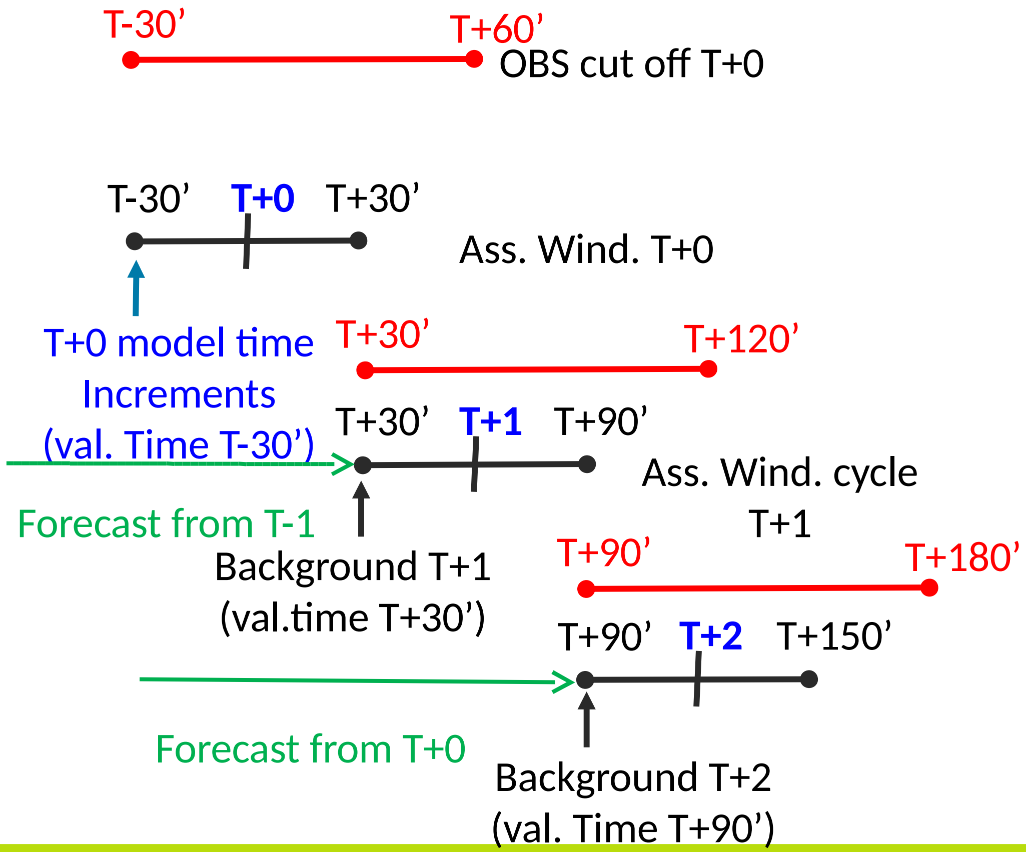
Idea for new cycle



- Cycle for T+0 (e.g. 01 UTC)
- Assimilation window start at T-30' and finish at T+30' (e.g. between 00:30 UTC and 01:30 UTC) .
- Background state from T-2 (e.g. 23 UTC).
- T+0 cycle will be need as background from T+2 (e.g. 03 UTC). 2 hours available.
- Cut off time can be enlarged as well.

Time lagging/time shifting

- Time-lagging: Add perturbations with longer lead-times (forecast time), but correct validity times.
- Time-shifting: Add perturbations that are displaced in time. It uses different validity time, equivalent to a smoothing in time.