The impact of the temporal spacing of observations on analysis accuracy

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The impact of the temporal spacing of observations on analysis accuracy:

implications for optimal distribution of polar-orbiting satellites

- Background
- Previous studies in Europe
- A new theoretical study - impact of temporal spacing of observations on analysis accuracy
  - highly idealised
  - less idealised – using FSO stats to assess observation information
- Conclusions

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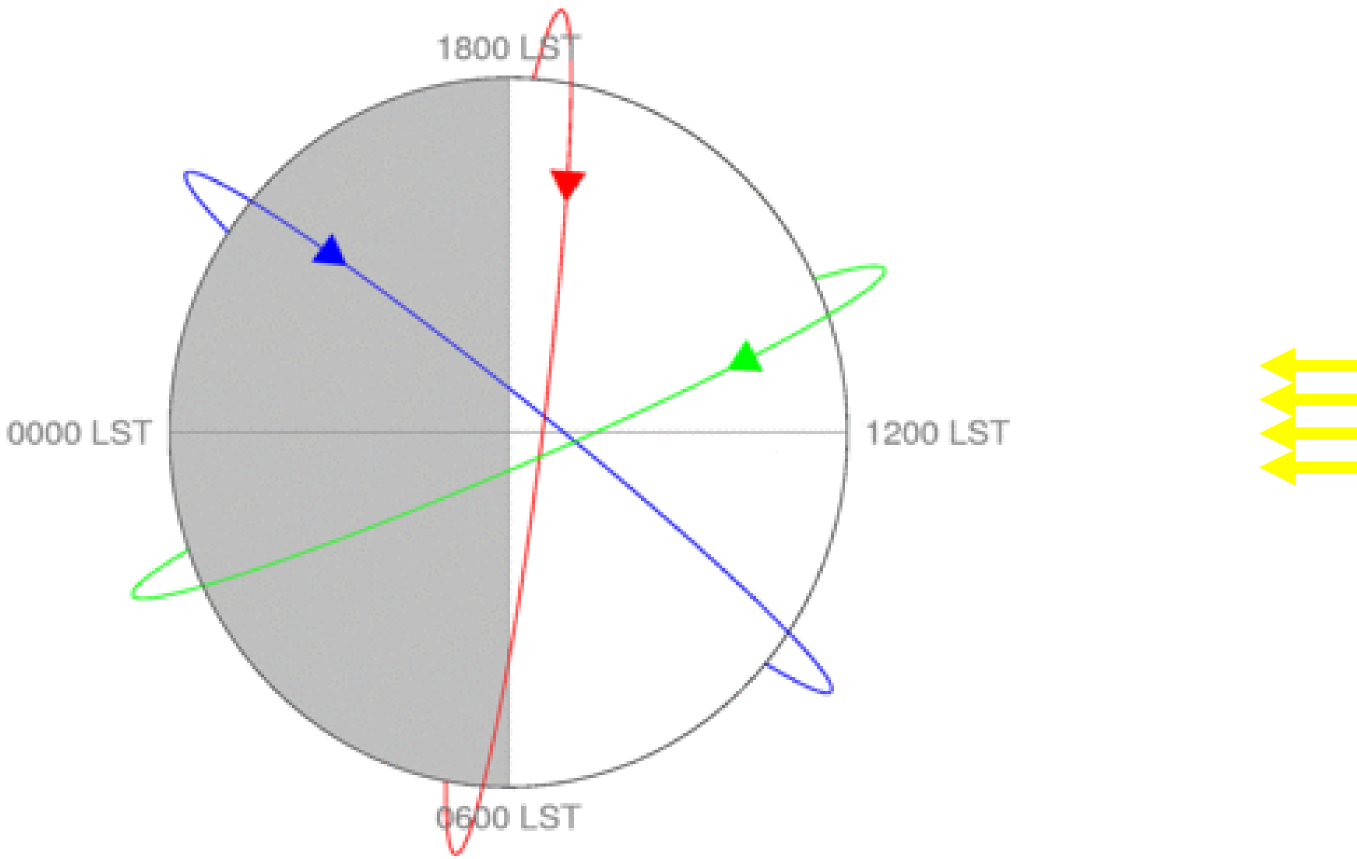
Bill Bell
Neill Bowler

Background:
WMO Vision for the GOS in 2025

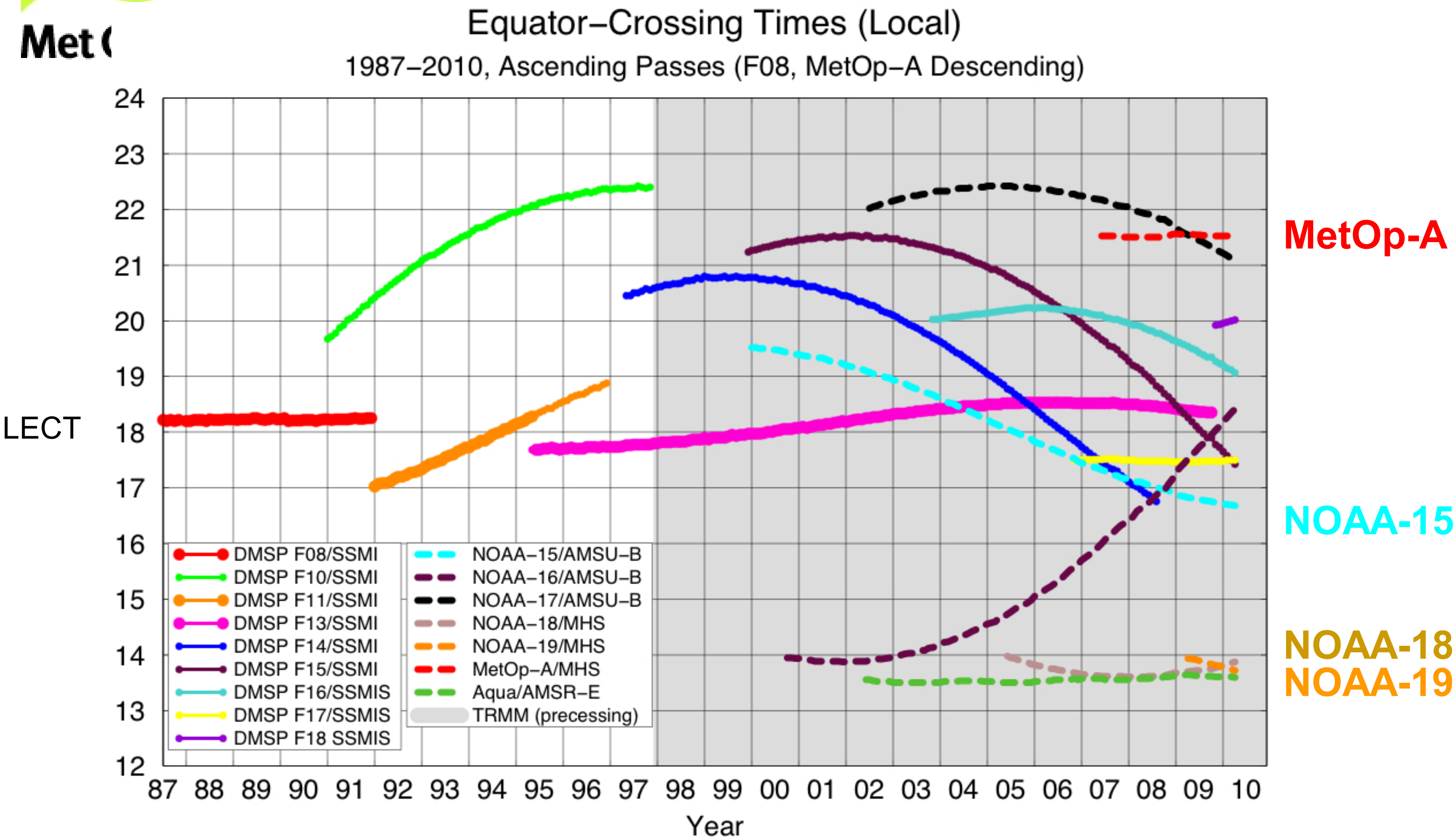


- approved by WMO-EC, 2009
- recommended baseline with in-orbit redundancy

Previous studies in Europe

Assimilation of ATOVS radiances at ECMWF.
Enza Di Tomaso and Niels Bormann.
EUMETSAT/ECMWF Fellowship Programme Res. Rep. 22

Orbits of current satellites



Thickest lines denote GPCP calibrator.

Image by Eric Nelkin (SSAI), 19 April 2010, NASA/Goddard Space Flight Center, Greenbelt, MD.

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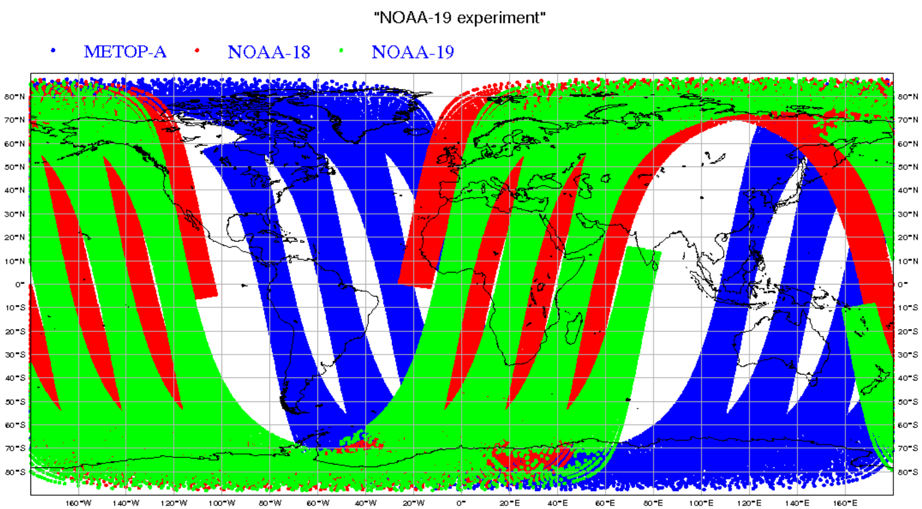
Data coverage

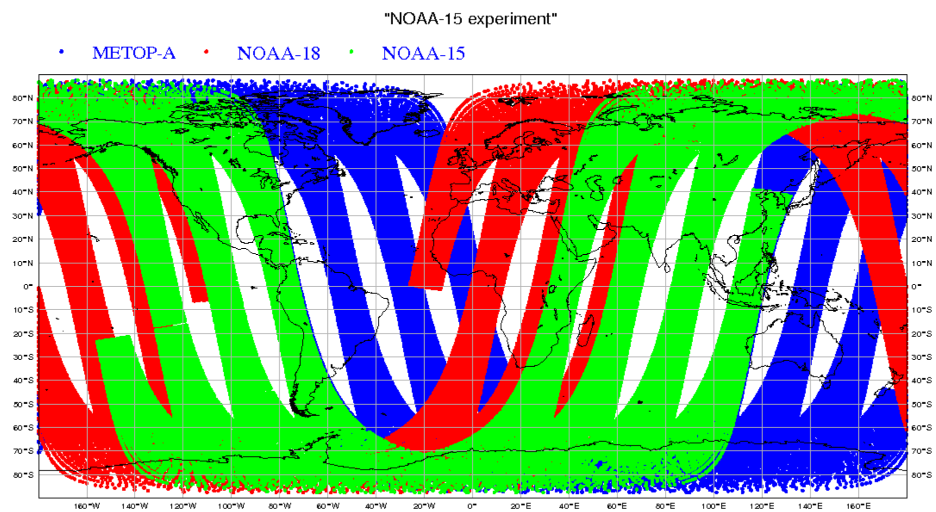
"NOAA-19 experiment"

* MetOp-A * NOAA-18 * NOAA-19



"NOAA-15 experiment"

* MetOp-A * NOAA-18 * NOAA-15

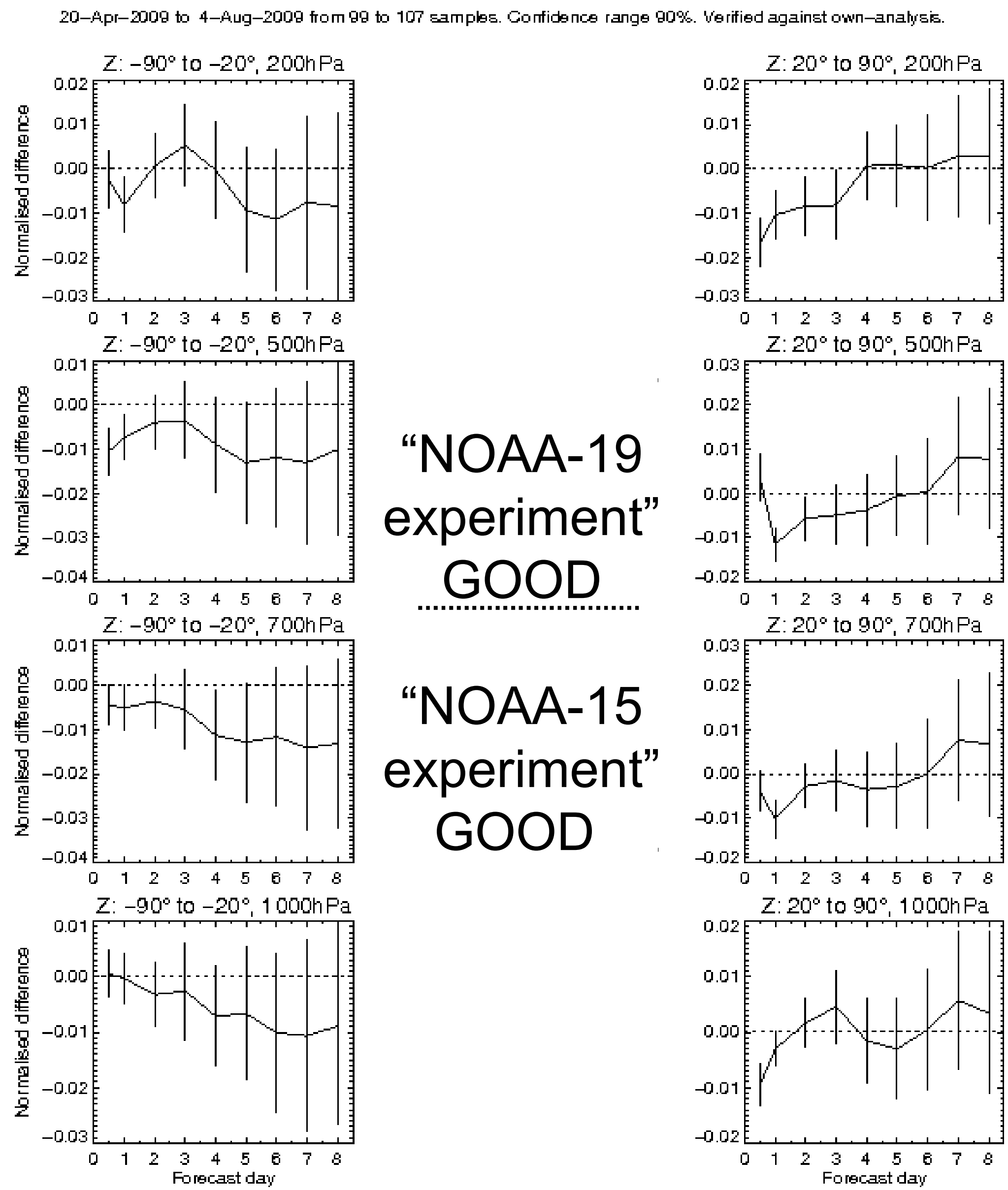


Sample coverage from a 6-hour period around 00Z

Forecast impact of ATOVS

" Averaged over extra-Tropics, impact of NOAA-15 experiment versus NOAA-19 experiment is neutral to slightly positive "

Note: AIRS and IASI not assimilated in these experiments



"NOAA-15 exp" RMSE – "NOAA-19 exp" RMSE

fbis – fbit

New theoretical study: the impact of temporal spacing of observations on analysis accuracy

or

how to do an OSSE in an Excel spreadsheet

Outline of theoretical study

- Very simple DA system
  - one variable in space
  - observations distributed in time
- Observations inserted in 12-hour cycle
  - to simulate 1-6 satellites
  - with temporal spacing to simulate 3 orbital planes
- Results found to be very sensitive to assumed rates of forecast error growth
  - different rates of doubling time for forecast error variance used:
  - 12 hours, 6 hours, 3 hours
- More details: Met O FR Tech Rep 573

Theory (1)

DEFINITIONS

	Error (co)variance	"Accuracy"
Analysis	A	A^{-1}
Background	B	B^{-1}
Observation	R	R^{-1}
Forecast	F	F^{-1}

Theory (2)

Kalman filter:

Analysis at time i:

$$A^{-1}_i \quad = \quad B^{-1}_i \quad + \quad R^{-1}_i$$

analysis accuracy — background accuracy — observation accuracy

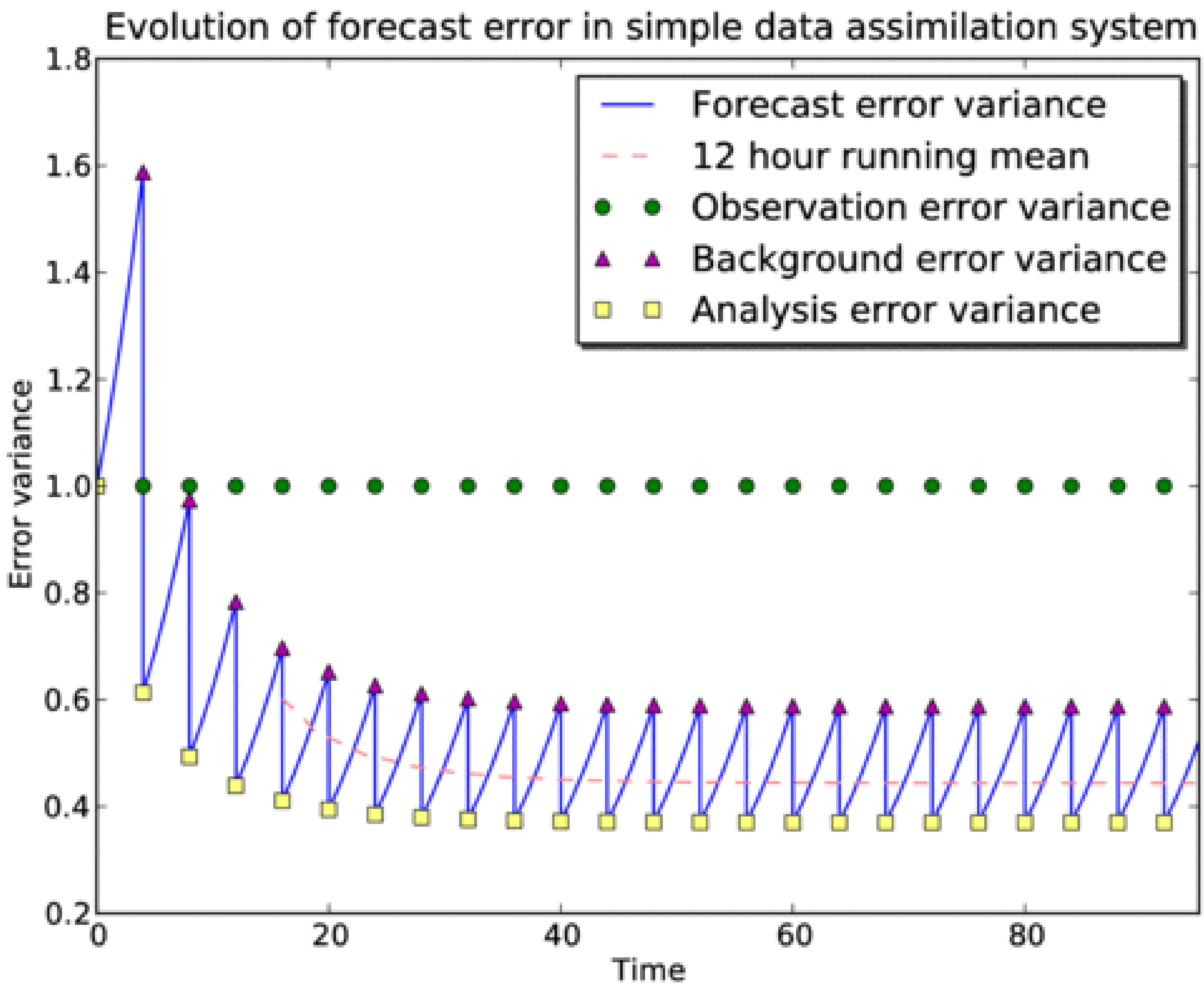
Forecast from time i-1 to time i:

$$B_i \quad = \quad \beta \, A_{i-1} \quad + \quad Q$$

Consistent with a forecast error growth model,

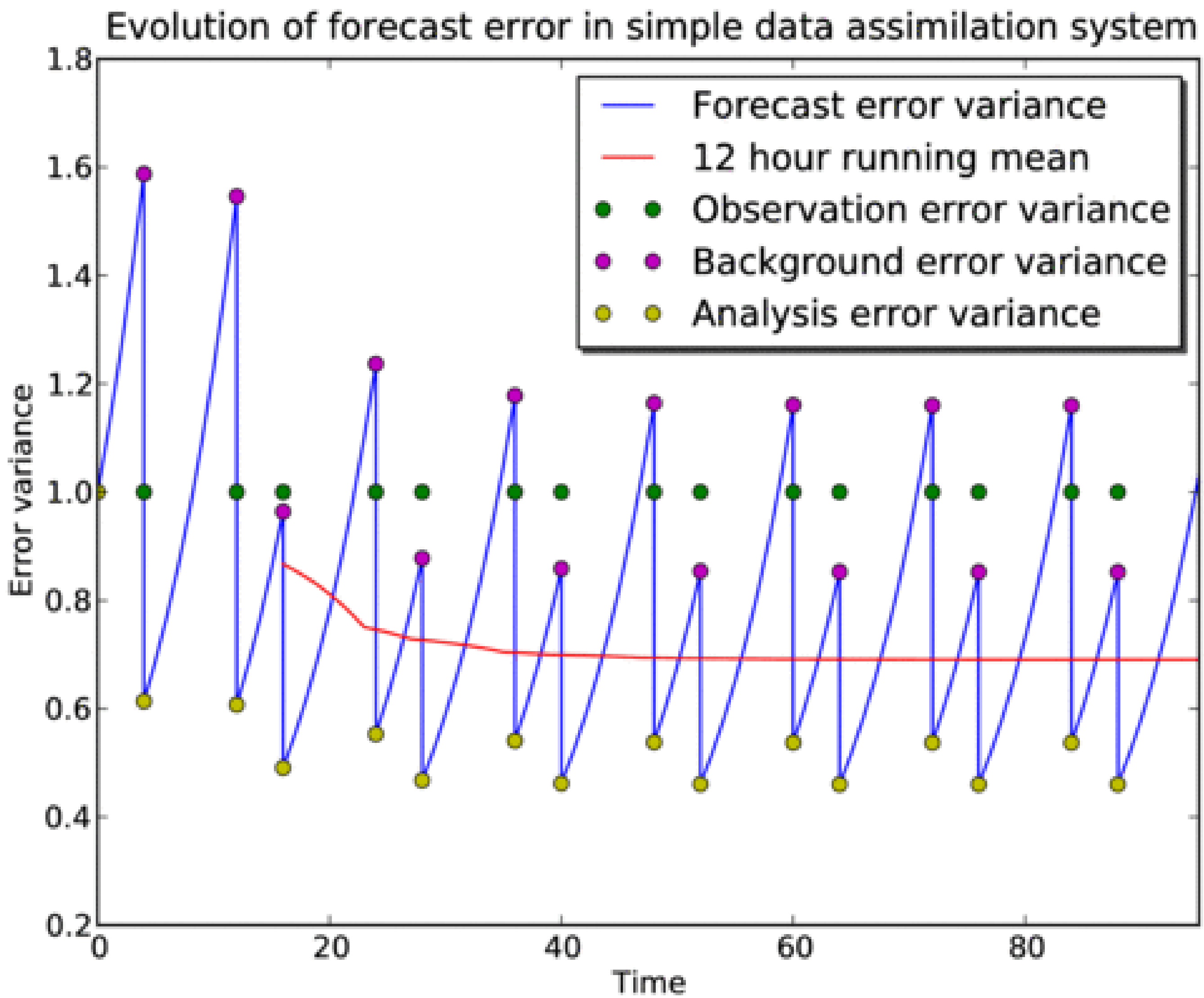
$$dF/dt = \alpha F + \gamma$$

An example



doubling time for forecast error variance = 6 h

Another example



doubling time for forecast error variance = 6 h

Theory (3)

With Q=0 → $A^{-1}_{i} = B^{-1}_{i} + R^{-1}_{i}$; $B_i = \beta A_{i-1}$

→ $A^{-1}_{i} = \beta A^{-1}_{i-1} + R^{-1}_{i}$

Taking time means:

$(1/N)\Sigma_{i=j+1}^{j+N} A^{-1}_{i} = \beta^{-1} (1/N)\Sigma_{i=j}^{j+N-1} A_{i}^{-1} + (1/N)\Sigma_{i=j+1}^{j+N} R^{-1}_{i}$

… but at equilibrium, $A^{-1}_{i} = A^{-1}_{i+N}$

$(1/N)\Sigma_{i=j+1}^{j+N} A^{-1}_{i} = (1-\beta^{-1})^{-1} (1/N)\Sigma_{i=j+1}^{j+N} R^{-1}_{i}$!!!

Theory (4)

$$(1/N)\Sigma_{i=j+1}^{j+N} A^{-1}_i = (1-\beta^{-1})^{-1} (1/N)\Sigma_{i=j+1}^{j+N} R^{-1}_i$$

Mean analysis accuracy:

- does not depend on observation spacing …
  - only on mean observation accuracy
  - i.e. how many observations, and how accurate they are
- is proportional to mean observation accuracy

HOWEVER,

no similar equation for mean analysis error covariance

- does depend on observation spacing

Discussion of theory

Why is mean analysis error variance the most appropriate metric for global NWP?

Why mean?

- because we wish to optimise the observing system for forecasts for all parts of the world

Why error variance (and not accuracy)

- because we are most interested in improving bad analyses (bad forecasts), and not those that are already good.

Experiments - Part I

The experiments:

different numbers of observations and

different observation spacings

relative observation time (hours) →			0	1	2	3	4	5	6	7	8	9	10	11
expt. number	**number of observations**	**constellation code**												
1.1	1	[1,0,0]	1											
1.2	2	[2,0,0]	2											
1.3	2	[1,1,0]	1				1							
1.4	3	[3,0,0]	3											
1.5	3	[2,1,0]	2				1							
1.6	3	[1,2,0]	1				2							
1.7	3	[1,1,1]	1				1				1			
	4	[4,0,0]	4											
1.8	4	[3,1,0]	3				1							
1.9	4	[3,0,1]	3								1			
1.10	4	[2,2,0]	2				2							
1.11	4	[1,2,1]	1				2				1			

Examples:

WMO Vision = [1,1,1]

WMO Vision with back-up = [2,2,2]

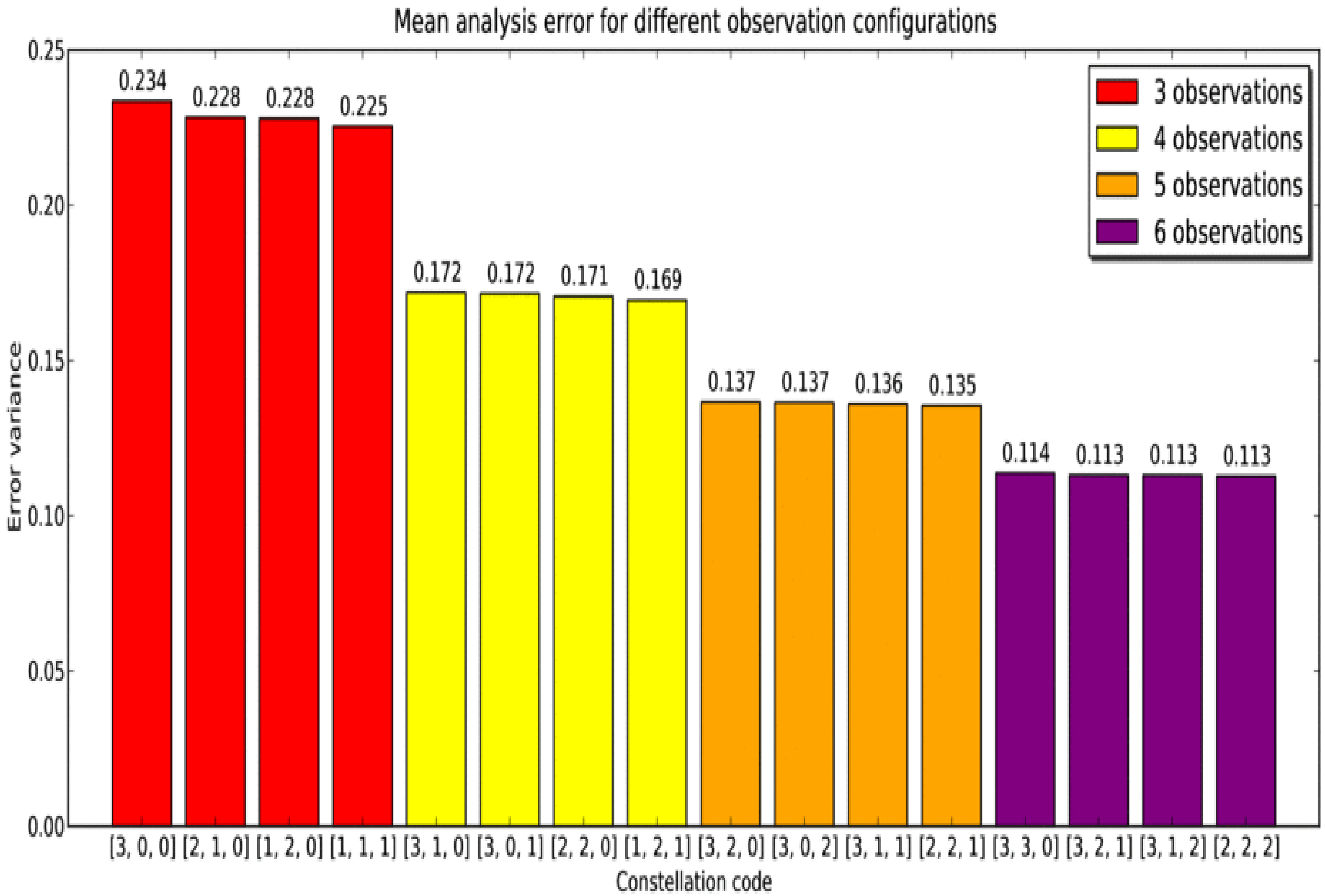
Metop-A + NOAA-18 + NOAA-19 = [1,2,0]

Metop-A + NOAA-18 + NOAA-15 = [1,1,1]

Mean analysis error variance:

forecast error variance doubling time = 12 hours

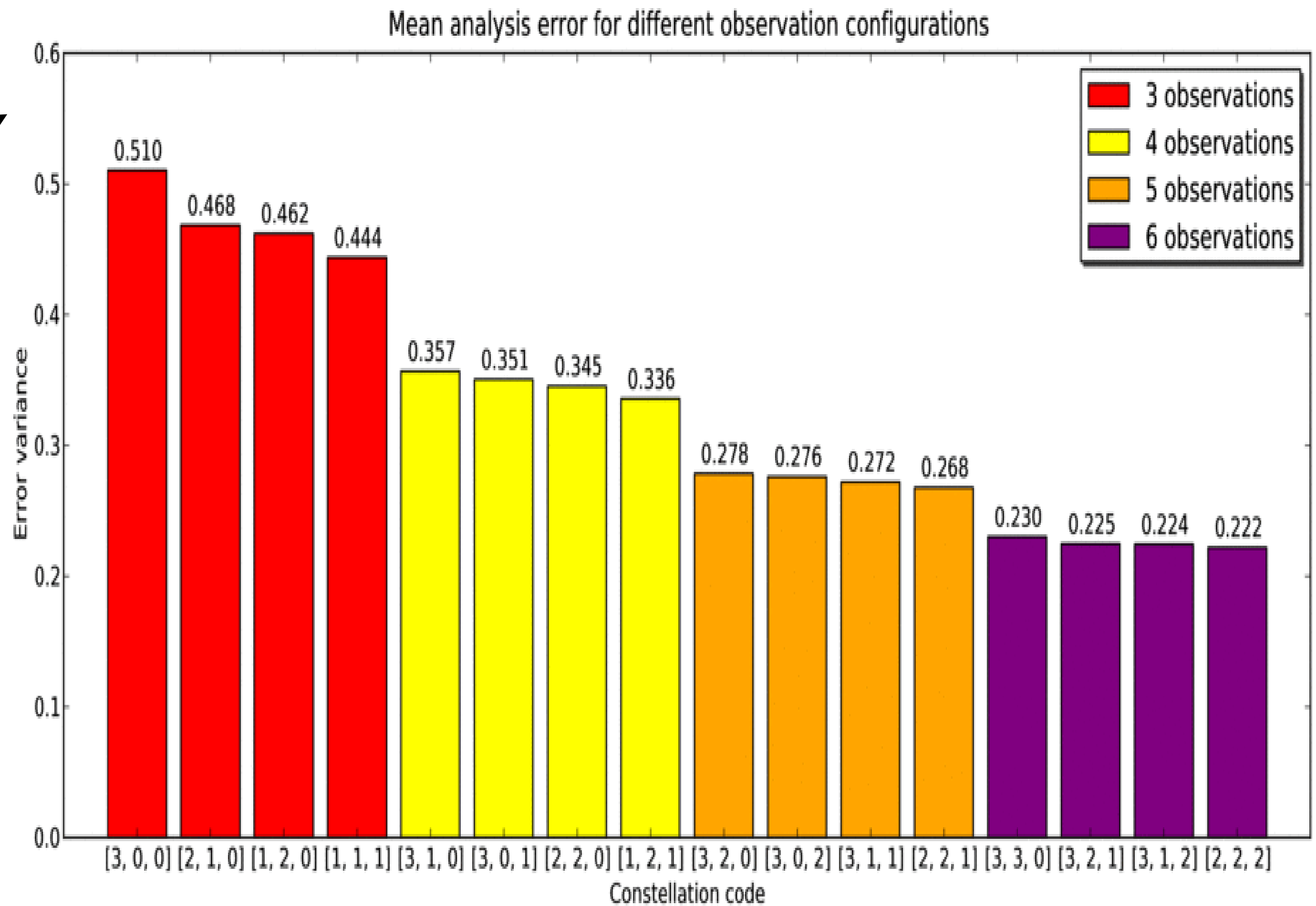
observation error variance = 1.0, for all obs



Mean analysis error variance:

forecast error variance doubling time = 6 hours

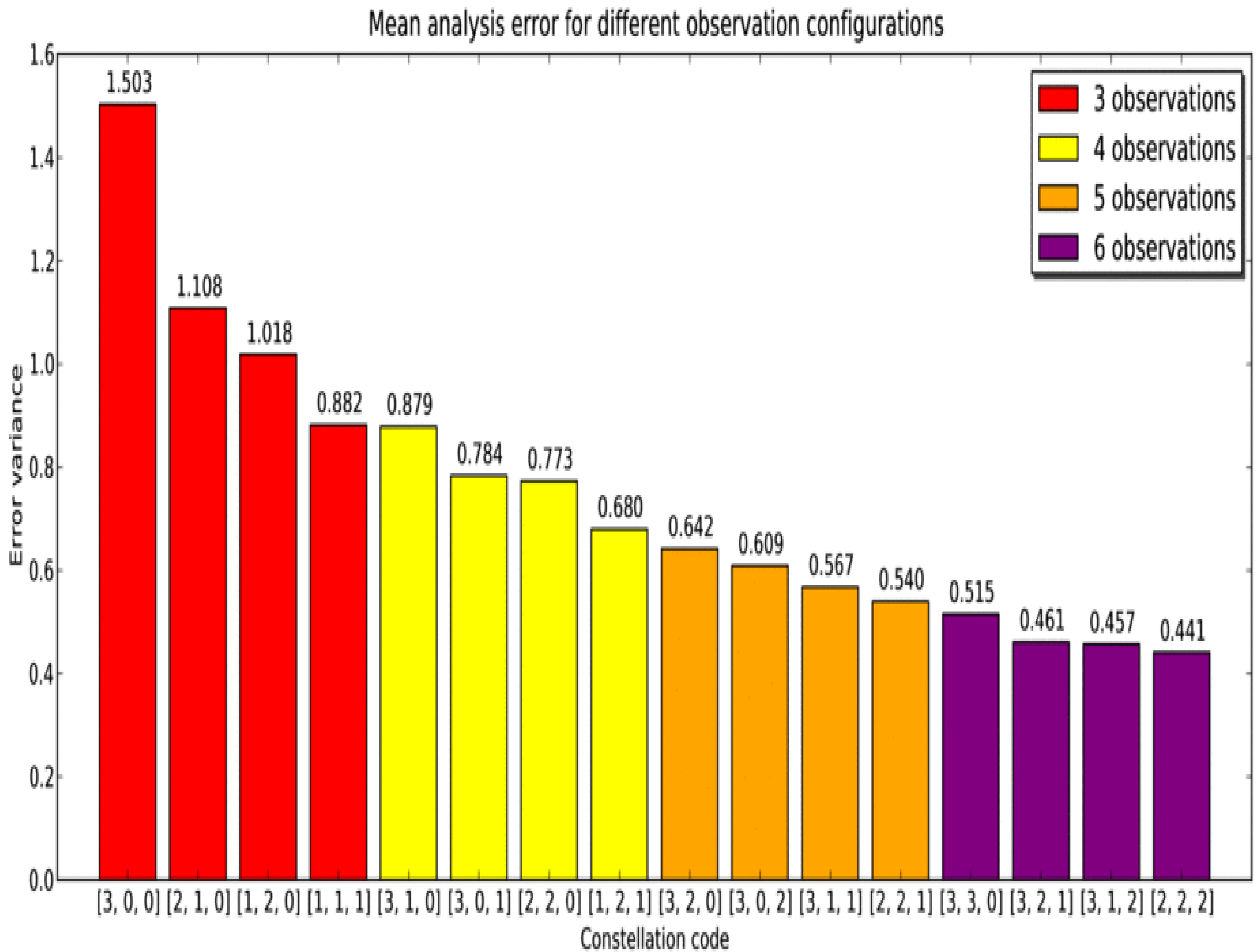
note change of scale



Mean analysis error variance:

forecast error variance doubling time = 3 hours

note change of scale



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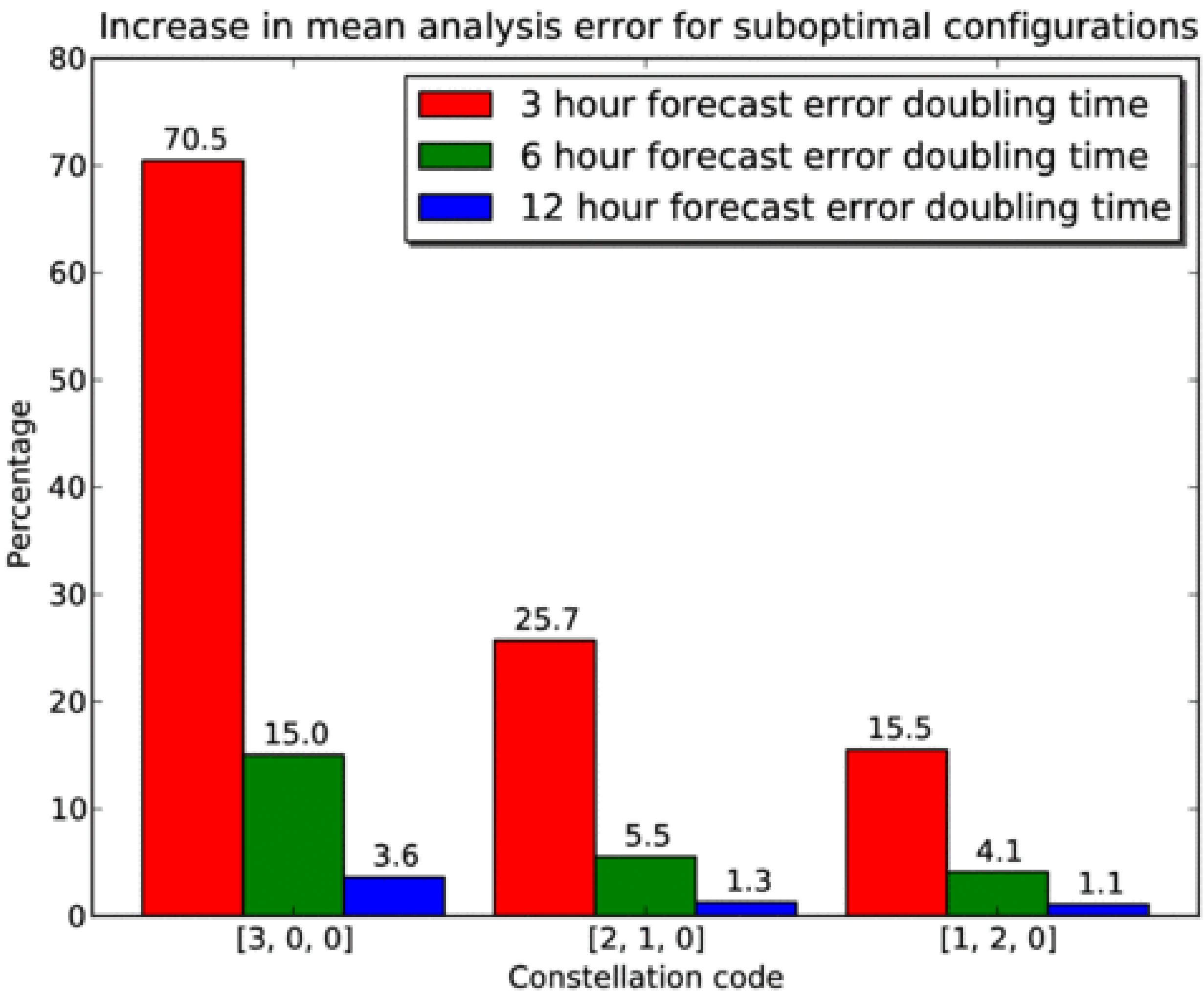
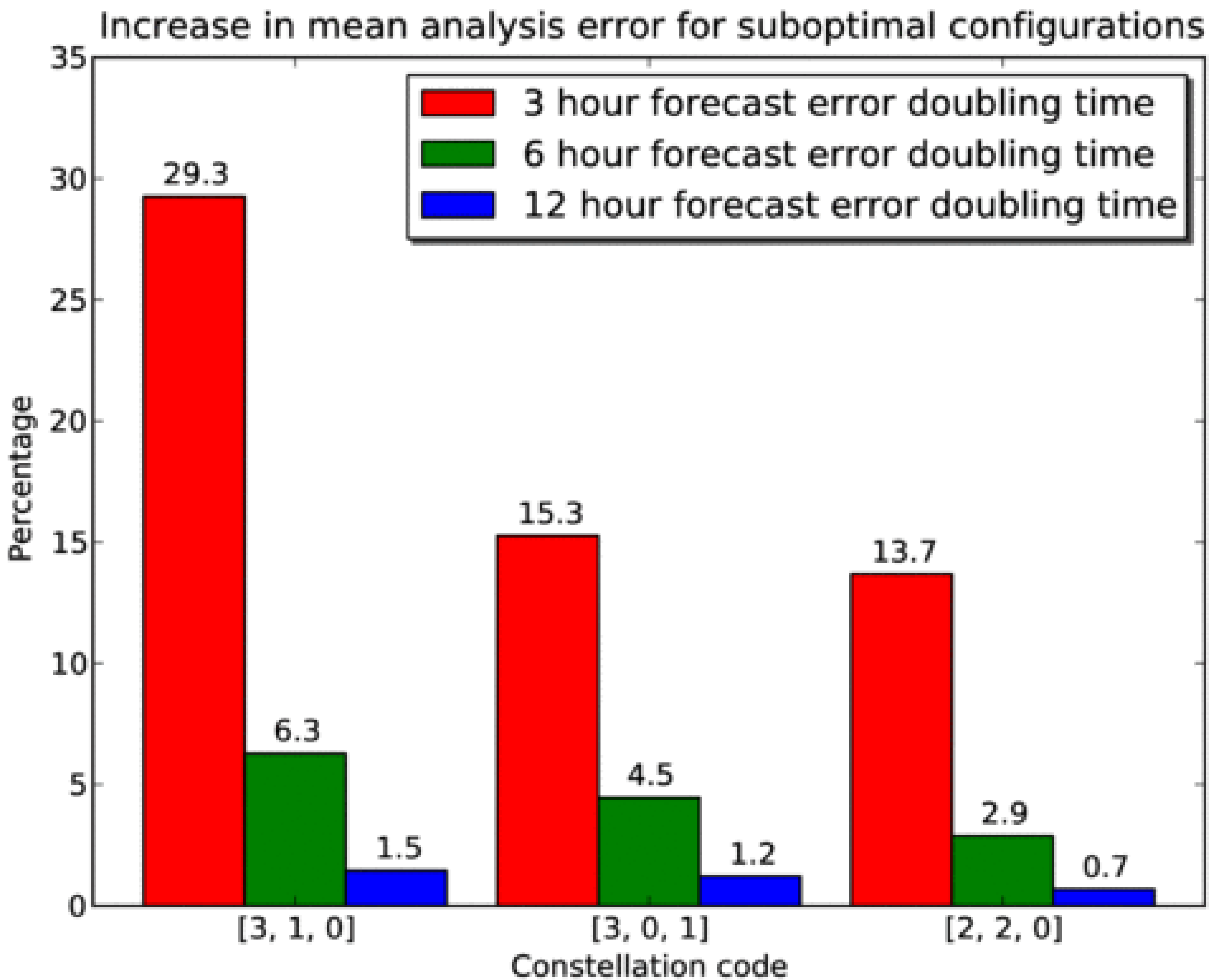
For 3-satellite constellations: percentage increases in analysis error variance relative to [1,1,1]



For 4-satellite constellations: percentage increases in analysis error variance relative to [1,2,1]



Relevance of theoretical results to real world?

Forecast sensitivity to observations (FSO) in global NWP:
(Joo, Eyre and Marriott. Met Office FR Tech. Rep. No.562, 2012. Also accepted by MWR.)

~64% of impact comes from satellite observations

…

of which ~90% from polar sounding data

…

higher for mid-latitude oceans

Part I – Conclusions

- Mean analysis error variance is most relevant metric when assessing impact of temporal spacing of observations on global NWP performance

- Dependence of mean analysis error variance on observation spacing is very sensitive to assumed rate of forecast error growth:
  - for a 12-hour doubling time of forecast error variance, dependence on observation spacing is significant but small,
  - for a 3-hour doubling time reaching ~25% increase in variance for plausible 3-satellite constellations, and ~8% increase for 4-satellite constellations.

- These simple experiments are relevant to real NWP systems, particularly for rapidly-developing storms over mid-latitude oceans.

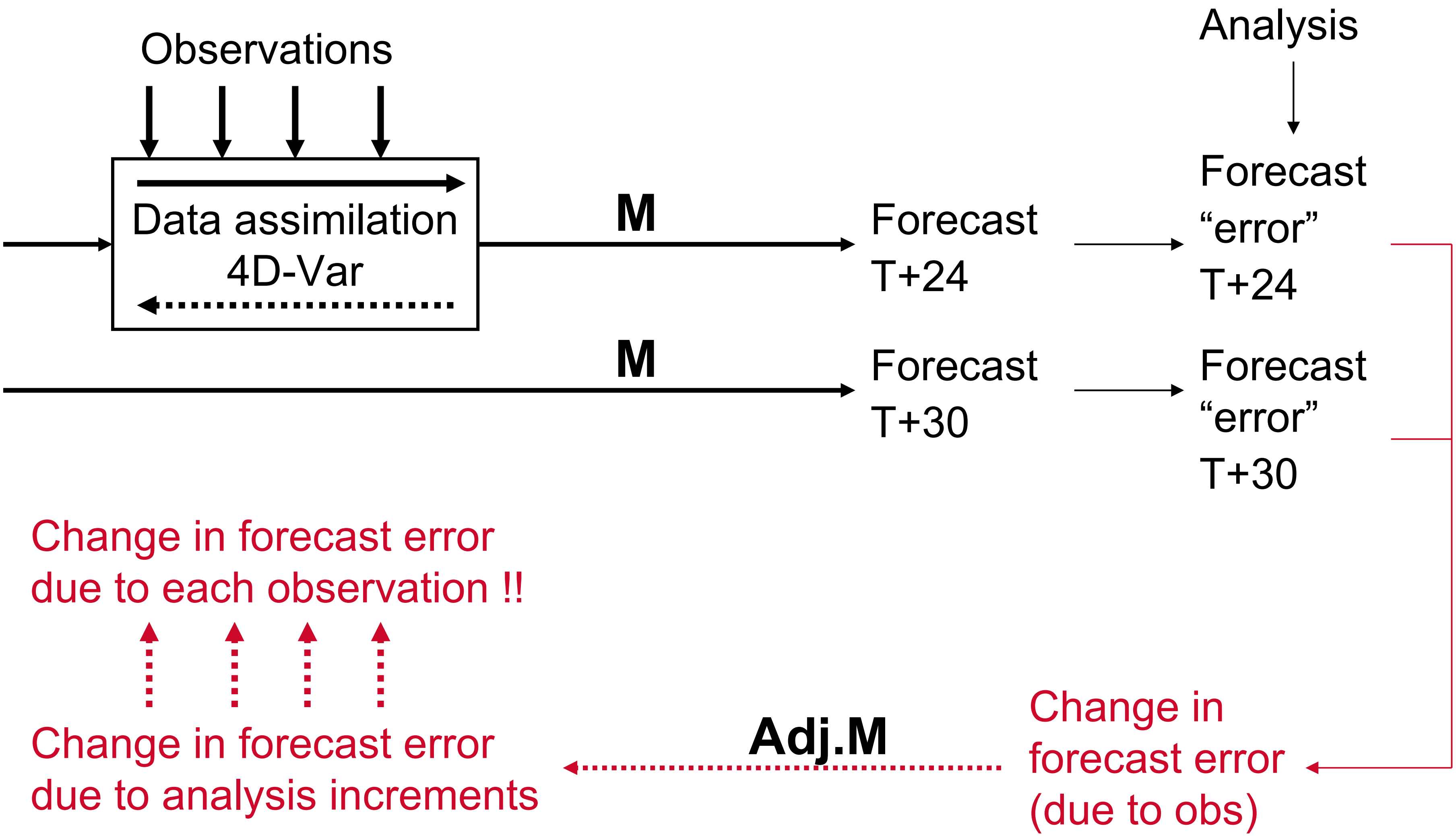
- Results support assumptions guiding the WMO Vision: that polar-orbiting satellites should be equally space in time, as far as is practicable.

Experiments - Part II

All observations are equal …

… but some are more equal than others !

Forecast sensitivity to observations (FSO) in Met Office global NWP



Forecast sensitivity to observations (FSO): importance of Metop data

Forecast sensitivity to observations (FSO): sorted by satellite platform

FSO: sorted in many ways …

a)

b)

…by technology

a)

b)

… by Metop instrument

Some more theory

$A^{-1} = B^{-1} + \Sigma_k R^{-1}_k$, where k is obs subset

$B = A + A B \Sigma_k R^{-1}_k$

$B - A = A B \Sigma_k R^{-1}_k$

But the FSO method measures $(B\text{-}A)_k$,

i.e. contribution to (B-A) from each observation type, k

→ FSO contribution for observation subset k is proportional to R^{-1}_k

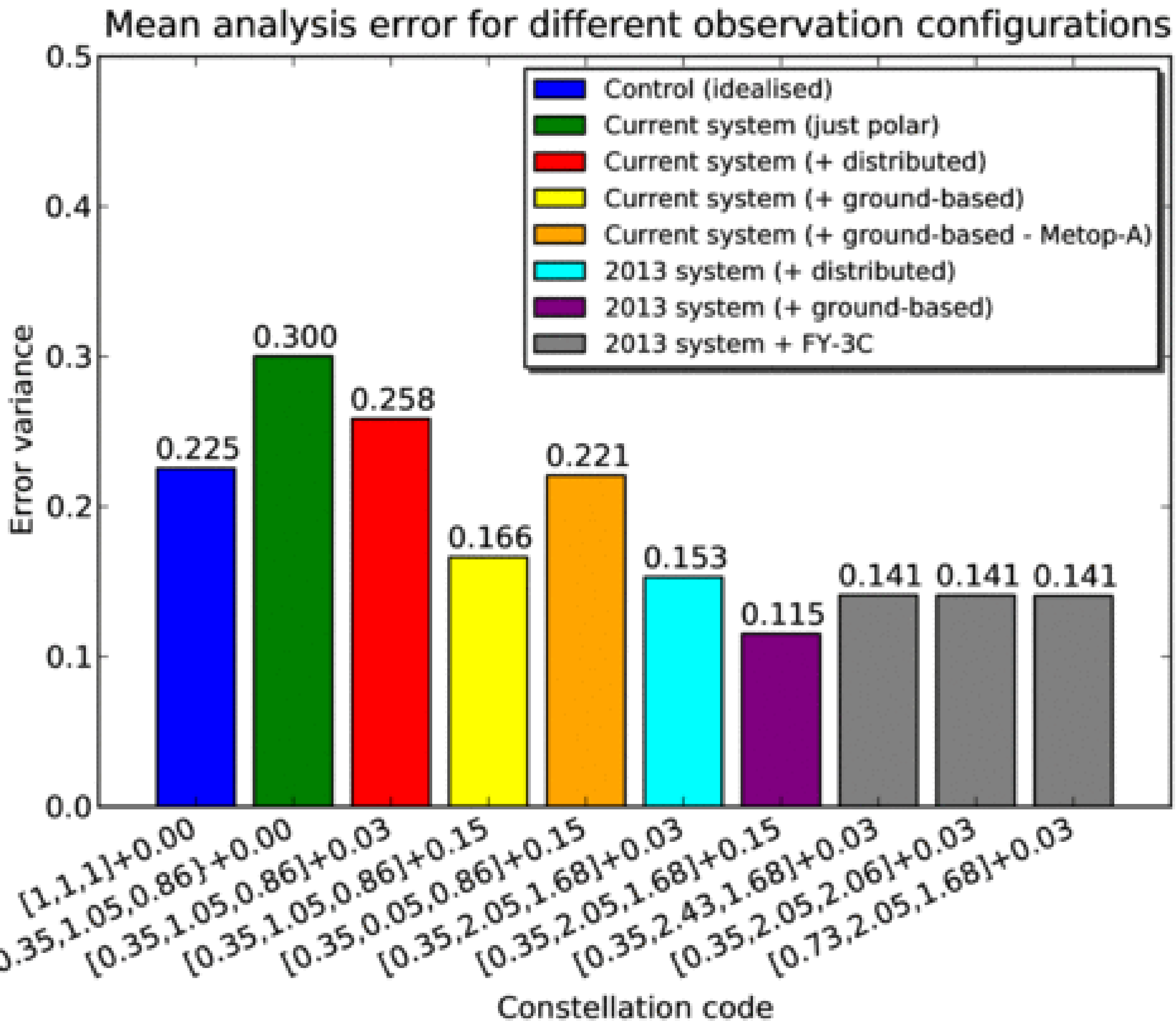
"Real-world" experiments

Satellite	***FSO %***	***FSO normalised***	***Orbit***
Metop-A	38.8	1.000	late morning
NOAA-19	14.3	0.373	afternoon
Aqua	13.7	0.353	afternoon
NOAA-15	11.3	0.291	early morning
NOAA-18	5.5	0.142	afternoon
Meteosat-9	4.9	0.126	geostationary
COSMIC	3.1	0.080	distributed
MTSAT	2.2	0.057	geostationary
GOES	2.1	0.054	geostationary
Terra	1.2	0.031	late morning
Coriolis	1.1	0.028	early morning
DMSP F-16	1.0	0.026	early morning
NOAA-17	0.5	0.013	late morning
GRACE	0.2	0.005	distributed
NOAA-16	0.1	0.003	late morning
ERS-2	0.1	0.003	late morning

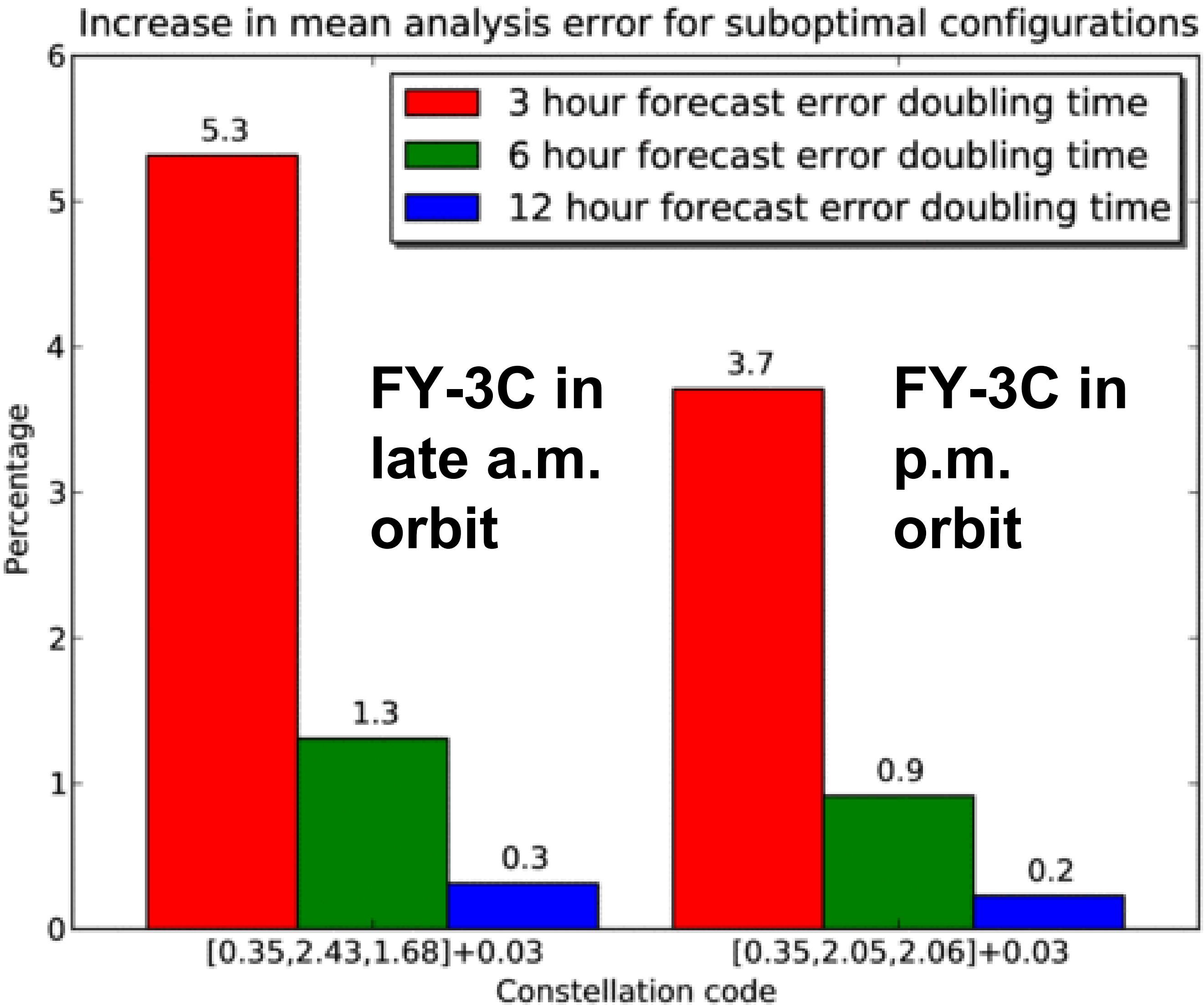
TOTALS: early a.m. = 0.345, late a.m. = 1.049, p.m. = 0.863, distrib.+geo = 0.322

Average analysis error variance:

forecast error variance doubling time = 12 hours



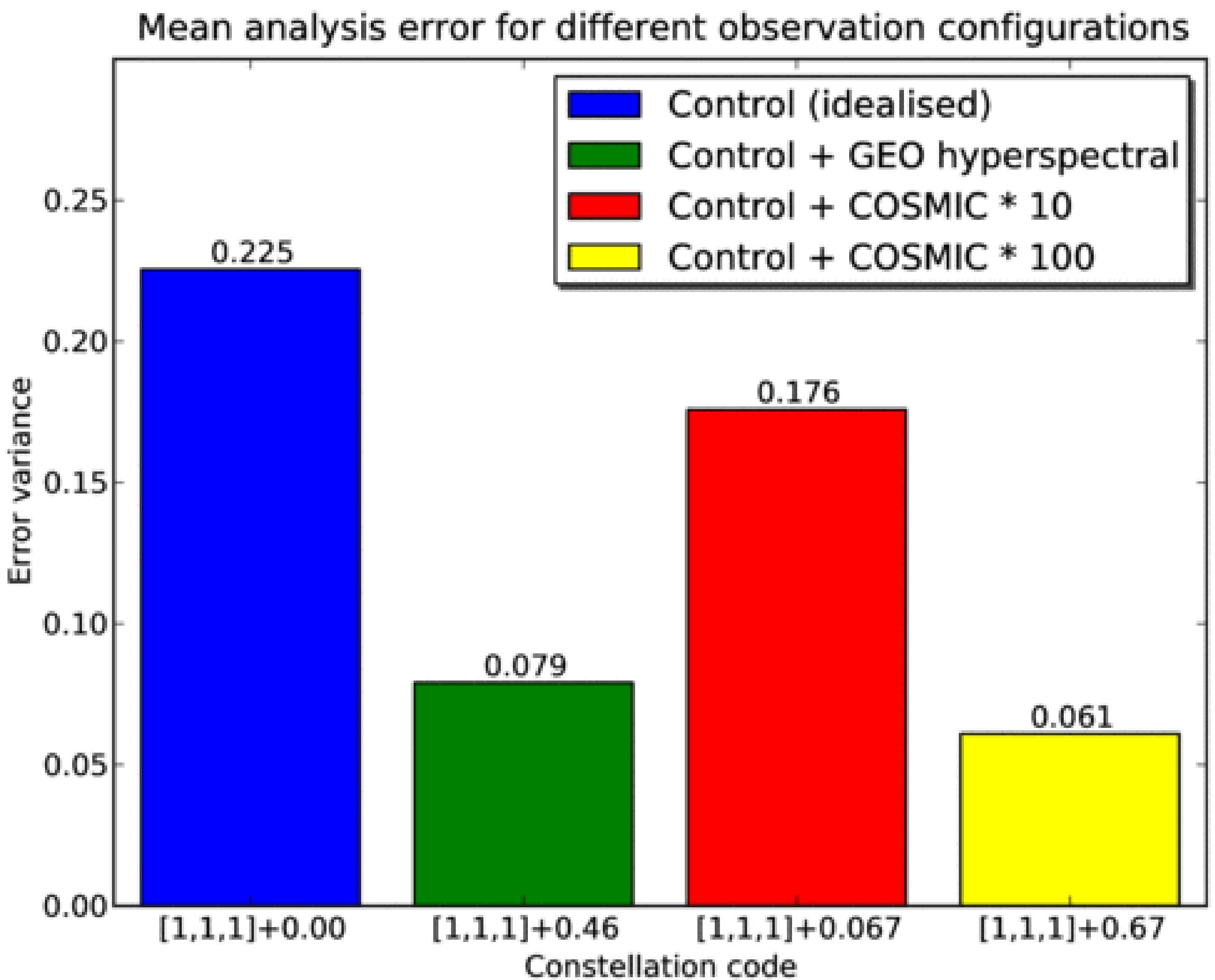
Impact of FY-3C: dependence on orbit



relative to FY-3C in early a.m. orbit

FY-3C observation accuracy = 0.35

Some future systems?



Limitations of this approach

- Many - very simple system!!!

- One variable, with Q=0 → A^{-1} proportional to R^{-1}
  - In practice, Metop-A accounts for 25% of FSO (R^{-1})
  - But denial of Metop-A → ~10% loss of forecast skill
  - Introduce non-zero Q:
    - breaks proportionality between A^{-1} and R^{-1}
    - … but can't account for FSO/OSE discrepancy

  ✂→ needs at least 2 variables (one observed, one not)

- Observation error correlations – neglected
  - Probably OK for present-day systems
  - Questionable for future systems with many more obs

Overall conclusions

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Overall conclusions

- OSE and theoretical study results support guidance that observations should be roughly equally spaced in time
- Impact of observation spacing on NWP is greatest when forecast error growth rates are high, as likely in rapidly-developing storms
- → At least one set of IR+MW sounding instruments in an early morning orbit is highly desirable. China, please note!

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Thank you! Questions?