Applications of radiative transfer models in NWP data assimilation and re-analysis

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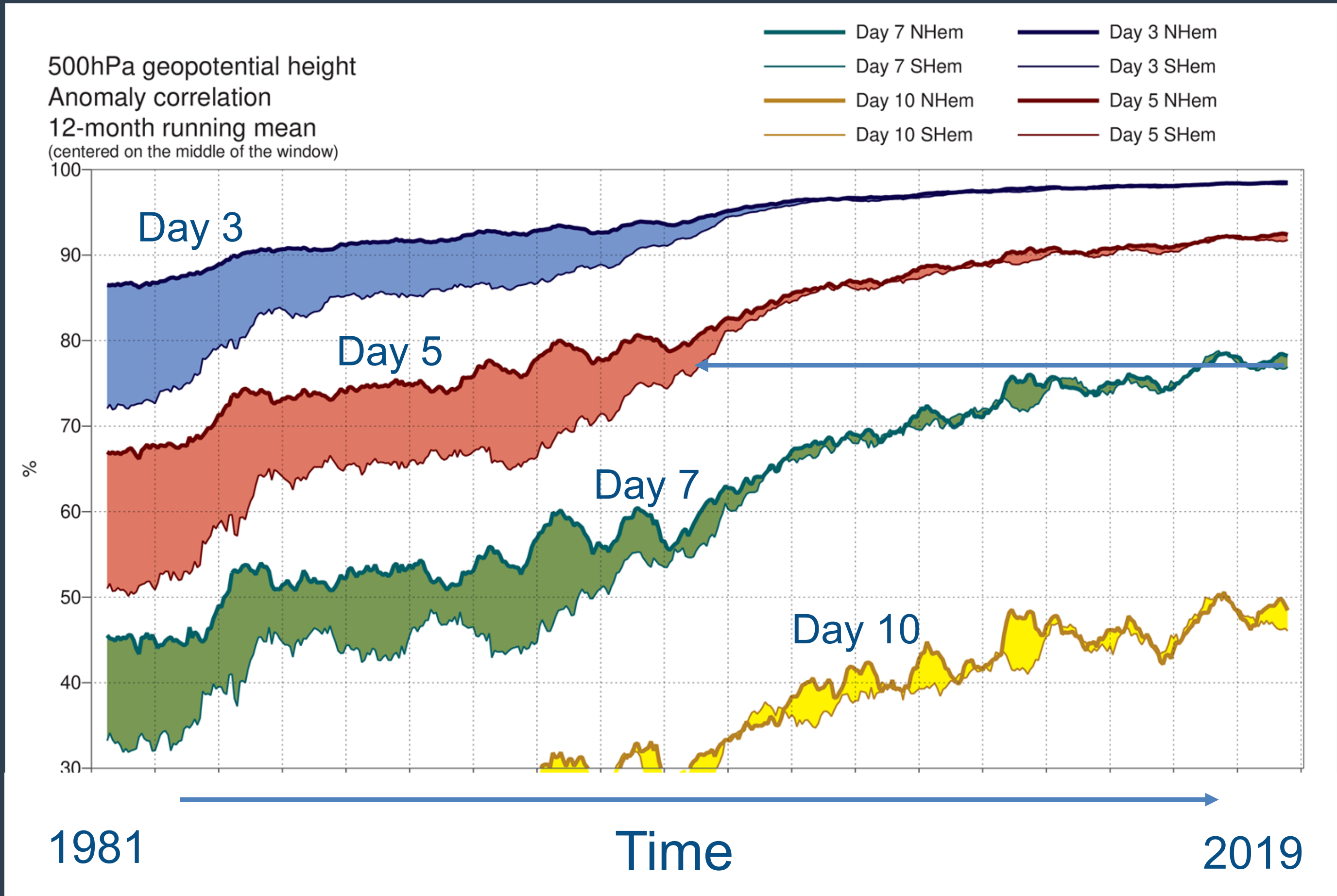
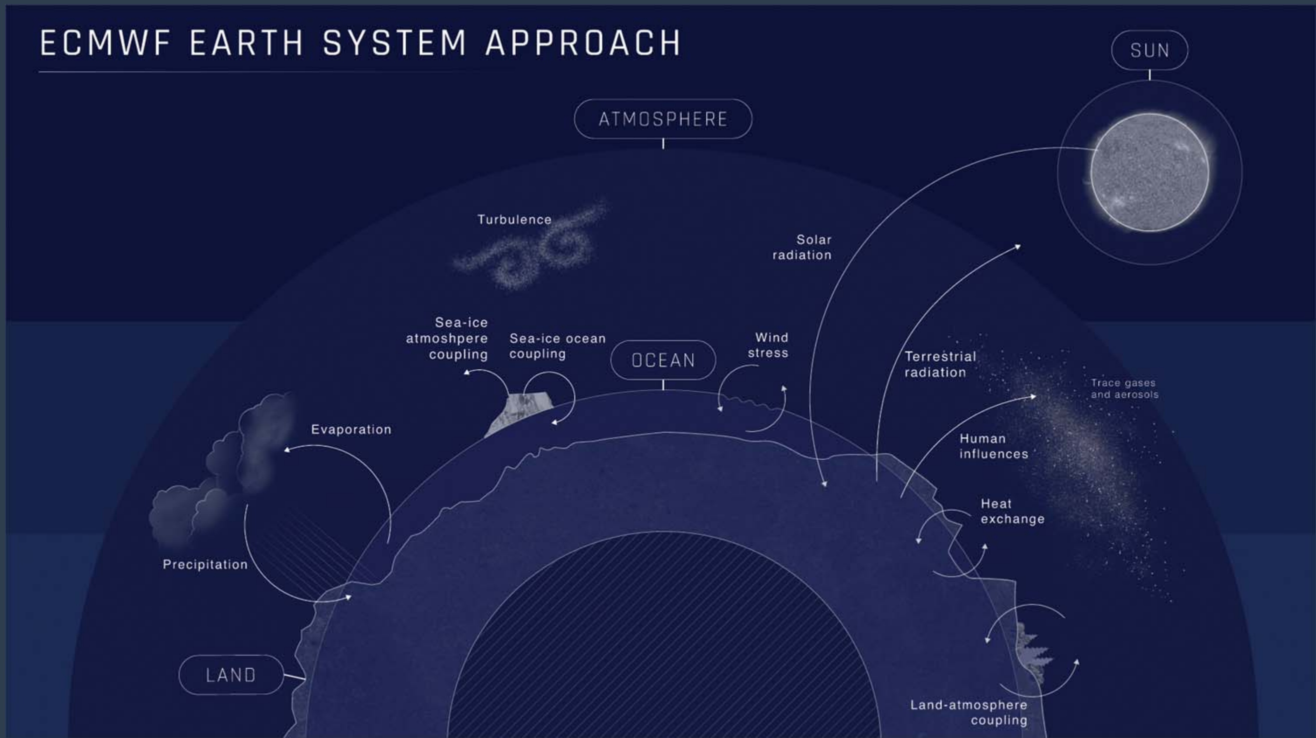
The goal is to continue to improve weather forecast skill



Slide adapted from ECMWF comms team

NWP strategy

- Earth System (implications for RTMs of surface etc.)
- Higher resolution (implications for RTM e.g. 3D RTMs)
- Ensemble based (implications for RTM – want to use all data to initialise)



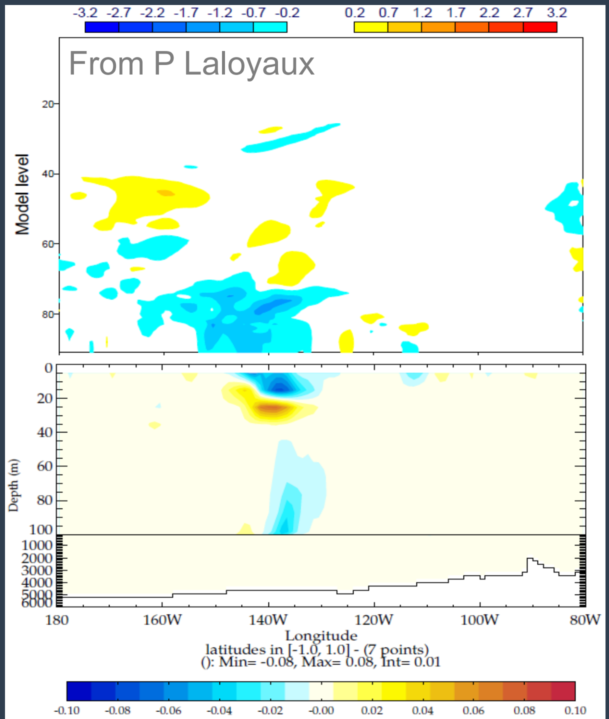
Slide adapted from P de Rosnay

Coupled Earth System Data Assimilation

Earth System approach – coupled forecasts

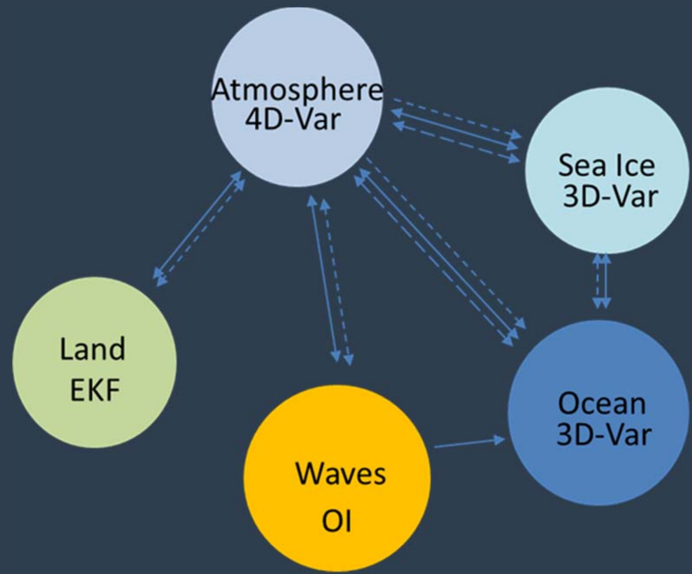
Coupled models need consistent analysis increments

→ high quality DA across all components -> Earth System RTMs



Atmospheric wind increment can impact ocean *

Explicit methodology coupling (e.g. 4D-Var outer loop) but also implicit observation operator coupling e.g. MW imagers



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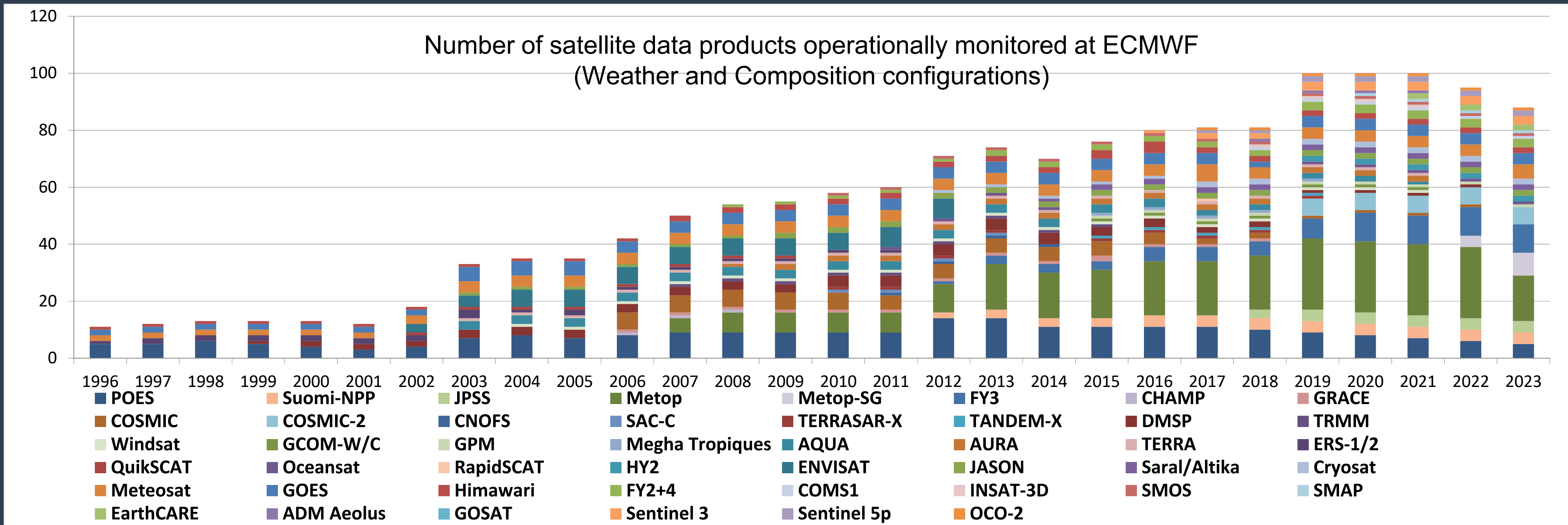
* A coupled data assimilation system for climate reanalysis. P. Laloyaux, M. Balmaseda, D. Dee, K. Mogensen and P. Janssen. QJRMS, 142: 65–78, 2016.

NWP use of observations

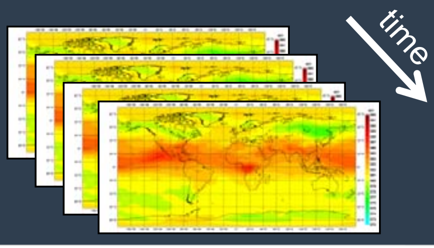
- Number
- Diversity
  - Earth System
  - Active as well as passive (Aeolus, EarthCARE, DPR on GPM)



Slide from A McNally

Basic Data Assimilation concepts

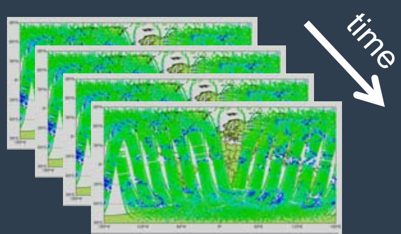
- L1 assimilation and need for RTM in observation operator



4D model state

$$J(x) = (x - x_b)^T \mathbf{B}^{-1} (x - x_b) + (y - \mathrm{H}[x])^T \mathbf{R}^{-1} (y - \mathrm{H}[x])$$

global time windows of measured radiances



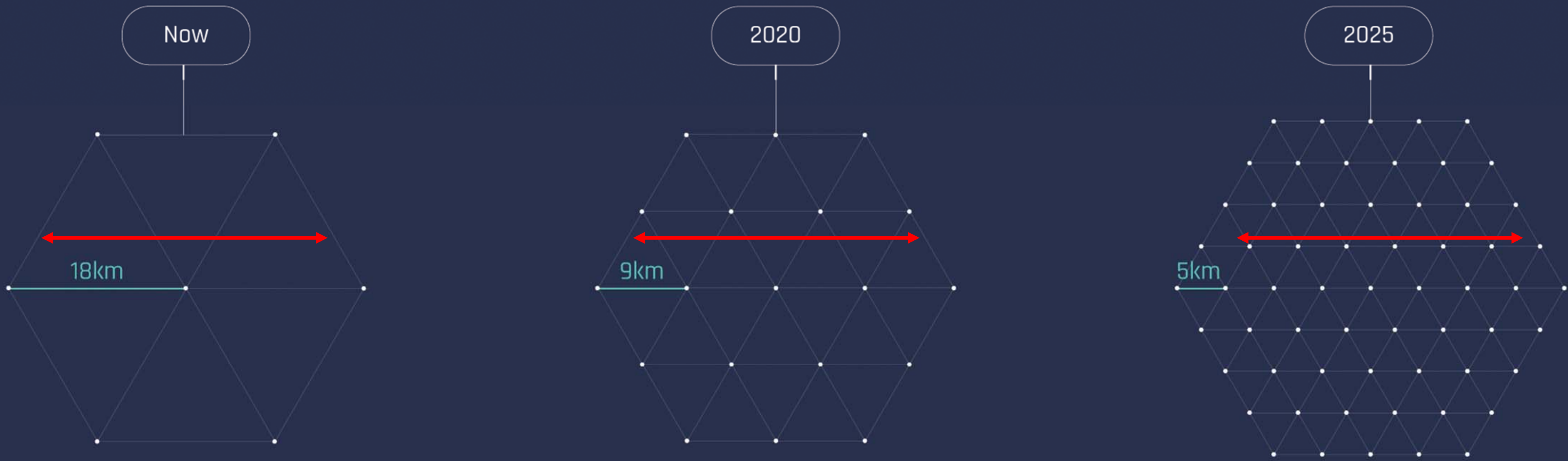
observation operator
= spatial interpolation + forecast model
radiative transfer model

$$L(\nu) = \int_0^\infty B(\nu, T(z)) \left[\frac{d\tau(\nu)}{dz} \right] dz$$

$\mathbf{X}_{t=0}$ → $\mathbf{X}_{t=t}$

Slide adapted from ECMWF Comms team

REFINING HORIZONTAL RESOLUTION



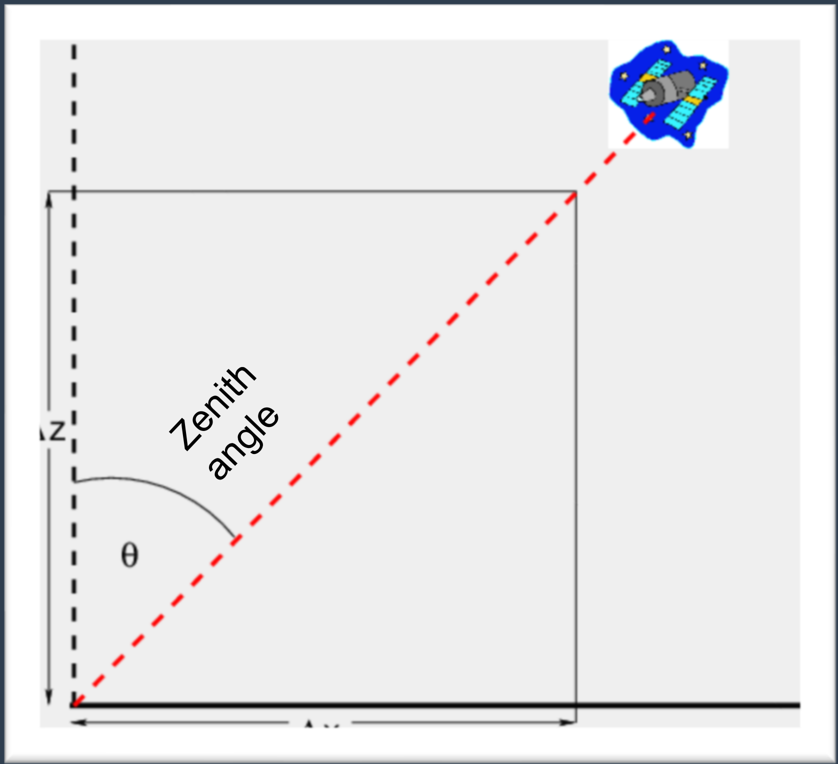
Now	2020	2025
1,661,440 grid points x 91 levels	6,599,680 grid points x 137 levels	16,072,000 grid points x 200 levels*
~ 151 million prediction points	~ 904 million prediction points	~ 3,214 million prediction points

*estimated vertical levels

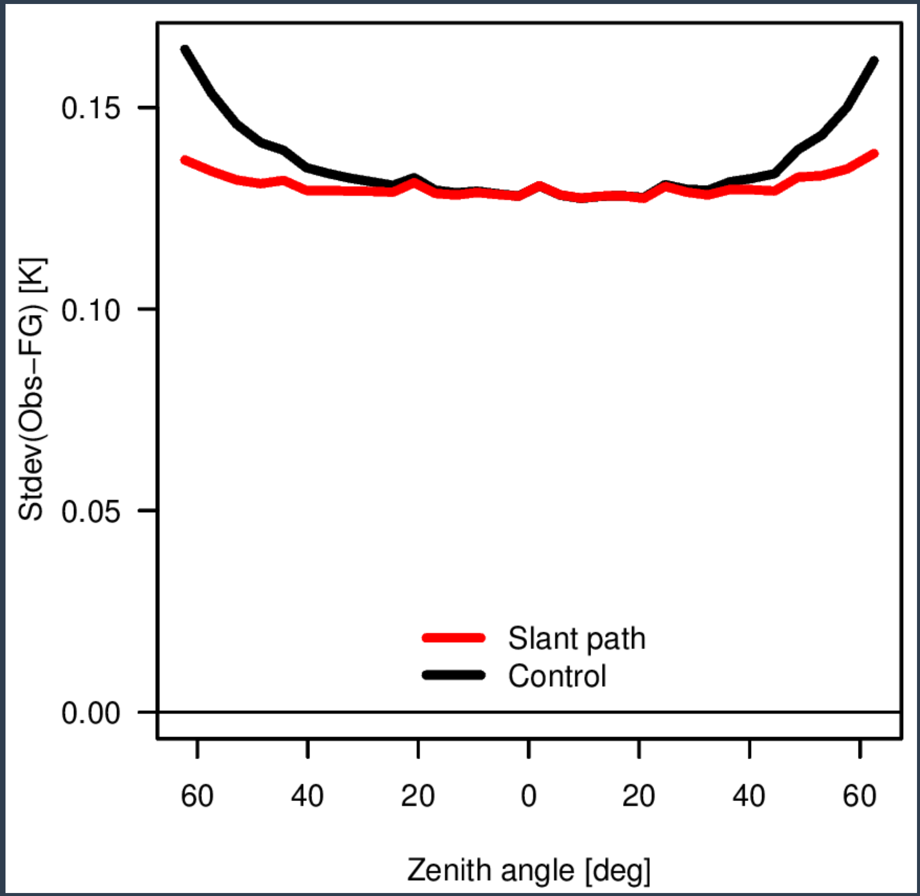
Slide from N Bormann

Examples of benefit arising from more costly RTMs / complex observation operators

- Slant path (Bormann, N. ECMWF Tech Memo 742)



Stdev(o-b), ATMS ch 9



Slide modified from A Geer

Costs in NWP: affordability of RTM

- 9km forecast model in data assimilation "outer loop"
- 2018 ECMWF operations: 704 parallel processes with 6 CPUs each

High-res trajectory (in 4D-Var) cost break down

Model physics	26%
Store trajectory	17%
Model dynamics	12%
Coupled wave model	12%
Others	(30%)
Observation equivalents	1.8%

Total cost in NWP
4D-Var 12%
Ensemble of 4D-Vars 16%

Obs equivalent 1.8% only, of which:
1.6% communication: moving data to observation locations
0.2% compute: observation forward models

Conclusion: we can afford to increase this 0.2% several times without causing significant cost issue in NWP – however memory requirements may be an issue.

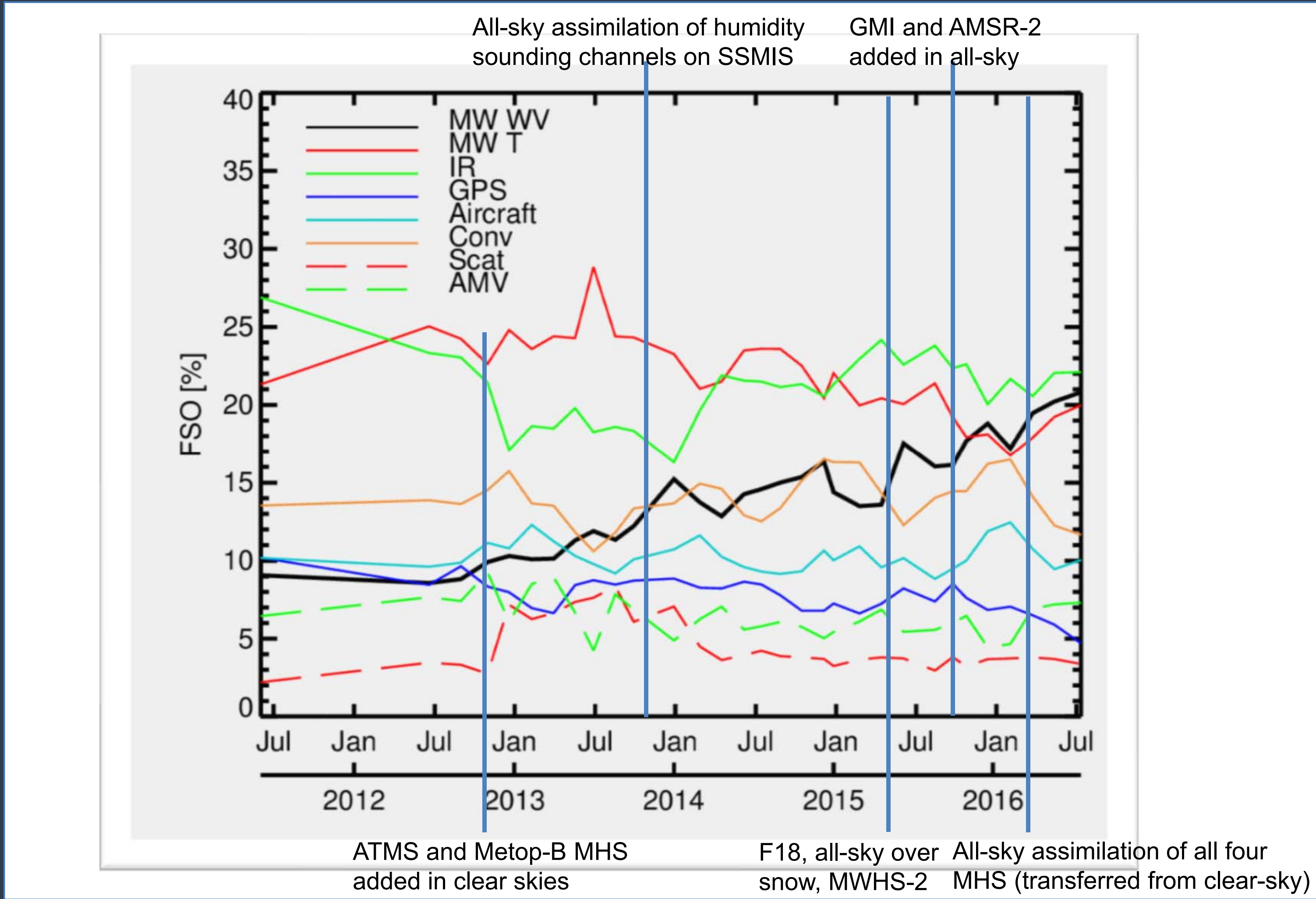
Slide adapted from A Geer

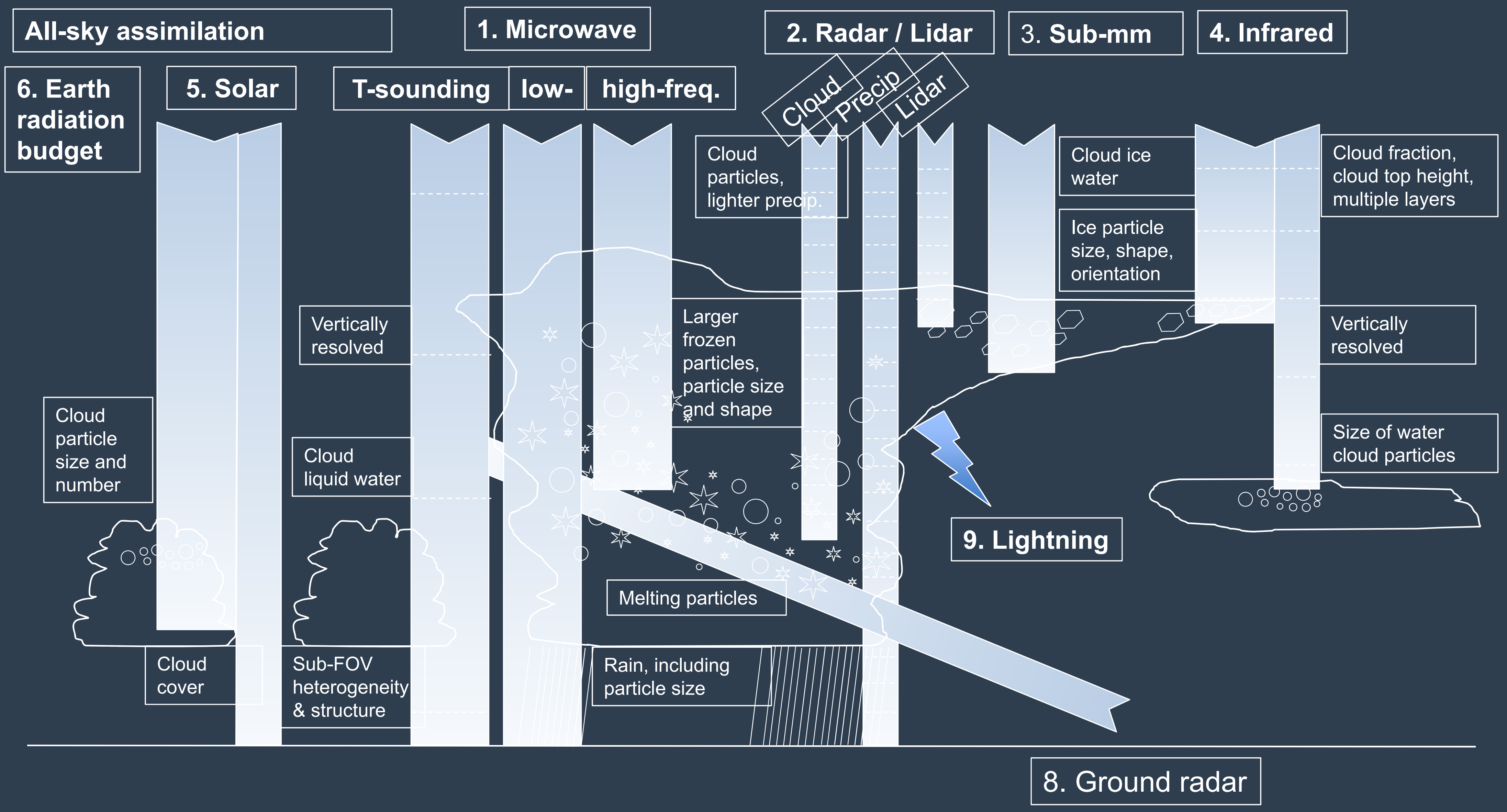
Benefit arising from improved observation operators in ECMWF all-sky

All-sky developments

- Improved RTM
- More data
- 183 GHz obs

Turned humidity sensitive radiances into a major player in NWP skill





Slide adapted from A Geer

Terrestrial surfaces

See Heather Lawrence presentation

Same physics in all bands and different applications so why different models with different assumptions?
e.g. for ocean,

- Passive microwave
- Infrared
- Scatterometer and other active microwave

Different models, different bits of code to maintain, all to solve essentially the same problem!

Unifying should help shake out issues that do not show up in a single band and make data assimilation more consistent

Also uncertainty very poorly characterised, Heather will come back to this in more detail

Similar questions and development needs for other surfaces…one day a unified surface model would be of great value with an object orientated approach (is JCSDA unified observation operator aiming for this?)

e.g. Code objects to run solver with layered dielectric slabs with roughness spectra for any surface, any band. With an interface layer to calculate inputs for specific problem being code being applied to.

Future requirements and conclusions

RTMs can afford more complexity, should aim for simplicity, but allow complexity where beneficial:

- **Cloud and Precip** Extension of all-sky concept: unified observation operators for cloud/precip with consistent RTMs (active, passive; IR, MW, sub-mm, VIS…)
- **Surfaces** Take on more all-surface concept: similar, consistent unified approach across spectral bands (e.g. ocean emissivity model IR+MW, ideally reference quality)
- **Composition** Variable CO2 and other trace gases, aerosol, handling anomalies e.g. HCN

Aim for Unification and Uncertainty characterisation (to SI standard if possible)

To support NWP strategies (and implicitly climate models, nowcasting and other applications):

- **Resolution** RTMs need to consider 3D structure (e.g. slant path RTM)
- **Ensemble forecasts** Better characterise uncertainty in RTM and allow for this in ensemble systems e.g. ECMWF's Ensemble of 4D-Vars, LETKF and other EnKF systems.
- **Earth System** RTMs to support Earth System approach with L1 assimilation and implicit coupling between Earth System components

Final thought….much work is needed to fully address requirements: 100s instruments, Earth System, resolution.

Is this best achieved by,

Many similar but incomplete RTMs with huge duplication of effort ☹

Or,

Collaboration to maintain systems with extensive capability to meet all future needs, with common interfaces to share capability, unified operators and extensive re-use of code ☺