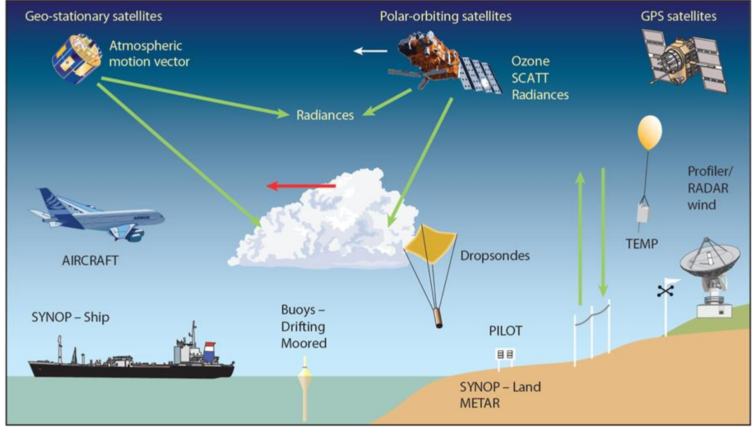
Towards consistent exploitation of Earth system observations in coupled assimilation systems

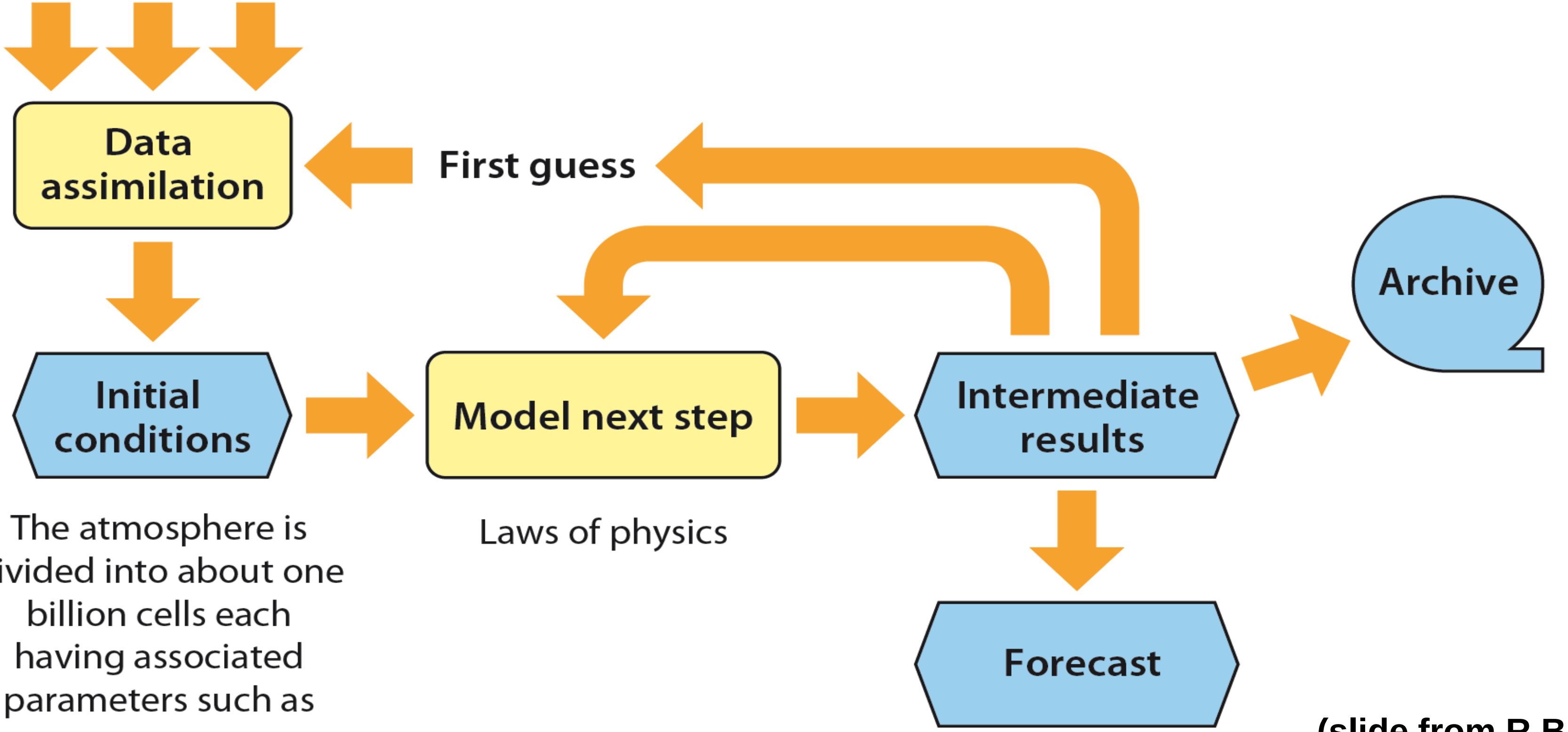
Patricia de Rosnay, Phil Browne, Eric de Boisséson, David Fairbairn,
Kenta Ochi, Dinand Schepers, Pete Weston, Hao Zuo

Thanks to: Magdalena Alonso Balmaseda, Beena Balan-Sarojini,
Mohamed Dahoui, Stephen English, Alan Geer, Yoichi Hirahara, Tony McNally,
and many others

ECMWF forecasts: how do we do them?



Approximately 60 million observations processed and used daily



The atmosphere is divided into about one billion cells each having associated parameters such as temperature, pressure, and wind direction.

Laws of physics

(slide from R Buizza)

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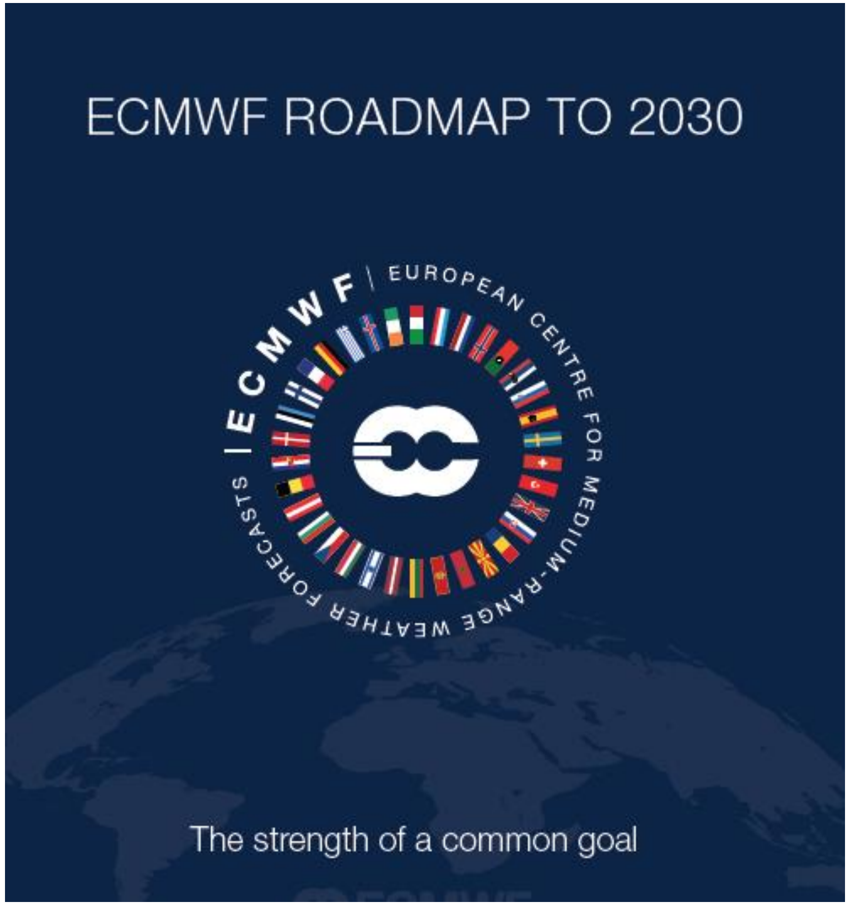
Earth system approach



Strategy 2021-2030

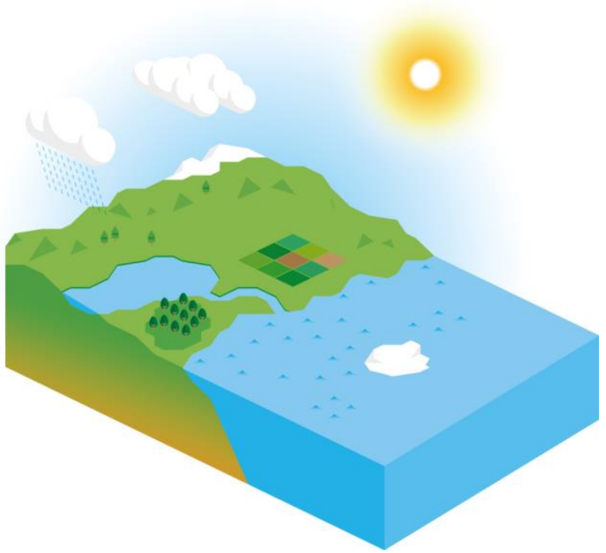
- Enhance consistency of assimilation approaches and optimal level of coupling between the various components of the Earth system

- Improve assimilation of satellite data sensitive to snow, sea and sea ice surfaces → “all-surface” approach

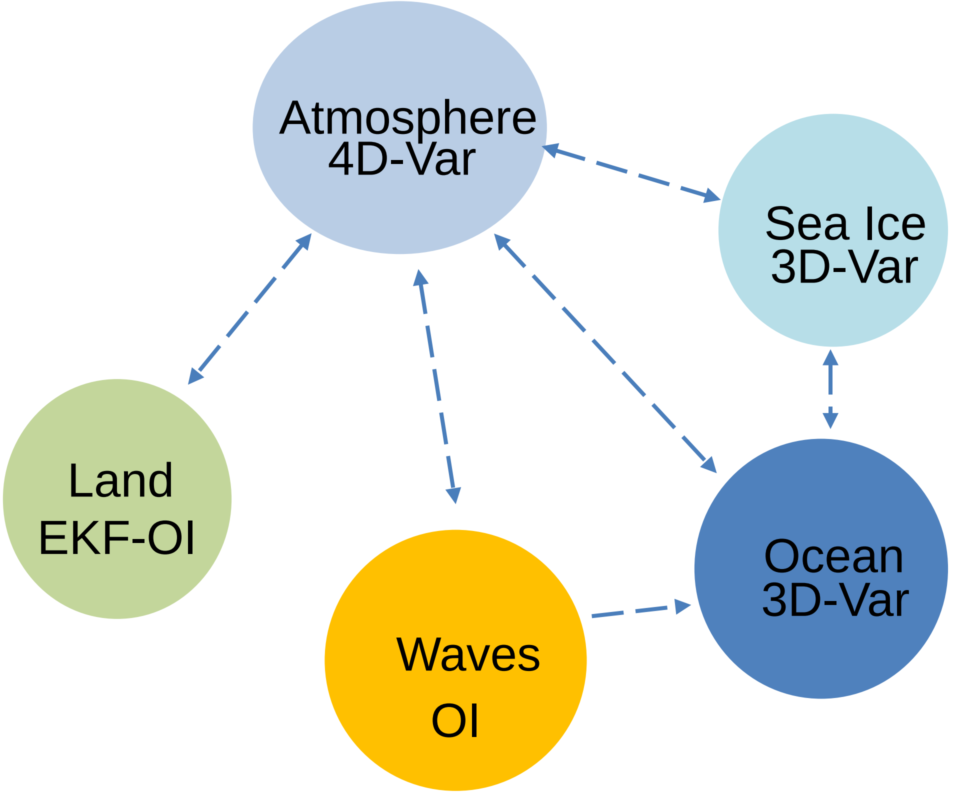
- Machine learning integrated in model and data assimilation to support performance enhancement

https://www.ecmwf.int/en/about/what-we-do/strategy

Earth system approach



Integrated Forecasting System (IFS)



- Coupled assimilation developments for NWP and reanalyses
- <u>Importance of interface observations</u> (e.g. SST, sea ice, snow, soil moisture)

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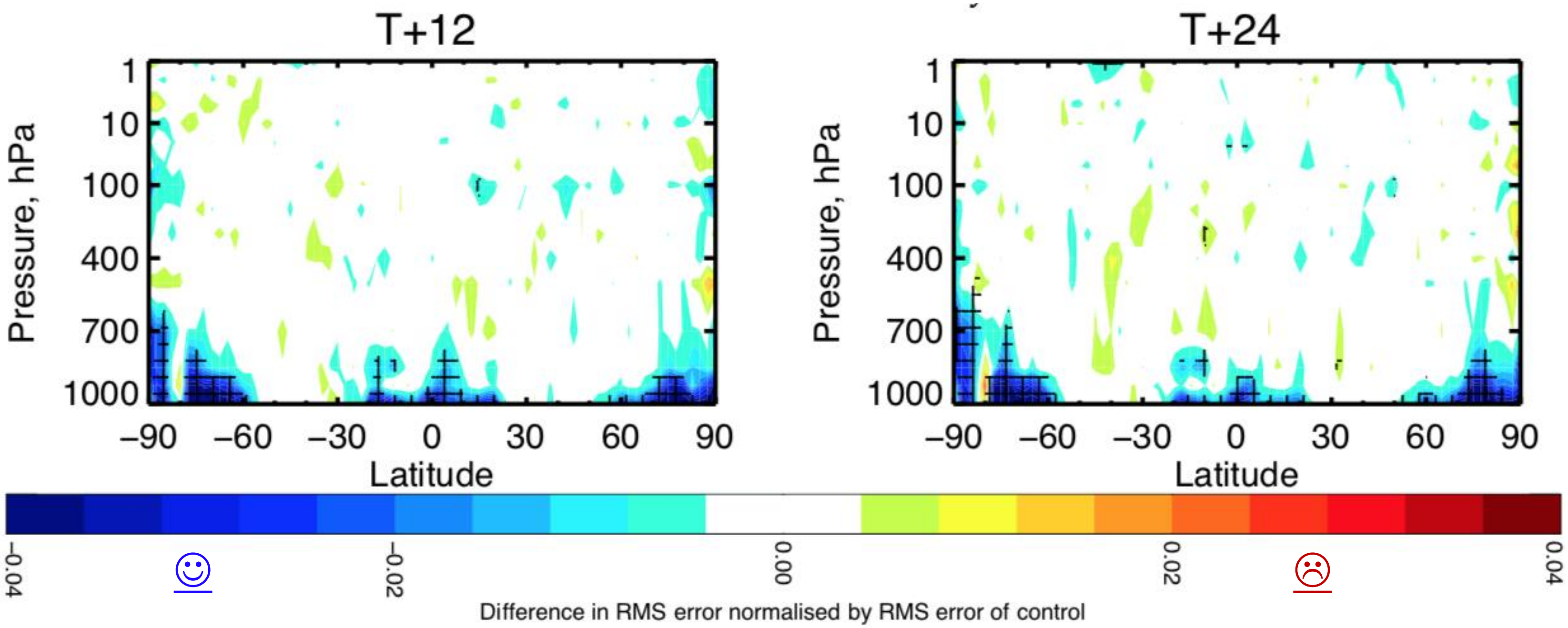
Ocean-atmosphere weakly coupled assimilation through sea ice and SST

June 2017-May 2018

Impact on Temperature Forecasts

Normalized RMSE difference
(coupled DA – uncoupled DA)



(b) dRMSE of temperature (K)
(June 2017 to May 2018)

Browne et al., Remote Sensing, 2019

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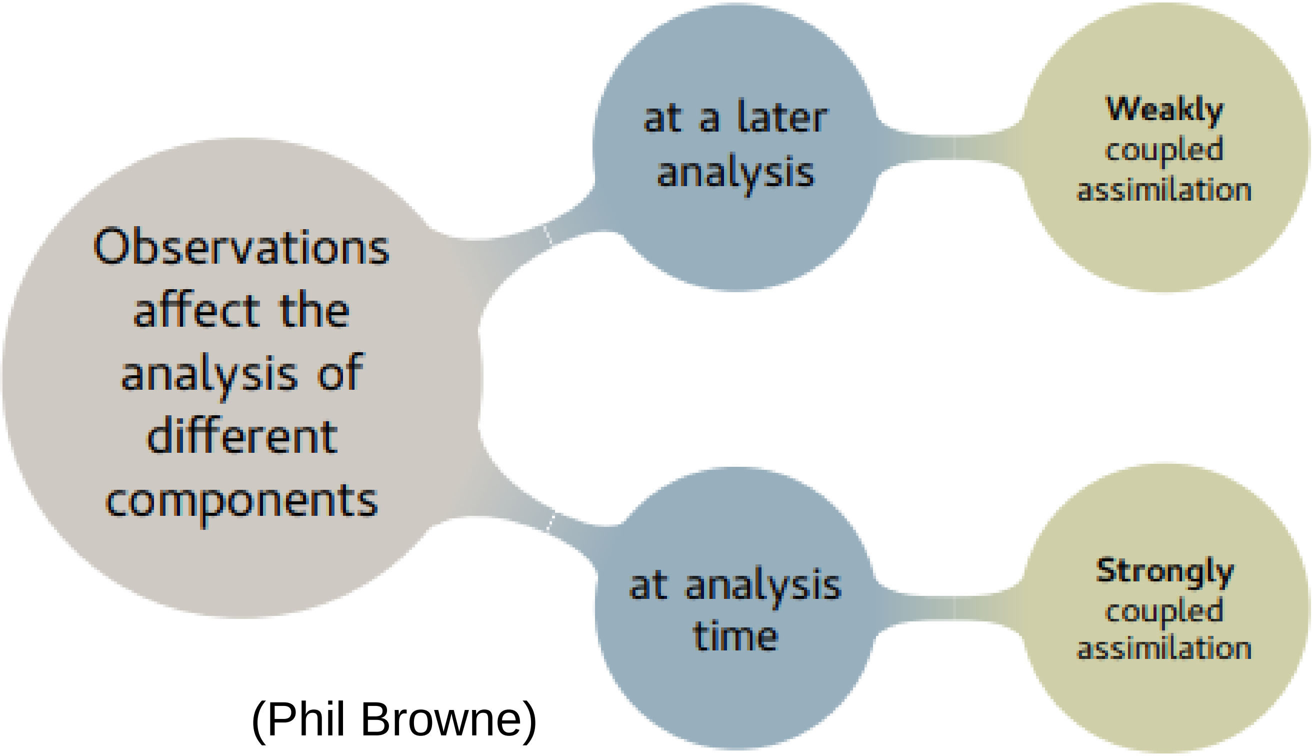
Coupled Assimilation introduction

- What: Exchange of information between data assimilation systems so that observations from one component can influence the analysis of other components (Penny et al., WMO white paper, 2017)
- Why: to provide balanced initial conditions across the coupled forecast model components (e.g. Laloyaux et al.,QJRMS 2016)
- How: Diversity of methodologies from weak to strong coupling (e.g. Fujii et al., QJRMS 2021, Browne et al., 2019; Fairbairn et al. JHM 2019; Schepers et al., ECMWF NewsLett 2018, Storto et al., MWR 2018; Karspeck et al., QJRMS 2018, Frolov et al., MWR 2016, Smith et al., TellusA, 2015);
  Also see talks from Monday's Coupled Assimilation Session at joint WCRP/WWRP Symposium

Coupled assimilation terminology

Formal definitions in:

Penny et al., 2017 *Coupled Data Assimilation for Integrated Earth System Analysis and Prediction: Goals, Challenges and Recommendations*. World Meteorol. Org. (WMO), WWRP 2017-3



(Phil Browne)

Weak coupling

Coupled assimilation spectrum

Full coupling

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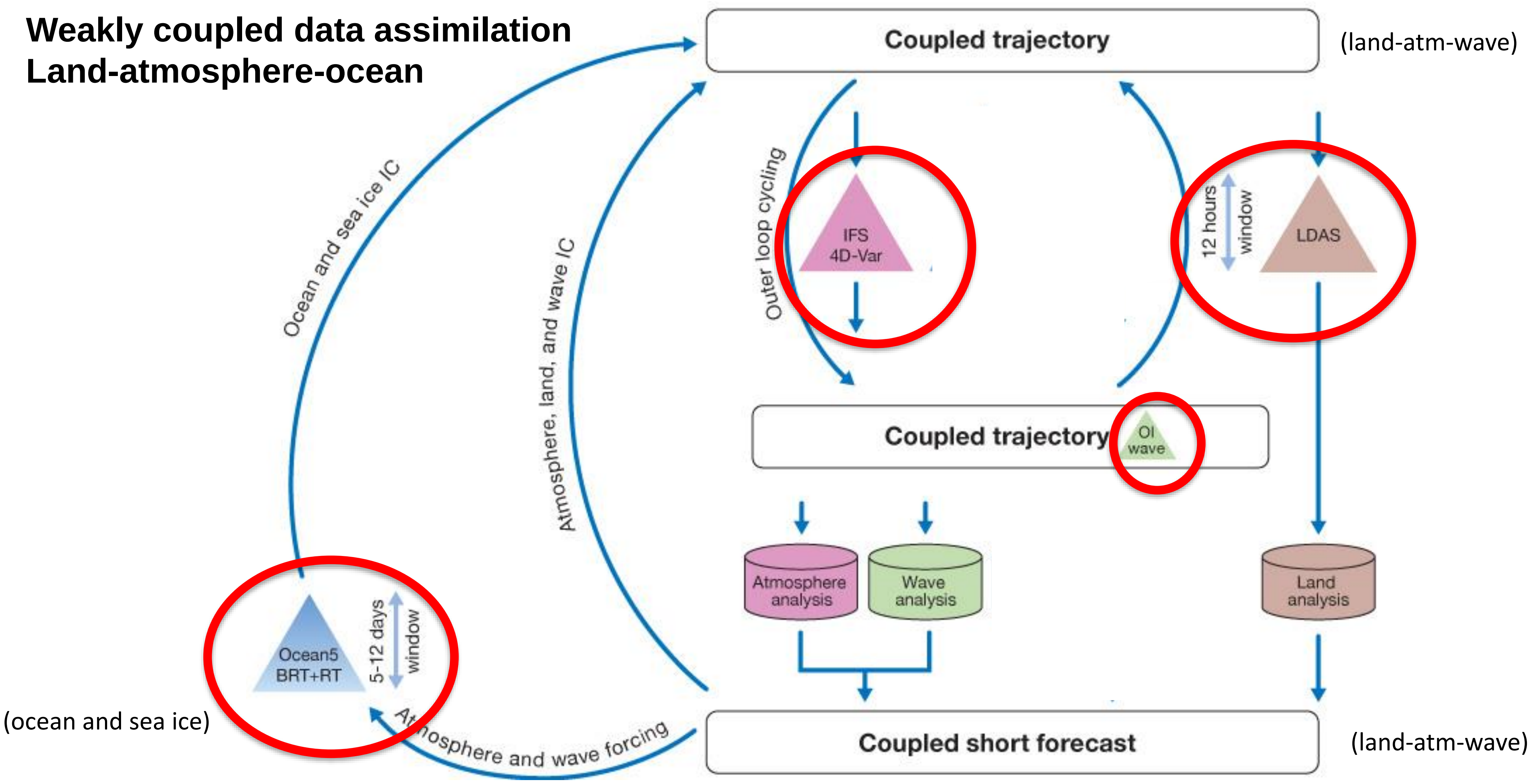
Coupled Assimilation for operational NWP at ECMWF

Weakly coupled data assimilation
Land-atmosphere-ocean



Coupled assimilation in operational systems

Methodology:

- Developments in each component, consistency, coupling strategy and level of coupling, etc
- Link to unified framework development (e.g. OOPS at ECMWF)

Infrastructure:

- Earth system → consistent & modular suite definition and file system across components
- Flexible stand alone and coupled tools for research and operations

Observation operators:

- Exploitation of observations that depend on more than one component (e.g. low frequency MW observations sensitive to the surface), explore AI/ML approaches

Observing system availability, acquisition and monitoring:

→ Also see Peter Lean's talk on Tuesday

- Access to observations, timeliness, common acquisition, observation pre-processing, file format, quality control, data selection, feedback files, monitoring, auto-alert system, …

Observing system and monitoring

Nee timely, sustainable and reliable access to observations across the Earth system components

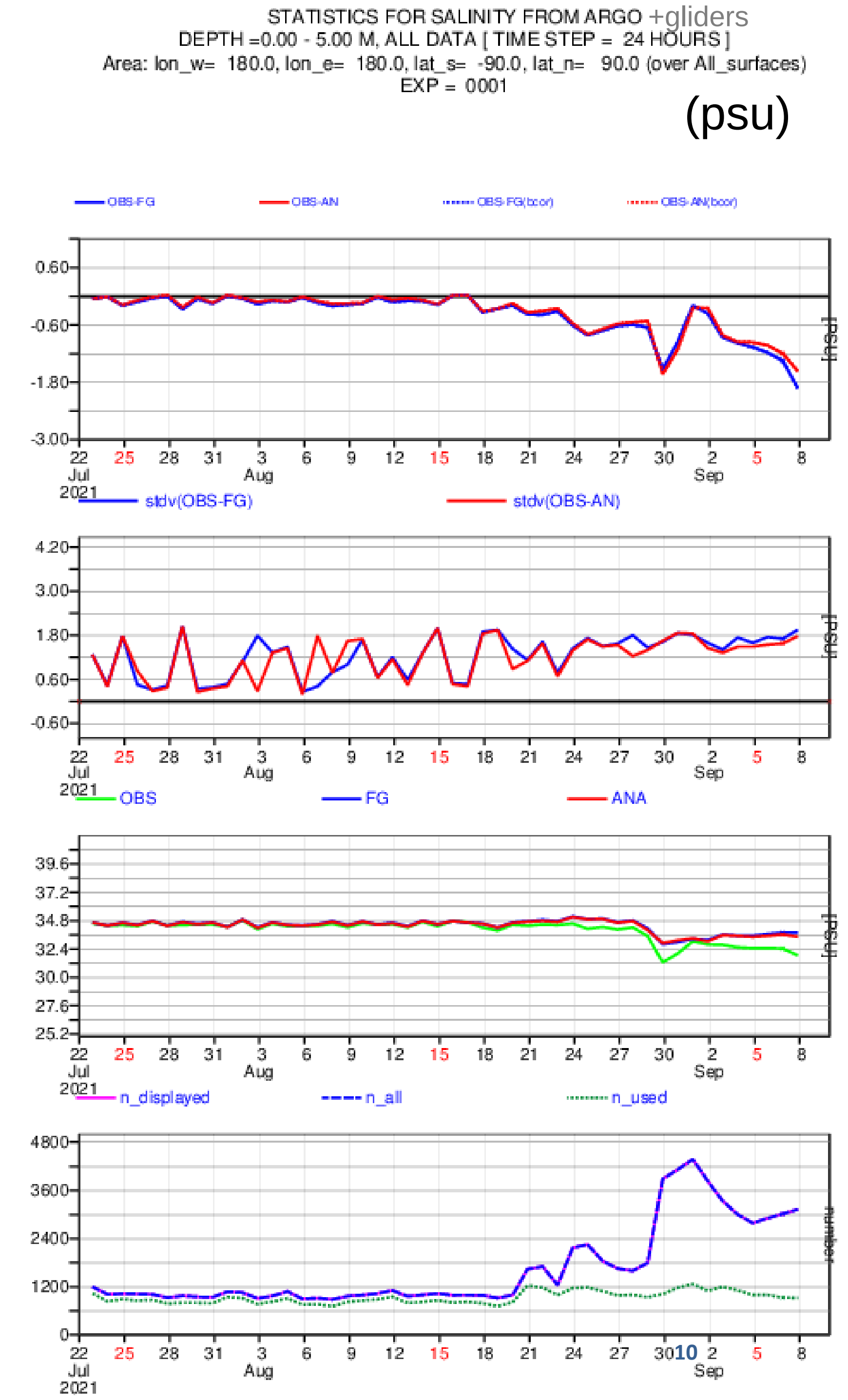
→ J. Siddorn, M. Sandells & C. Charlton-Perez talks on Monday

- **Observations sustainability** for land, cryosphere and for the ocean → level of support from governing bodies to ensure in situ data provision, relevance of WMO data policy evolutions; works of JET-EOSDE, GCW, SG-CRYO, GOOS, etc…

- **Observations acquisition:**
  - Operational acquisition streams needed, e.g. Interface Control Document for Sea Level and SST Observations acquisition
- **Observations monitoring:**
  - Ocean operational monitoring (since 2017)
  - Land operational monitoring (since 2013), SYNOP monthly 'blocklist' & auto-alert (since Sept 2020)

https://www.ecmwf.int/en/forecasts/quality-our-forecasts/monitoring-observing-system

ECMWF



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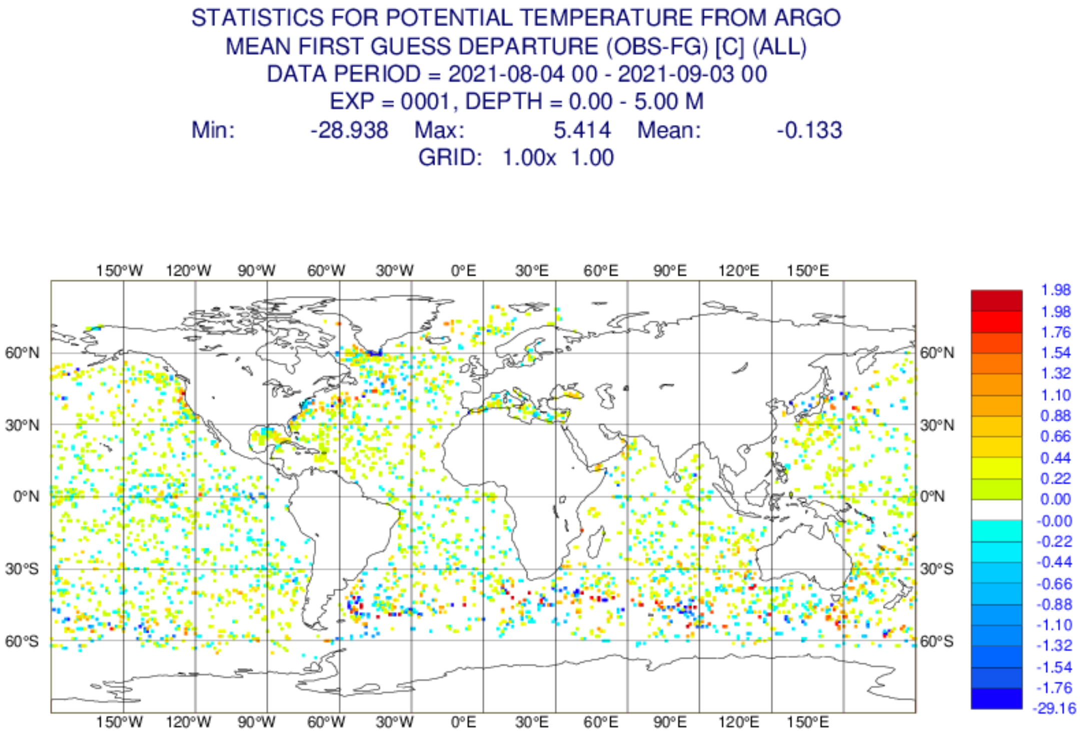

https://www.ecmwf.int/en/forecasts/quality-our-forecasts/monitoring-observing-system

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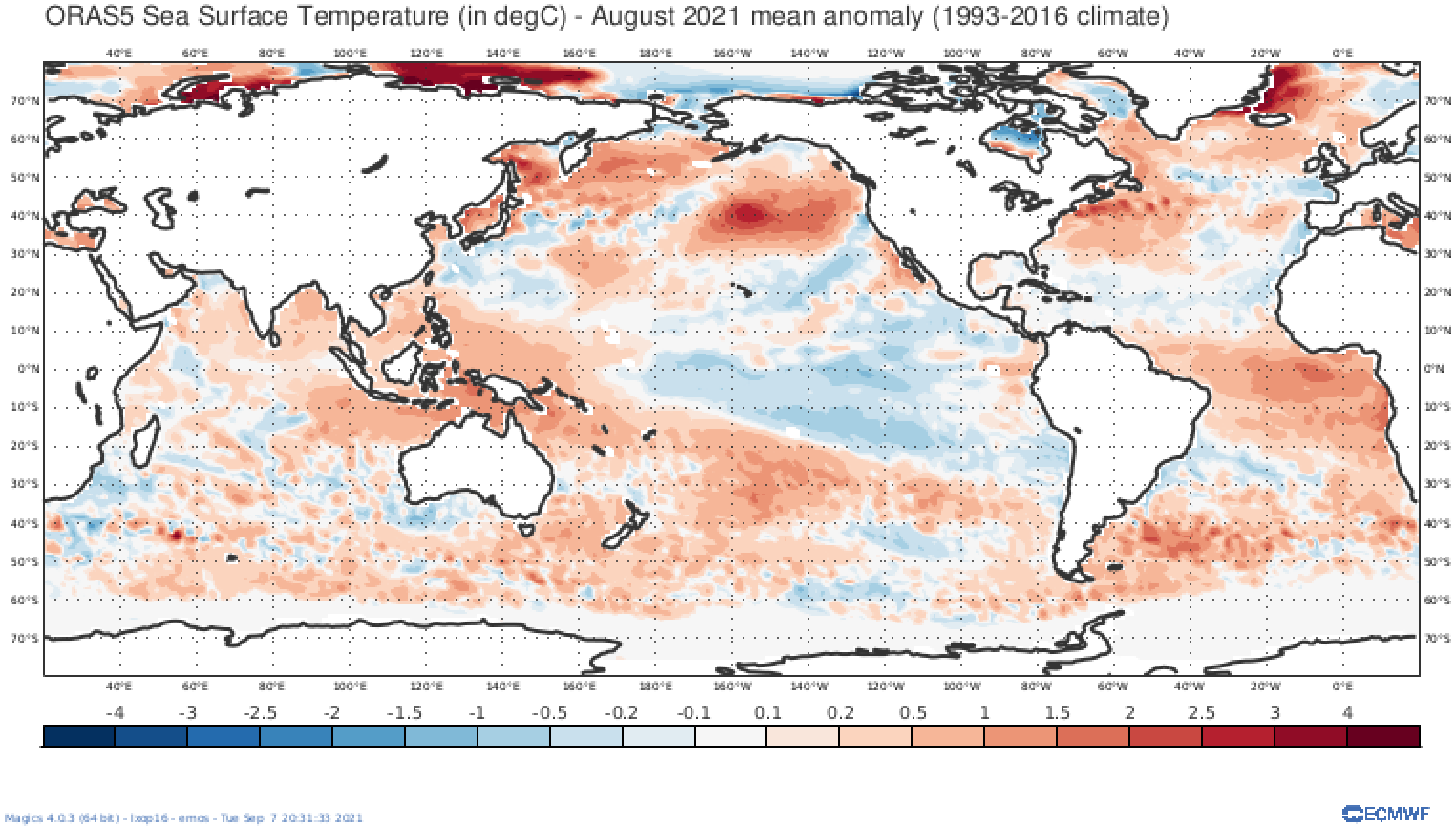
Ocean system monitoring

Based on OCEAN5

Zuo et al., Ocean Sci 2019

- ORAS5 (reanalysis) monitoring: model space monitoring as part of the OCEAN5 suite
- Monthly statistics and anomalies
- Publicly available on: https://www.ecmwf.int/en/forecasts/charts/oras5/



Marine Heat Wave monitoring, **Boisséson et al, ECMWF NewsLett 2021**
Boisséson et al., submitted 2021

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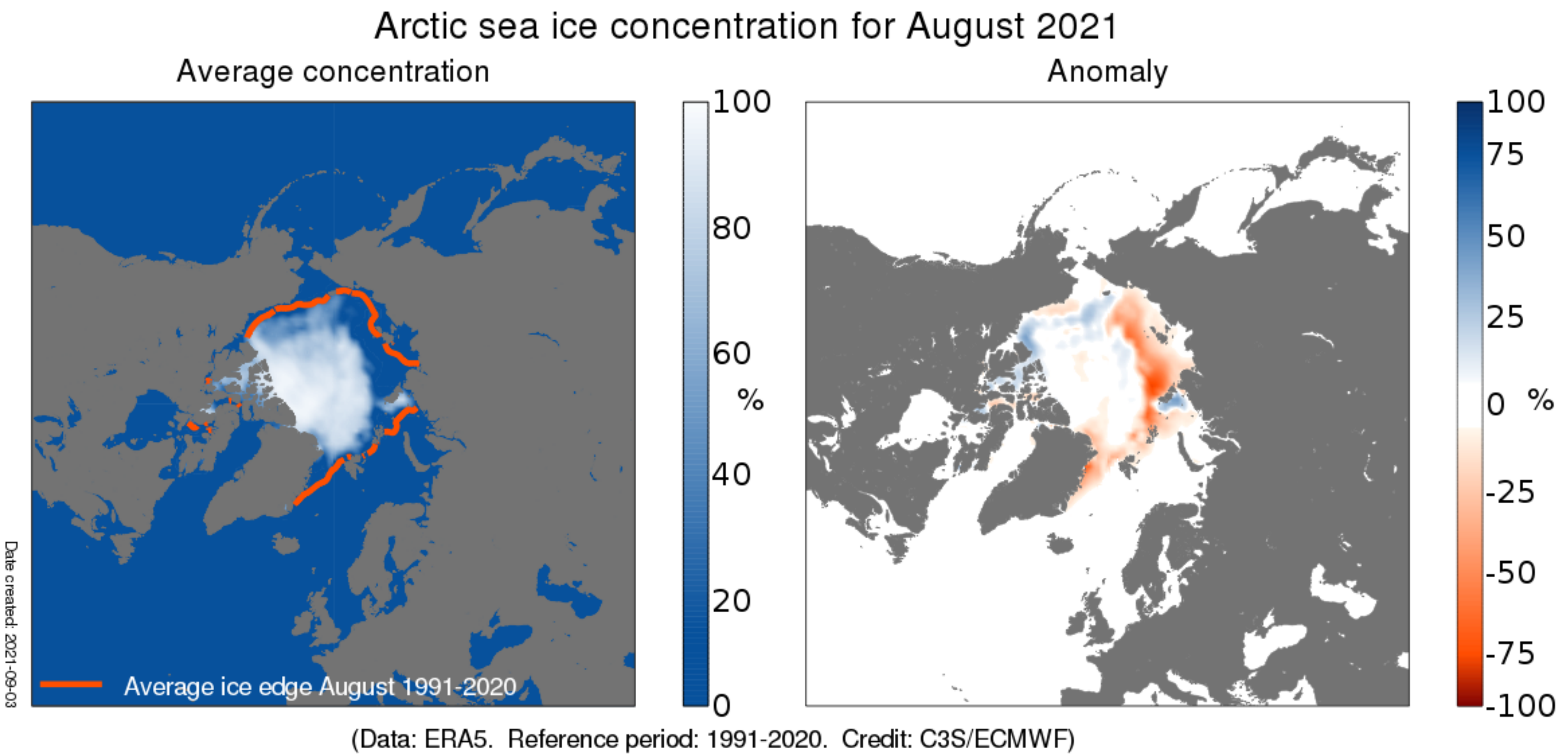
Copernicus C3S climate monitoring

Based on **ERA5**
Hersbach et al., QJRMS 2020

Climate Bulletin



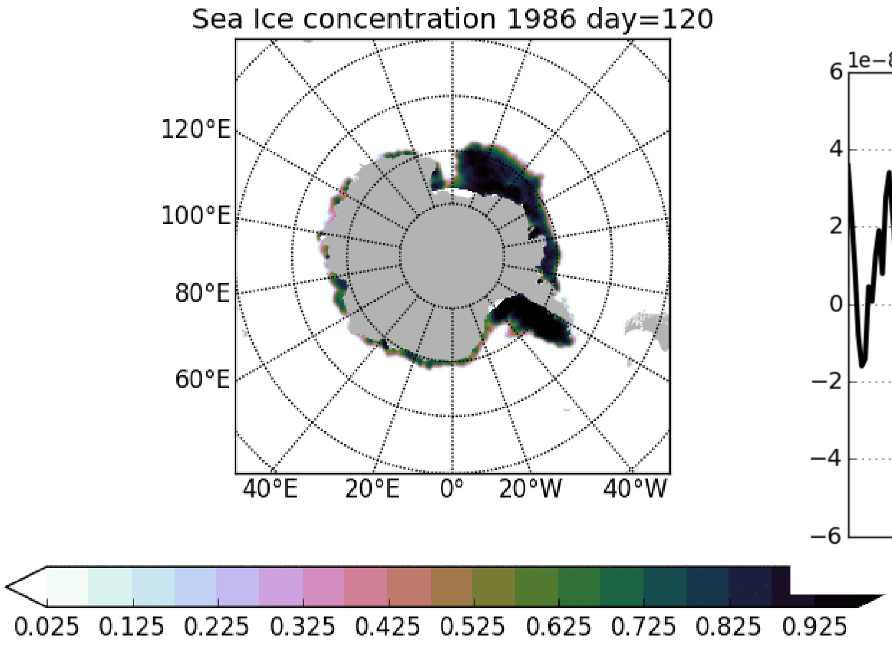
Negative anomaly along north-eastern Greenland and along the Siberian sector, except in the eastern Kara Sea

https://climate.copernicus.eu/sea-ice

Importance of observation consistency for reanalyses

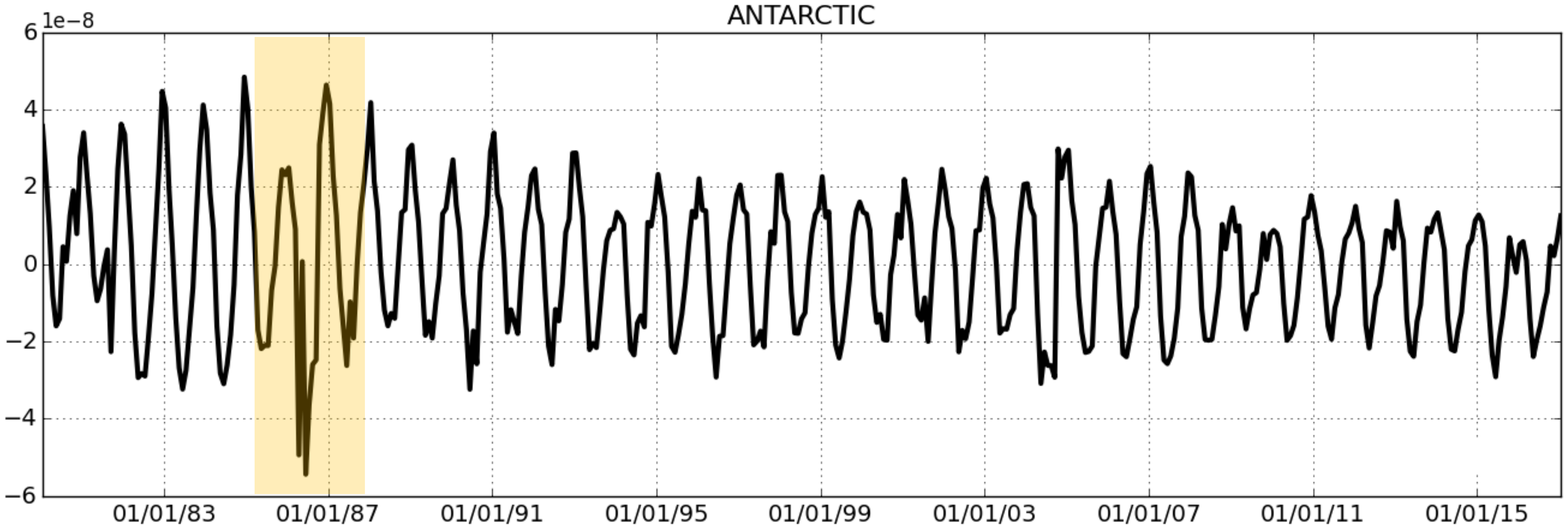
Sea Ice Concentration (SIC) observations missing during part of April-May 1986

Gap infilling in OSTIA analysis



ORAS5 Antarctic SIC increments

After assimilation of OSTIA SIC



ORAS5 Antarctic sea-ice concentration show historical low in Spring 1986, which was a results of assimilating infilling SIC (no sea-ice growth) in this period.

→ Next ocean reanalysis ORAS6 (in preparation): problem solved using level 3 OSI SAF

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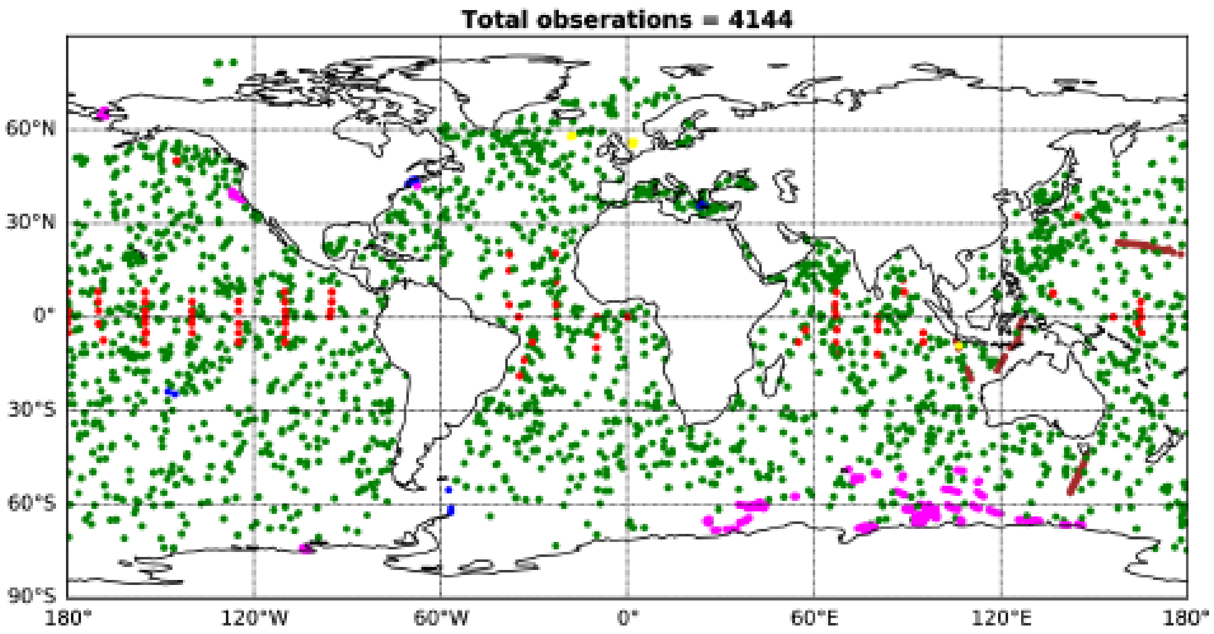
Hao Zuo

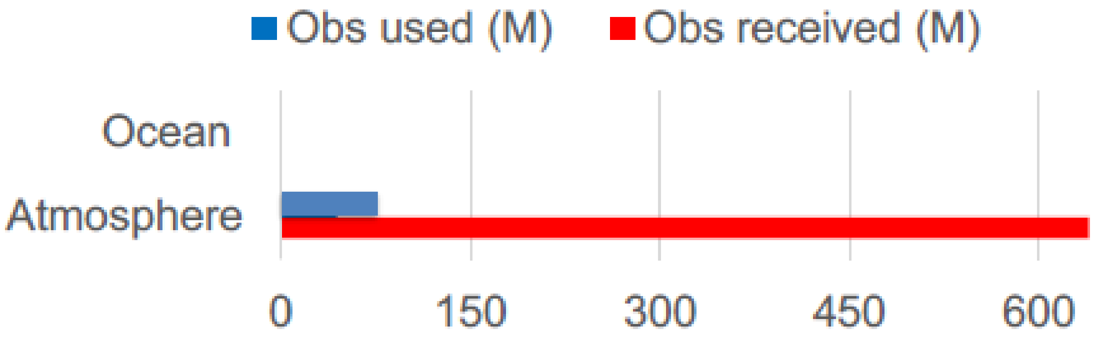
Ocean Observing System for NWP

Also see talk from John Siddorn on Monday

Ocean in-situ observations in 5-days (After QC, Feb 2019)

CTD:450	APB:0	UOR:0	Seaglider:124
Argo:2149	XBT:90	Mammals:931	Mooring:400





Ocean observations (in situ + satellite) represent ~ 0.1 to 1 % of the observations received and used daily at ECMWF

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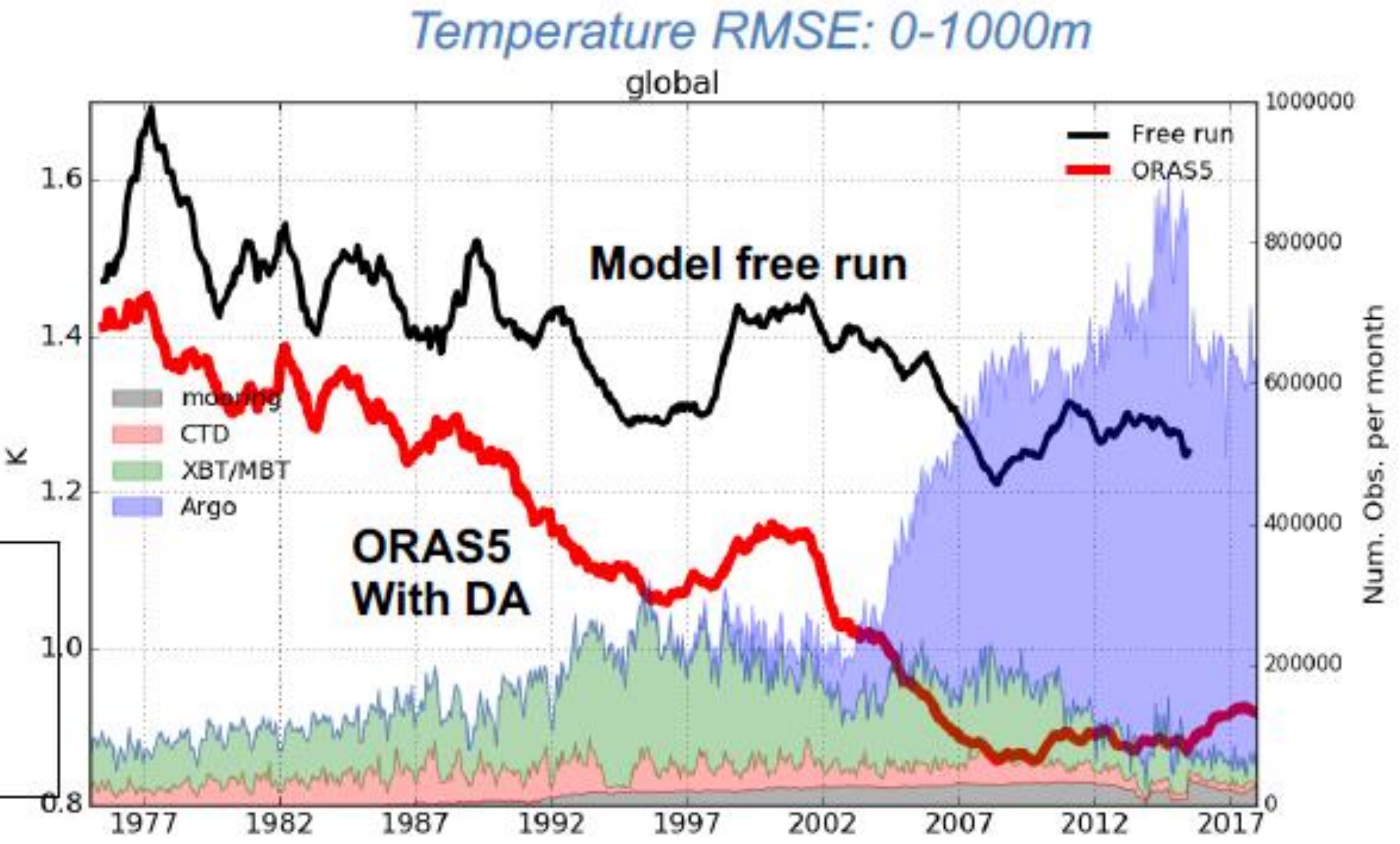
Ocean observation impact on ocean reanalysis

~65% of the total RMSE reduction comes from assimilating in-situ data

MRB: moored buoy
OSD: CTD sonde
XBT: Expendable bathythermograph
PFL: Argo float



Zuo et al. Ocean Sci. 2019

→ Assimilation of in situ ocean observations helps to constrain the 3D ocean, providing better estimates of the initial condition for the coupled forecasting system

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Ocean observation impact on ENSO prediction

Ocean5 provides ocean and sea ice initial conditions for all ECMWF coupled forecasting systems (HRES, ENS, SEAS5)

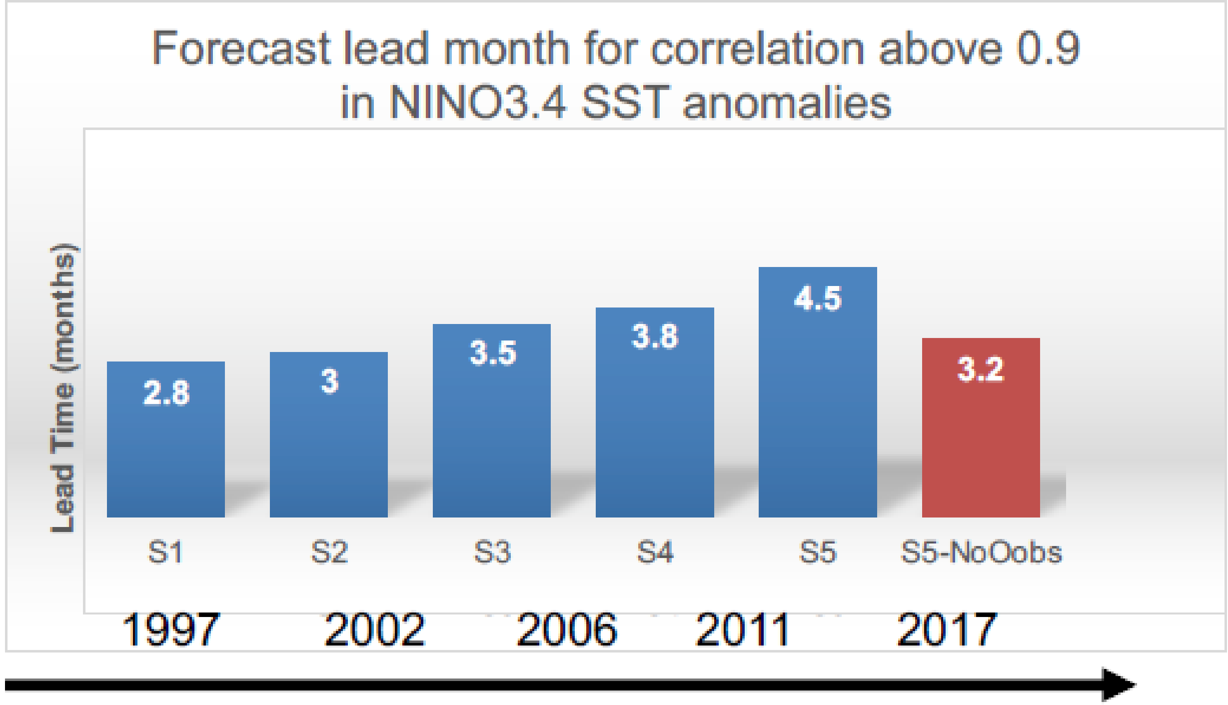


Figure from Magdalena Alonso Balmaseda

Gain about 1.3 months in ENSO prediction
Without ocean observations DA we would loose ~15 years of progress

Impact of Sea Ice Thickness initialisation on NWP

Observing System Experiments to initialise coupled extended range forecasts

Impact of assimilation of Cryosat-2 SMOS sea ice thickness assimilation in the ocean system

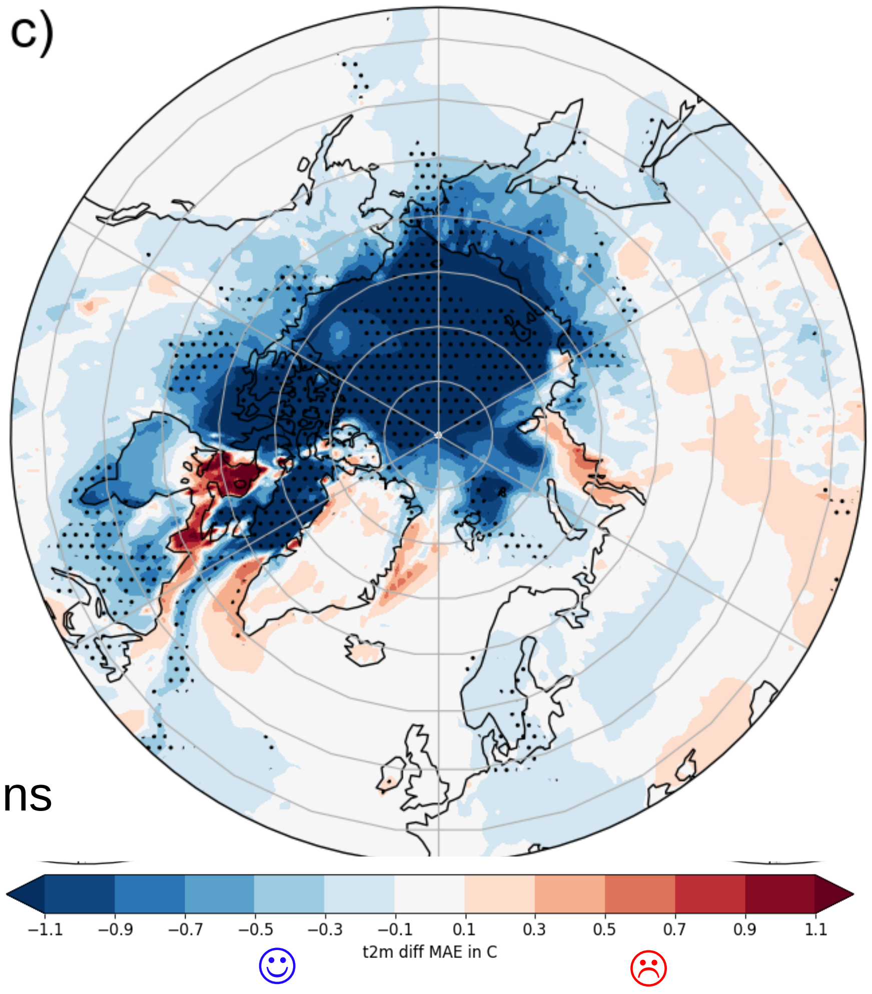
→ Significant improvement in sea ice and SST

→ Significant improvements in 2m temperature forecasts in the melt season

Balan Sarojini et al., The Cryosphere, 2021

- Key role of sea ice observations for NWP and reanalyses
- Synergy between altimeter and microwave data; relevance of future misisons such as CIMR/CRISTAL
- ESA/GCW sea ice intercomparison project perspectives

Impact on T2m (K) MAE
Forecast for SON initialised in May



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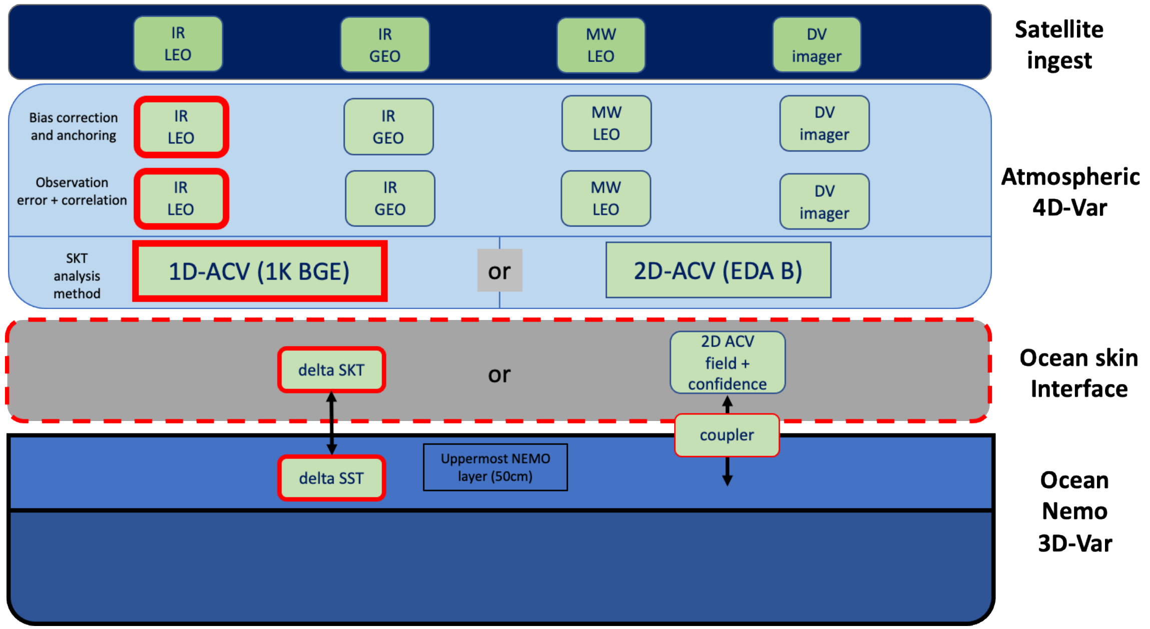
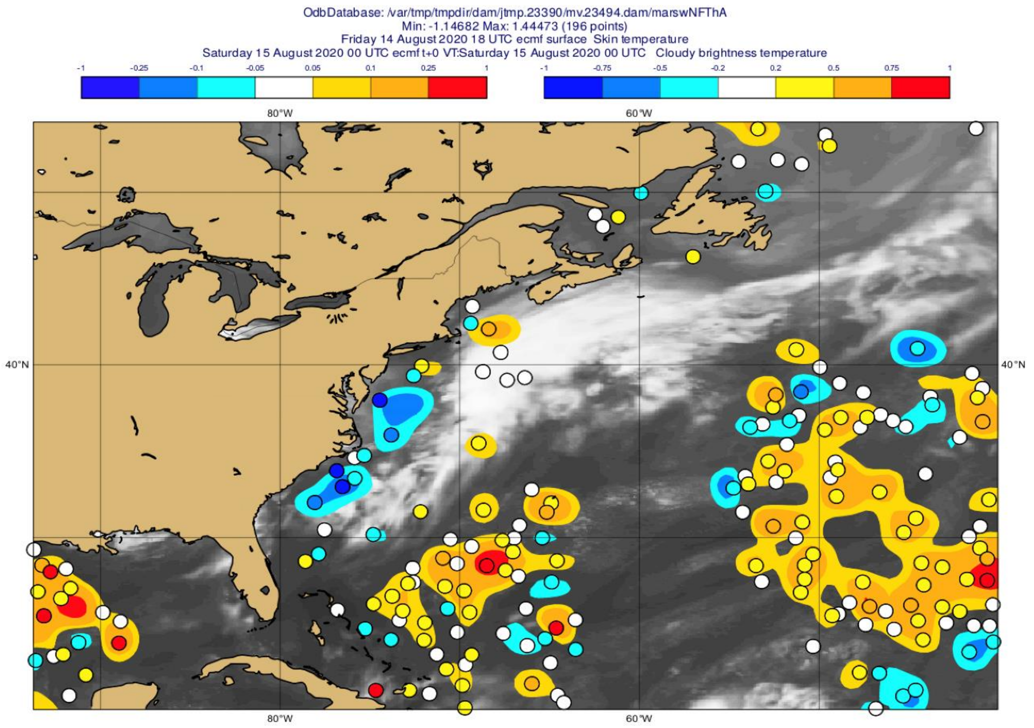
In-house SST analysis development

Tony McNally et al. → Friday am

Use skin Temperature derived from satellite radiances in the 4D-var Extended Control Variable (ECV) to constrain SST in the outer loop coupled DA

SST analysis options





→ Moving to consistent level 1 observations coupled assimilation to constrain atmosphere and surface temperature
→ 1D-ECV and 2D-ECV (Massart et al., GMD 2021) approaches investigated
→ SKT Extended Control Variable coupled DA relevant for land too

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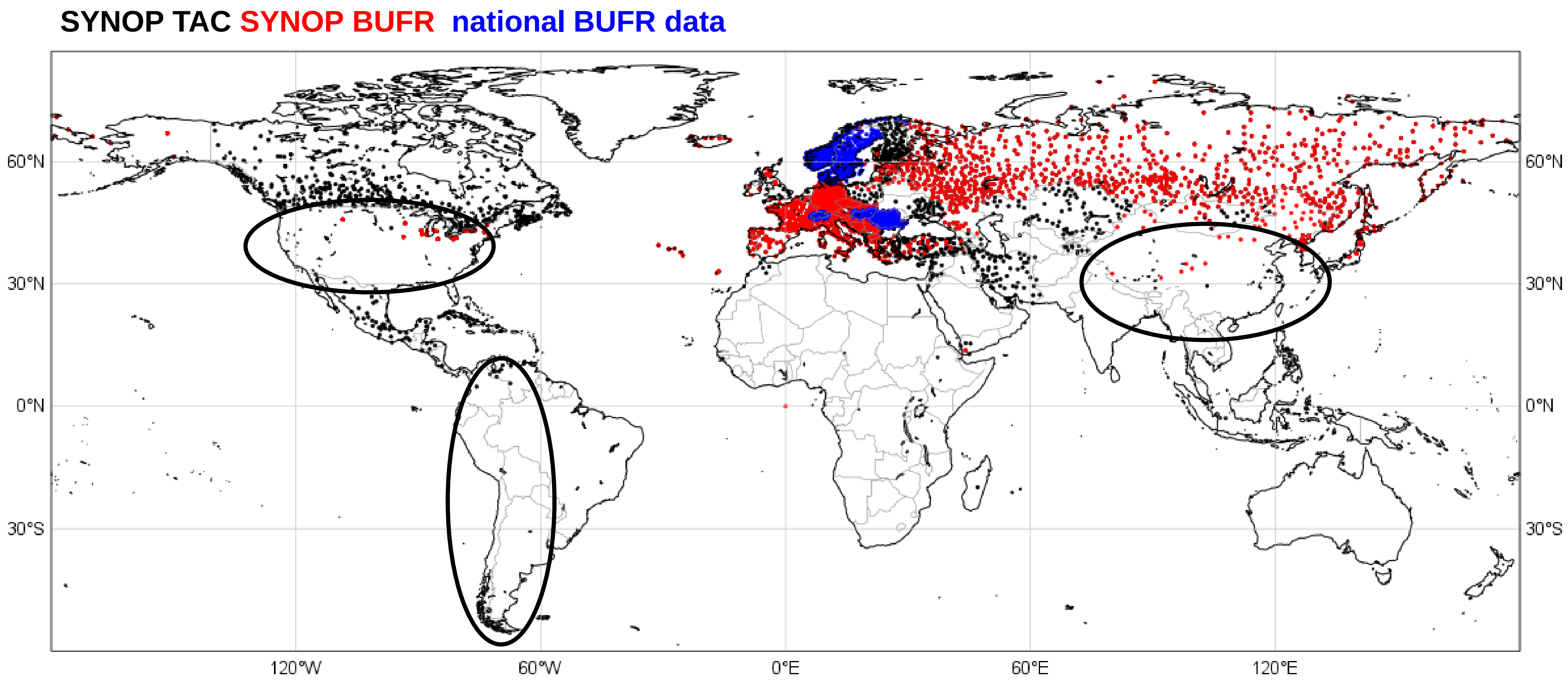
Land observing system: the example of in situ snow depth

Near-Real-Time access to observations

15 January 2015



Snow depth availability on the Global Telecommunication System (GTS)

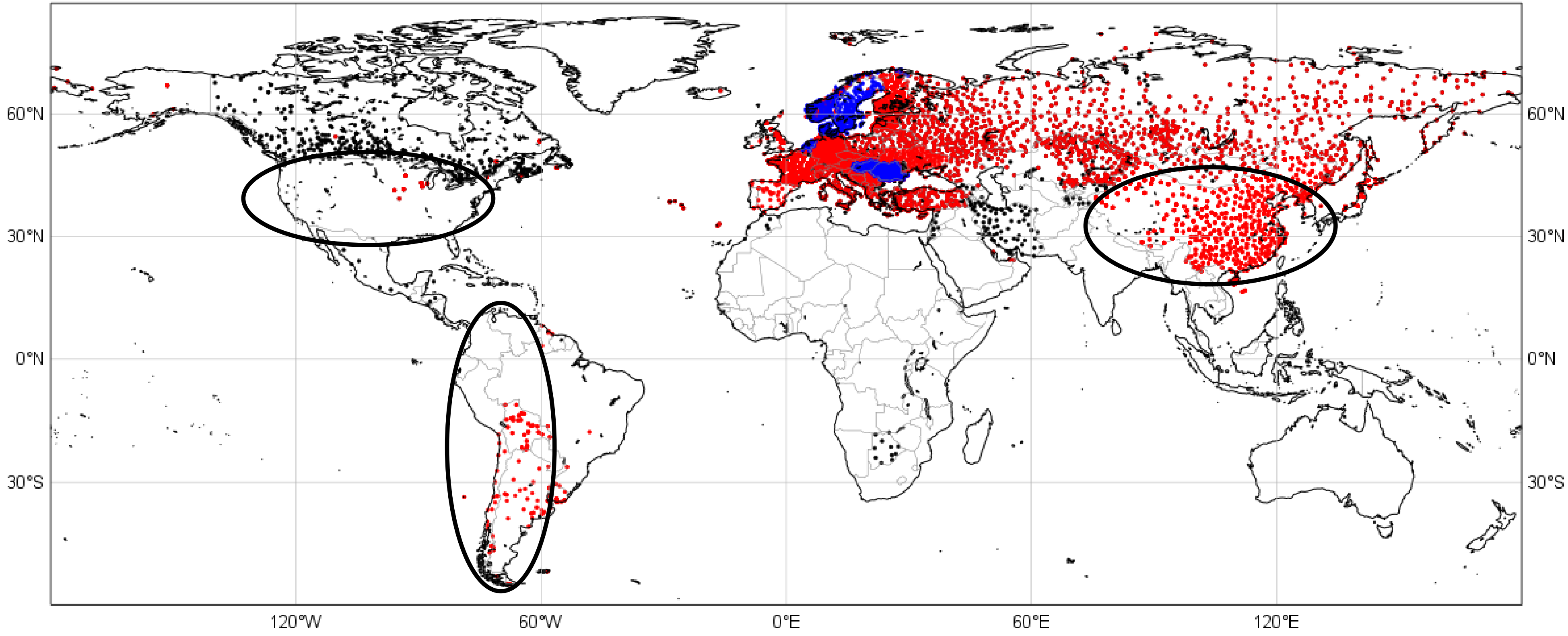
ECMWF

Land observing system: the example of in situ snow depth

Near-Real-Time access to observations

15 January 2021

SYNOP TAC SYNOP BUFR national BUFR data



Snow depth availability on the Global Telecommunication System (GTS)

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Global Cryosphere Watch & Snow Watch
→ International exchange of snow data

- WMO Executive Council EC-69 (<u>2017</u>) Resolution 15 on international exchange of snow depth data

"…zero snow depth (absence of snow) should be reported … "

" Requests Members to exchange in situ snow measurements in real time in BUFR through the Global Telecommunication System …"

- Snow Water Equivalent (SWE) in BUFR (<u>2018</u>): for NRT exchange of SWE data via GTS

  IPET-CM = Inter-programme expert team on code maintenance

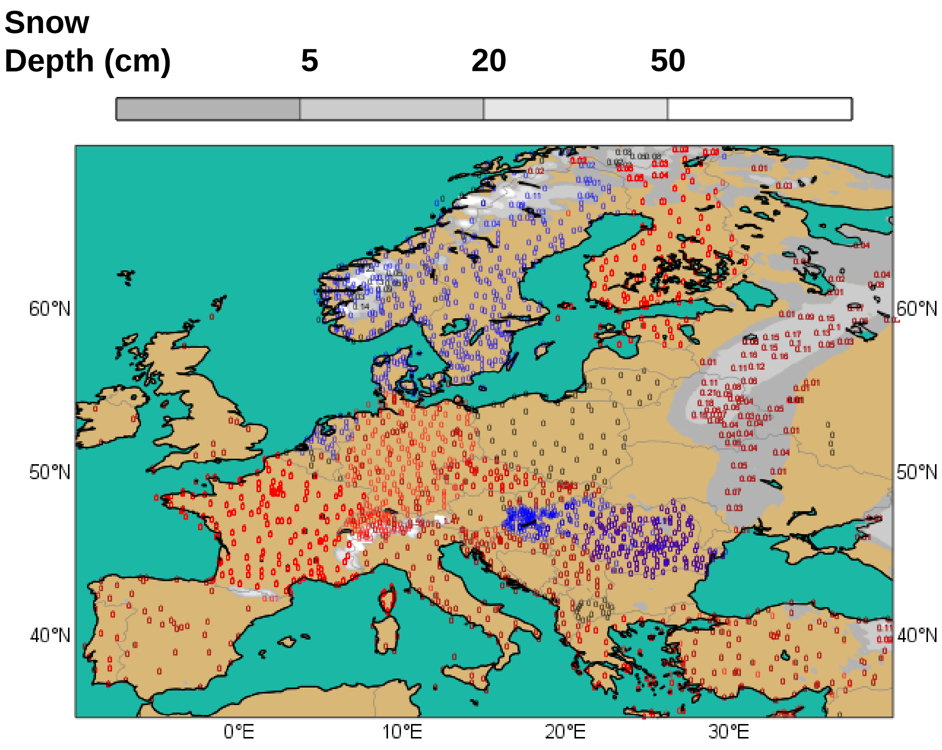
  New SWE BUFR sequence (3 07 103) approved y WMO and available to report SWE on the GTS

- <u>Ongoing</u>: NOAA conversion of SNOTEL to snow BUFR for GTS dissemination (test BUFR file sample received and in good shape)

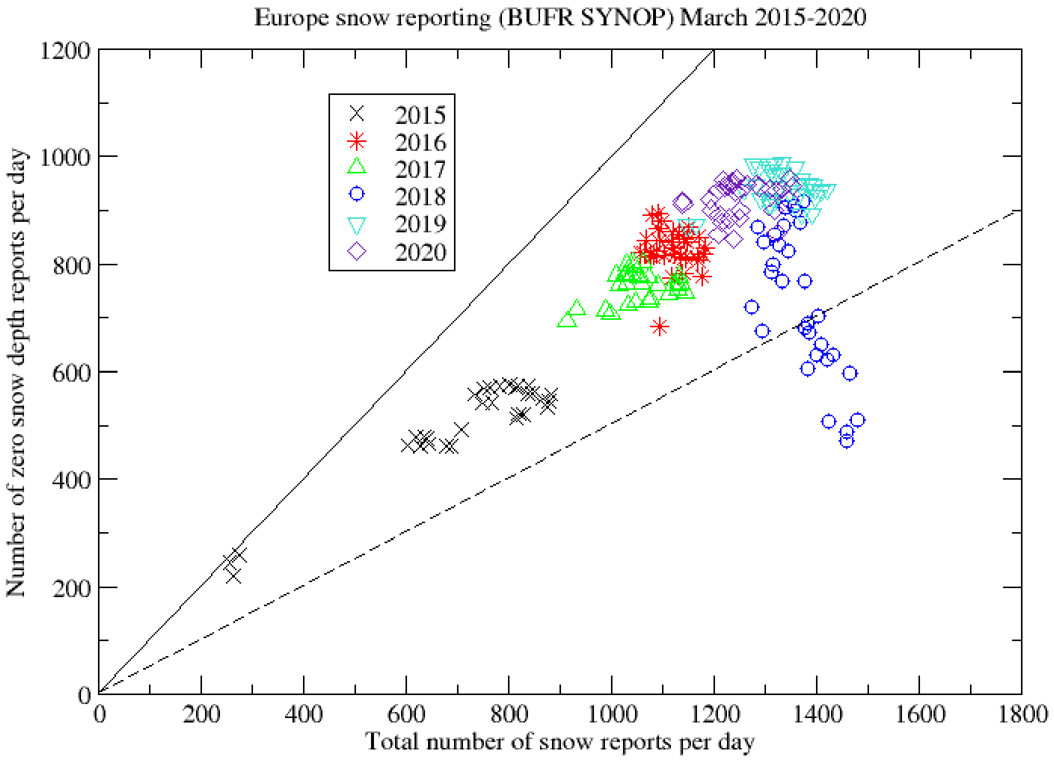
Strong support also from GODEX-NWP (Global Observation Data Exchange for NWP)

Snow data exchange and WMO

Lack of observations with no snow in some areas



WIGOS Newsletter April 2020 (de Rosnay, Pullen, Nitu)



Increase in available snow depth data from distinct SYNOP stations reporting in BUFR SYNOP on GTS from 2015 to 2020.

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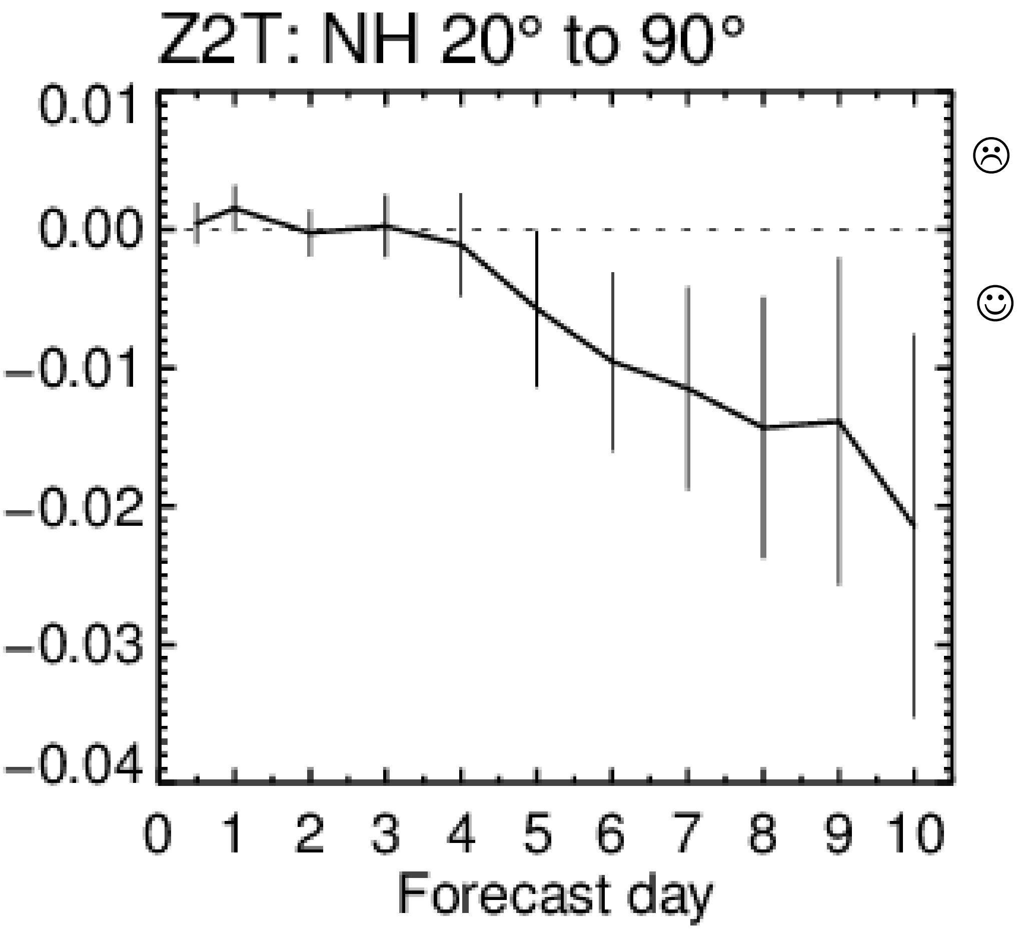
Coupled land-atmosphere OSEs

Impact of in situ national BUFR data (additional data from 6 countries in Europe)

DJFMA 2014-2015



- OSEs in gobal (weakly) coupled land-atmosphere assimilation system

-> T2m forecasts error reduction at medium range

Coupled land-atmosphere OSEs

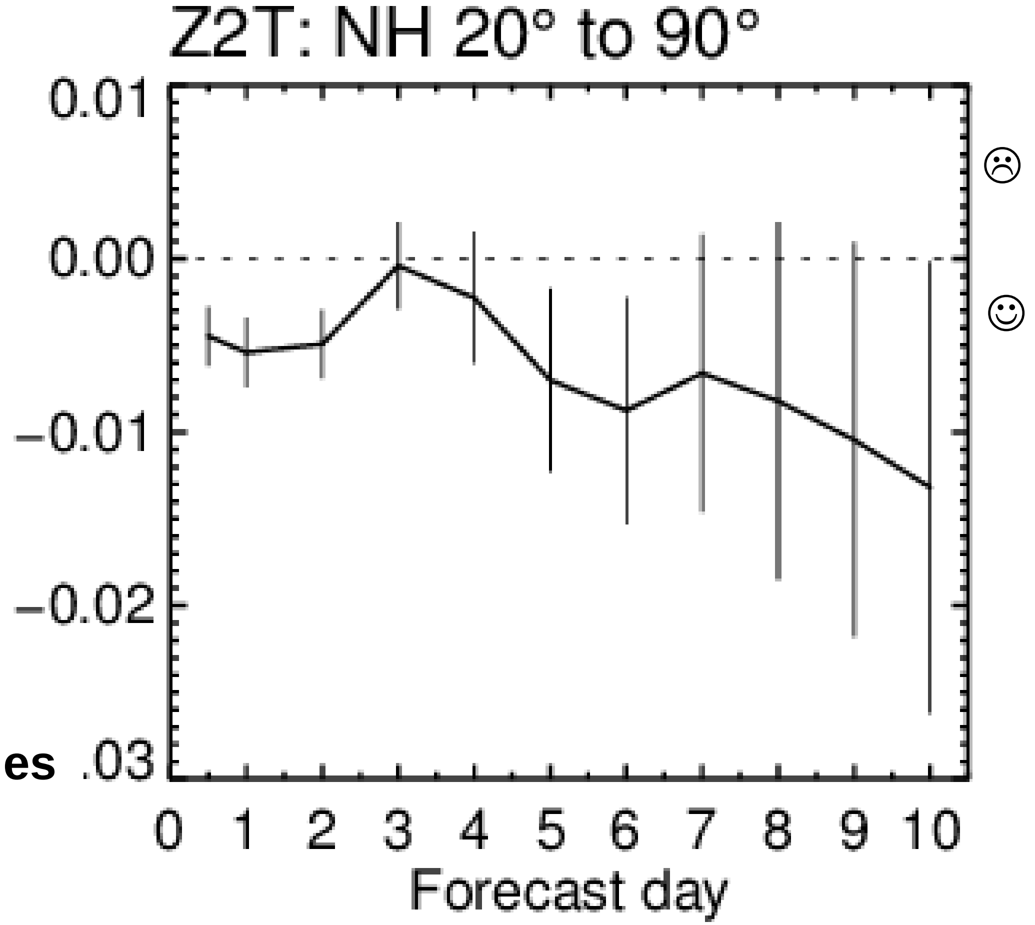
Impact of IMS (Interactive Multisensor Snow and Ice Mapping System) snow cover

- OSEs in gobal (weakly) coupled land-atmosphere assimilation system

-> T2m forecasts error reduction at medium range

→ **Contribution & complementarities of each observation types to improve T2m forecasts at short and medium ranges**

DJFMA 2014-2015



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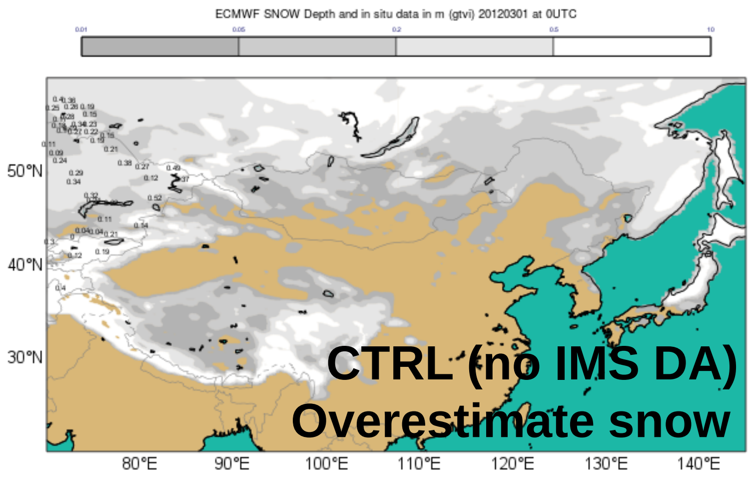
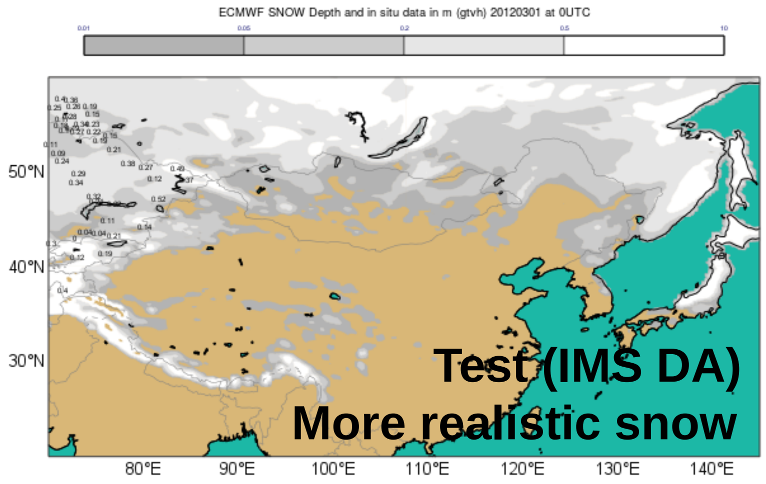
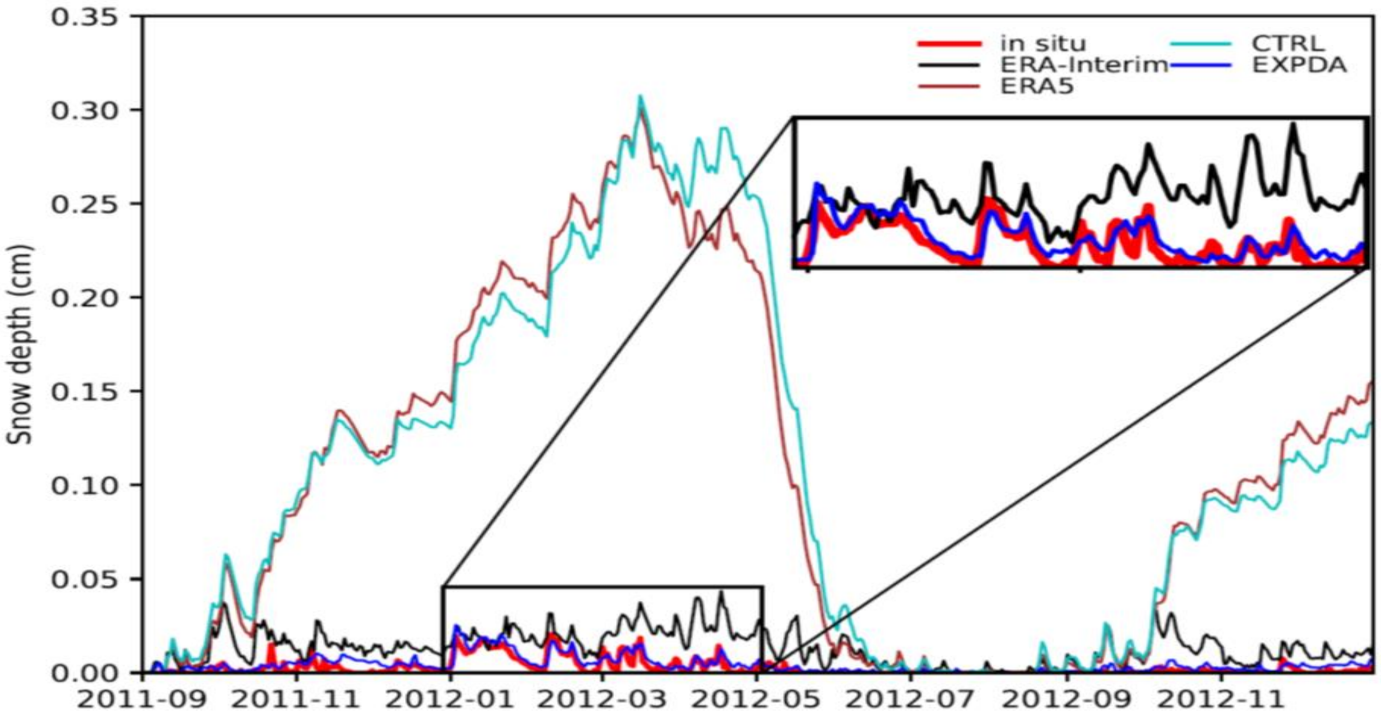
Snow cover coupled data assimilation impact over the Tibetan Plateau





Snow cover DA removes snow and improves snow depth



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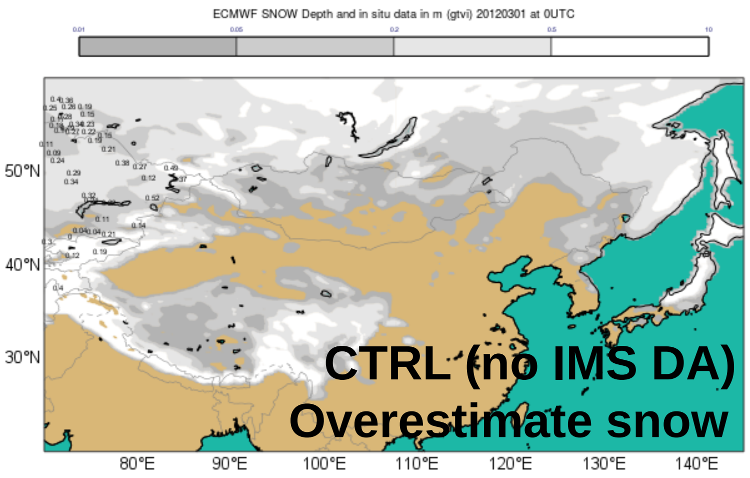
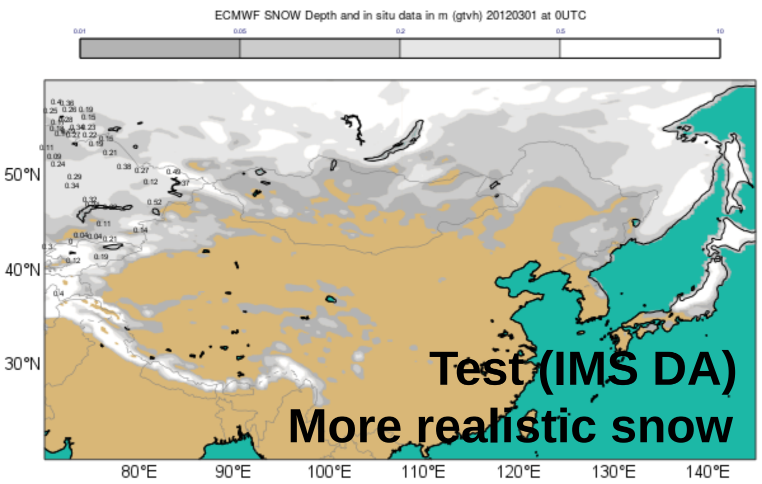


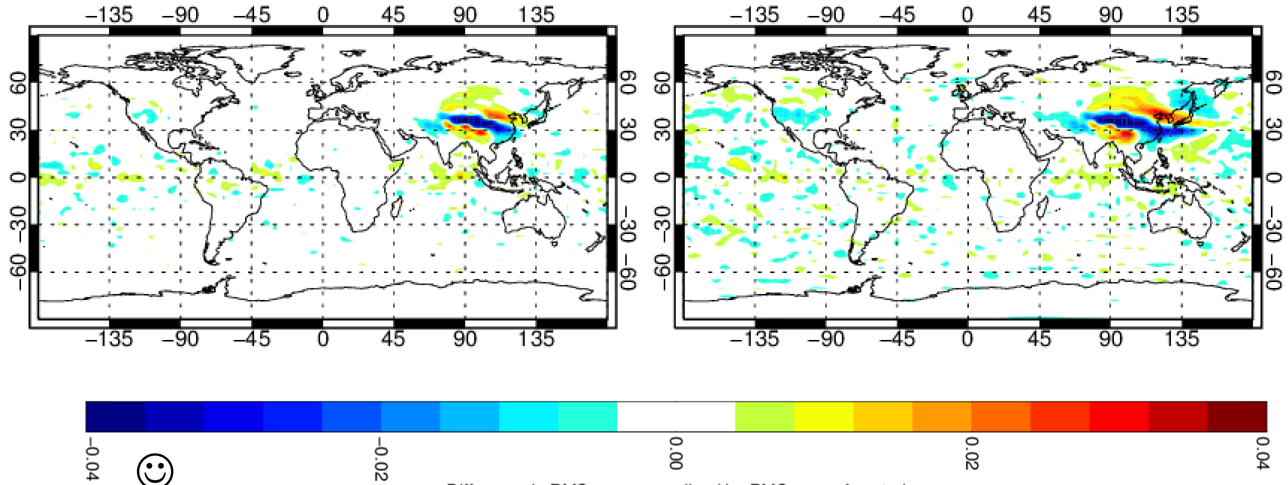


Impact on albedo and momentum
→ Modifies the jet circulation

Change in zonal wind
Oct 2011 – June 2012

T+24; 500hPa

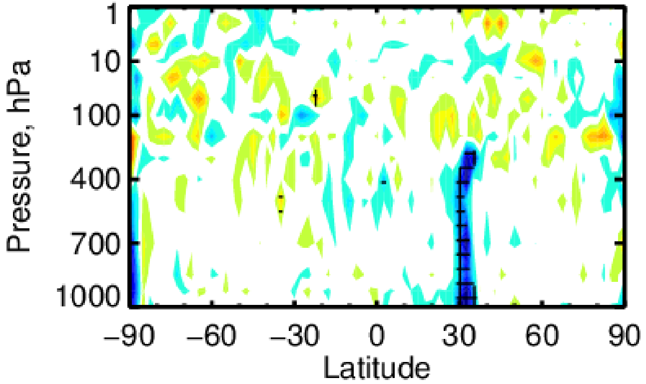
T+48; 500hPa



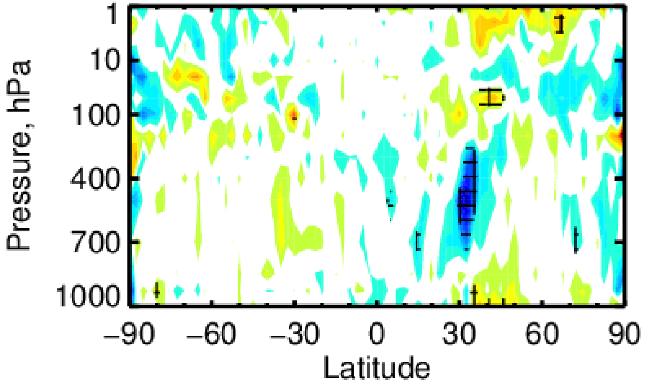
Difference in RMS error normalised by RMS error of control

Change in humidity FC error
Oct 2011 – June 2012

T+12



T+48



Soil moisture satellite observations used operationally

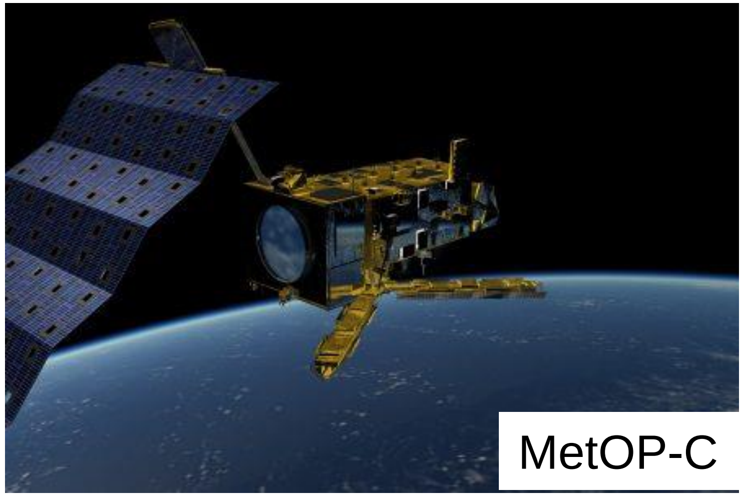
Active microwave data:

ASCAT: Advanced Scatterometer

On MetOP-A (2006-), MetOP-B (2012-), MetOP-C (2018-)

C-band (5.6GHz) backscattering coefficient

EUMETSAT Operational mission



Passive microwave data:

SMOS: Soil Moisture & Ocean Salinity (2009-)

L-band (1.4 GHz) Brightness Temperature

ESA Earth Explorer, dedicated soil moisture mission

(Munoz-Sabater et al., GRSL, 2012)

Scatterometer soil moisture also used in ERA5
(ERS-SCAT, Metop/ASCAT)

(See Cristina Charlton-Perez talk on Monday)

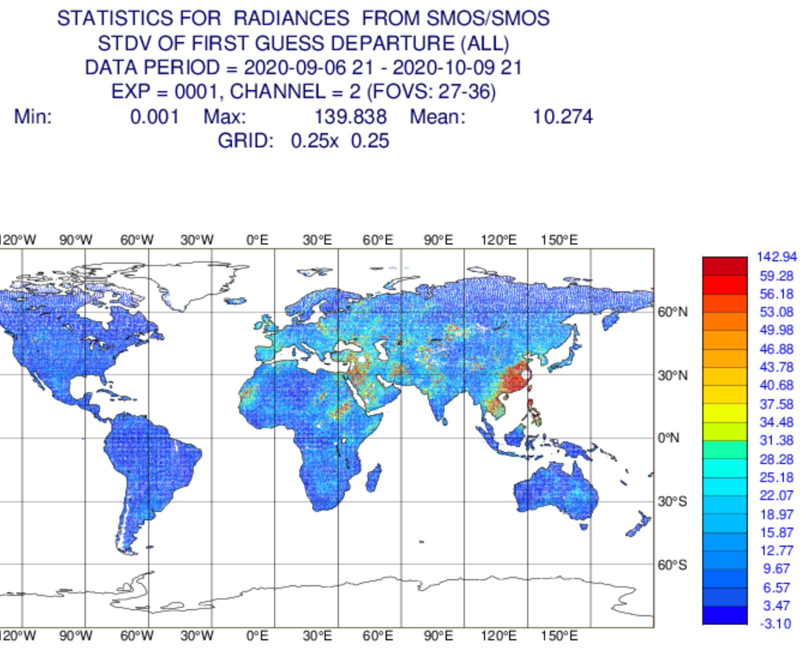
ECMWF

Observation monitoring and quality control

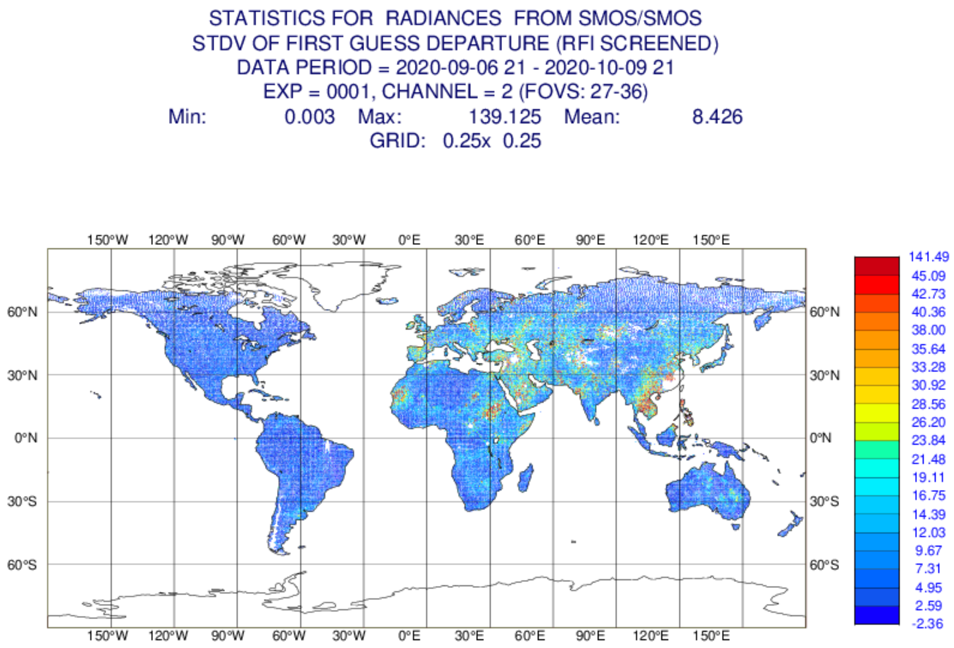
SMOS brightness temperature operational monitoring

- Summer 2020: a large area of RFI (Radio Frequency Interference) contamination over South-East China
- Improved screening does a better job of filtering it out but still not perfect
    - Need for further improvements in RFI filtering flags
    - **Importance of <u>quality control</u>**

Pete Weston

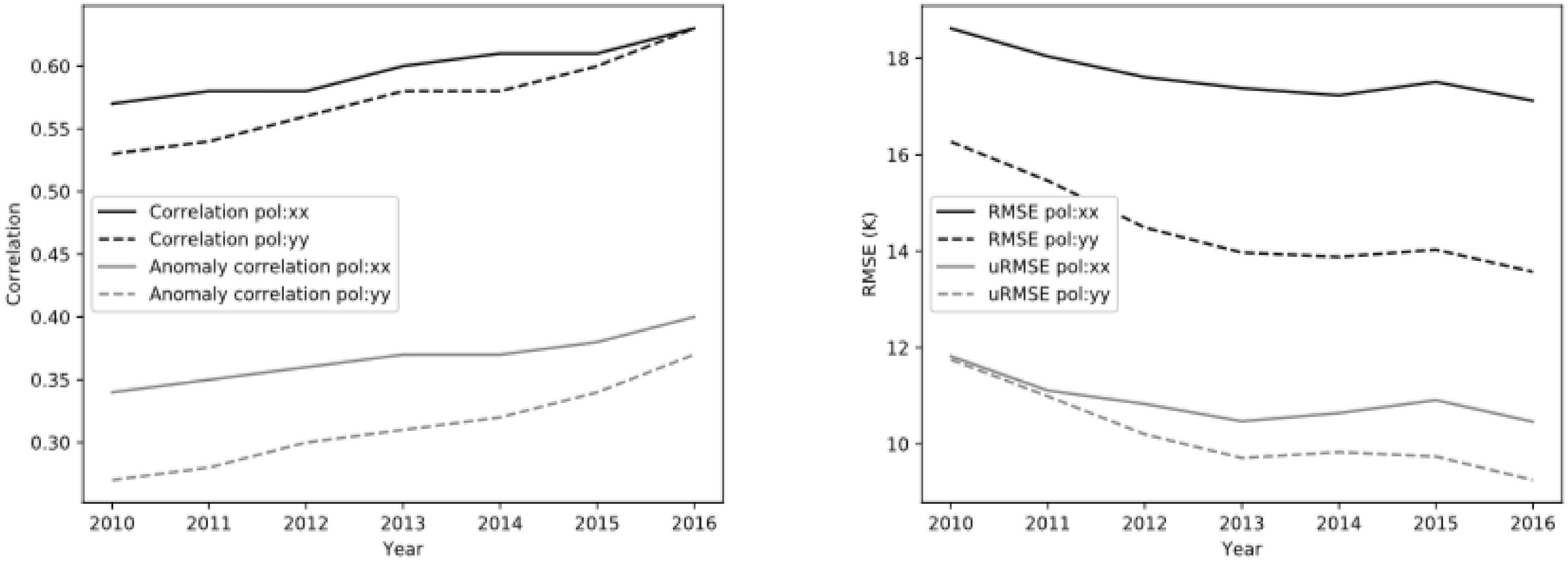


Basic RFI screening



Stronger RFI screening

SMOS multi-year monitoring of brightness temperature data



(a) Correlation

(b) Root mean square error

CMEM: Community Microwave Emission Modelling platform

de Rosnay et al, RSE, 2020

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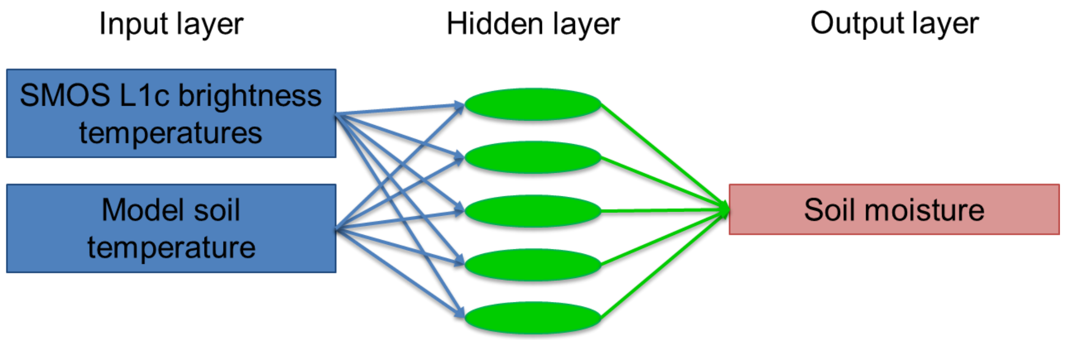
SMOS neural network soil moisture assimilation



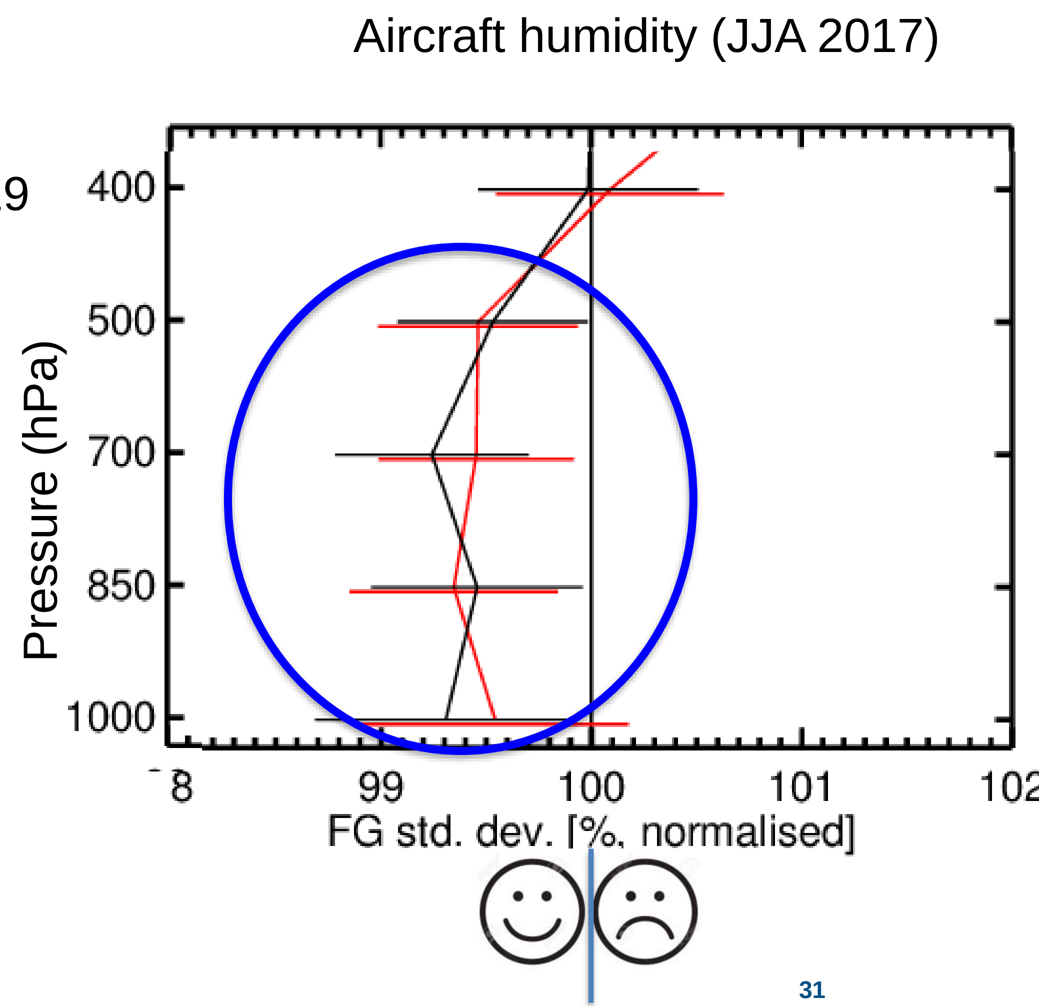
ECMWF: Rodriguez-Fernandez et al., HESS 2017, Rem. Sens 2019

GMAO: see Kolassa et al., Rem. Sens. 2018 and talk on Thursday

A priori training of the SMOS neural network processor
-> retraining when L1Tb or IFS soil change
Online training possibilities?

Further explore ML/AI for forward modelling both for passive and active MW data (e.g. ASCAT: Aires et al, QJRMS 2021)

NWP
SMOS soil moisture impact



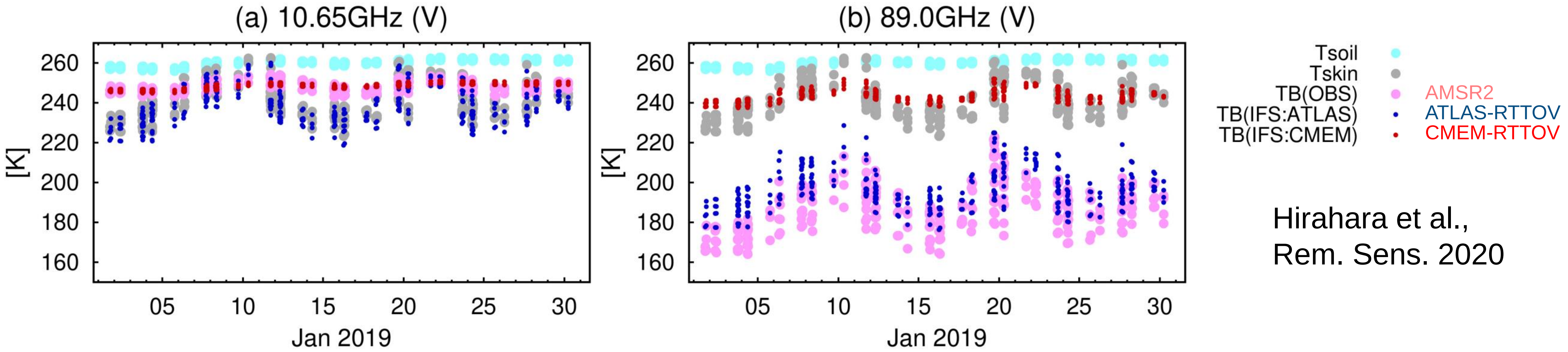
Towards assimilation of surface-sensitive satellite data over snow covered areas

- Interface between CMEM and RTTOV in the IFS for surface sensitive observations
- Multi-layer snow radiative transfer scheme (HUT, Lemmetyinen et al., 2010) in CMEM

→ support developments to extend the "all-sky" to "all-sky" and "all-surface" approach

→ See talk from Catherine Prigent (today)
→ See talk from Alan Geer (Friday)

CMEM-RTTOV coupling:



Hirahara et al., Rem. Sens. 2020

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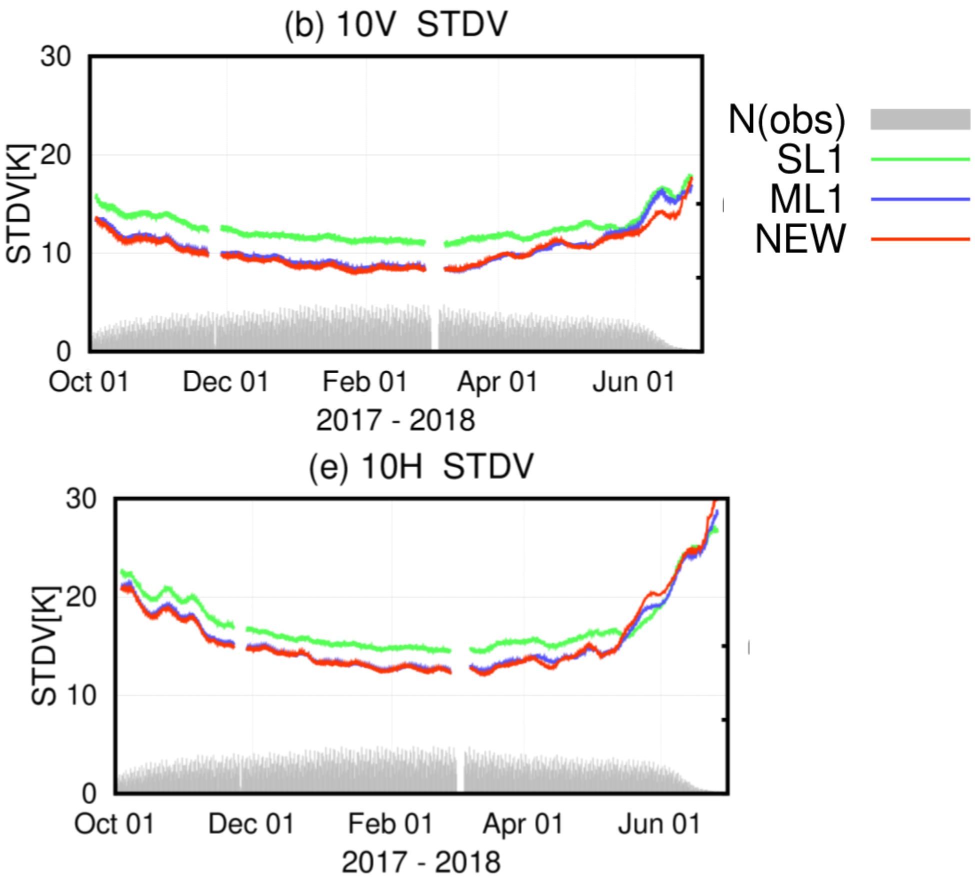
Multi-layer snow emission

NH snow-covered area
(w/o glacier and high vegetation)

Multi-layer snowpack model
(Arduini et al. JAMES 2019)

→ Impact on snow emissions?

→ Multi- vs single-layer snow emission model compared to AMSR2 10GHz data



→ Multi-layer snowpack scheme improves the fit to AMSR2 observations

Hirahara et al.,
Rem. Sens. 2020

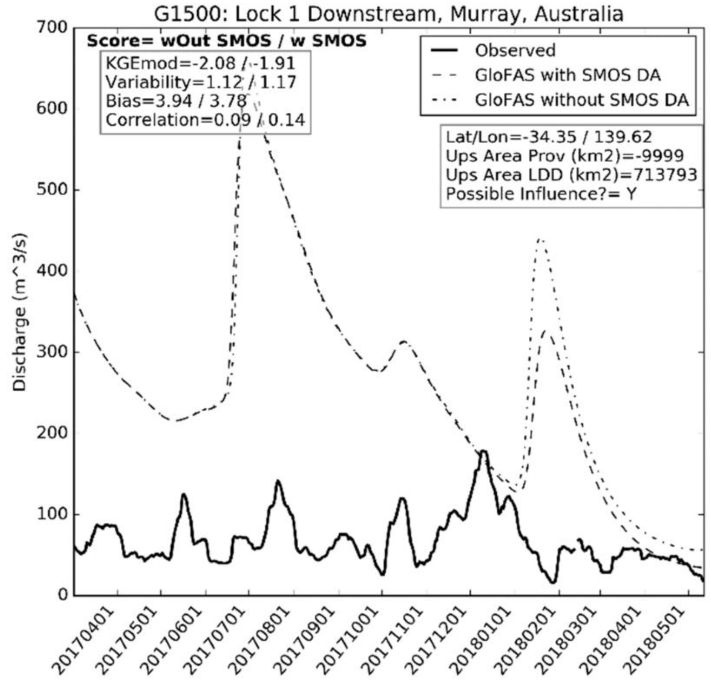
SMOS applications for the Copernicus Emergency Management Service (CEMS)

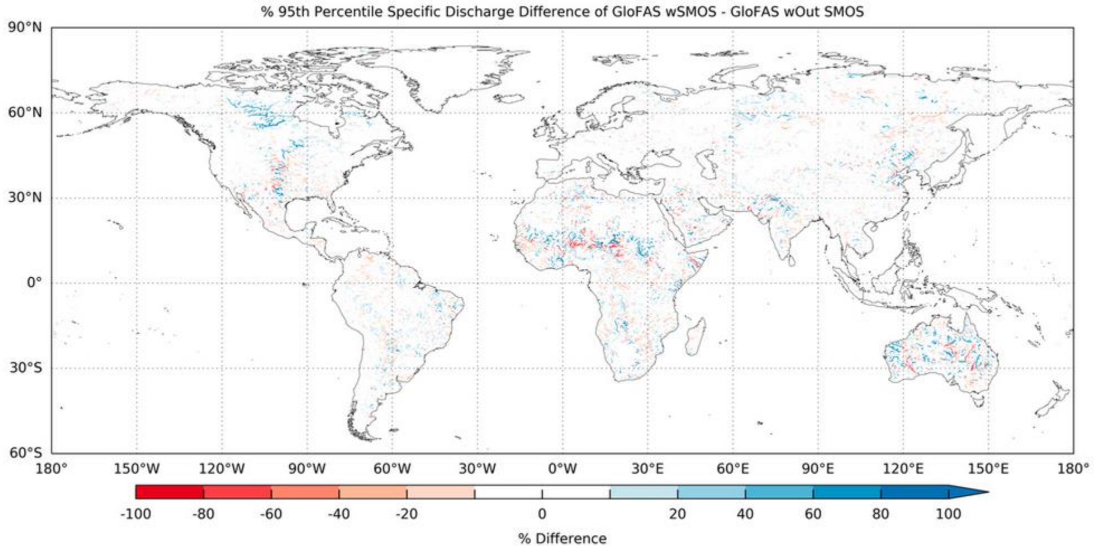
Data assimilation impact upon hydrology

Emergency Management

- Data denial experiments with SMOS

Baugh et al., Rem. Sens. 2020



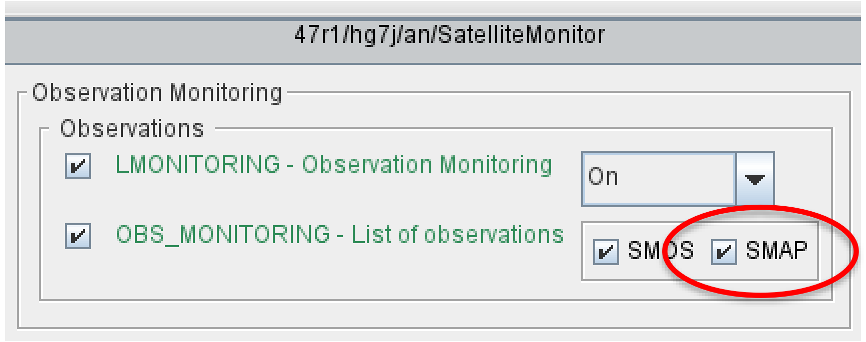


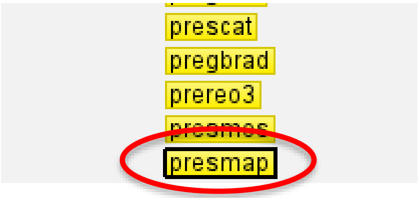
- Neutral impact of SMOS on river discharge
- Very small impact mostly on peak flow
- Poor representation of river regulation, irrigation and lake storage
- Further work towards coupled land-hydrology DA

ECMWF

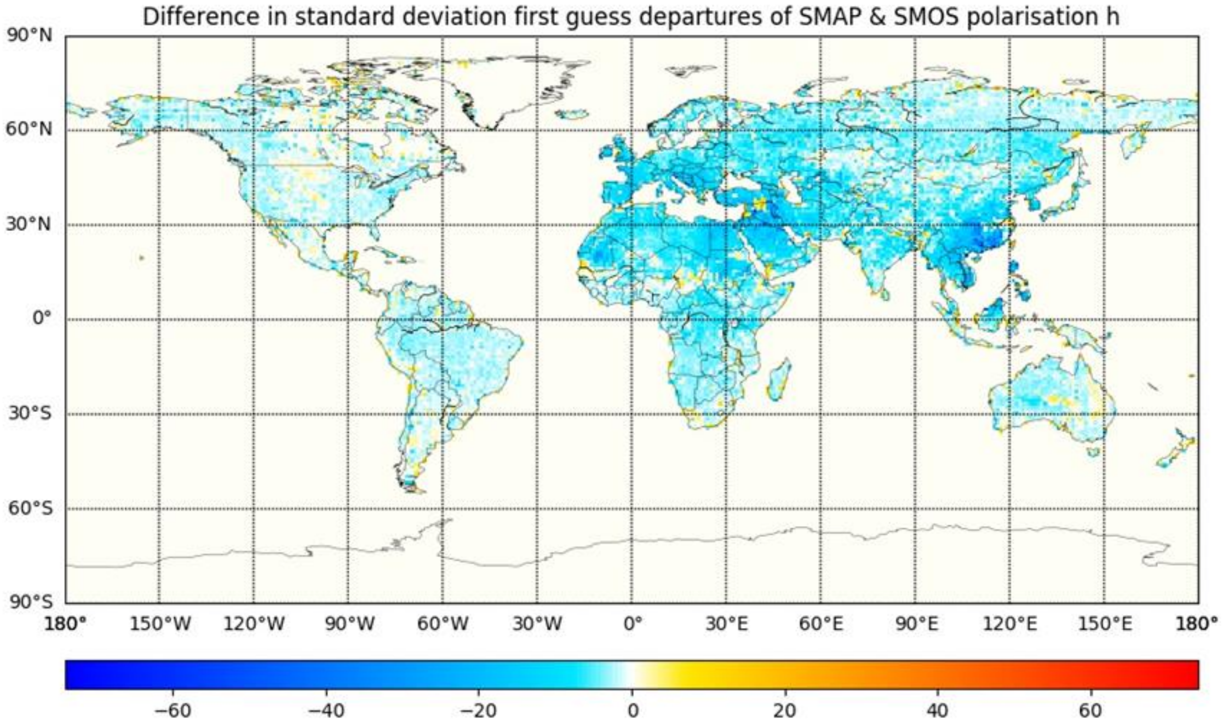
SMAP L-band observations

Operational IFS monitoring since May 2021





- Set-up operational NRT acquisition
- Scripts suite and prepIFS changes complete
- SMAP Observation interface (Obs Data base, ODB)
- Script and Fortran changes
- Suite definition and prepIFS
- Monitoring webpage update
- Next: SMAP assimilation evaluation



→ Consistent work flow than for atmospheric observations

Pete Weston

Summary …

- Progressive implementation of coupled assimilation at ECMWF for operational NWP and future generations of reanalyses (NWP, Copernicus Services, and high resolution Destination Earth)

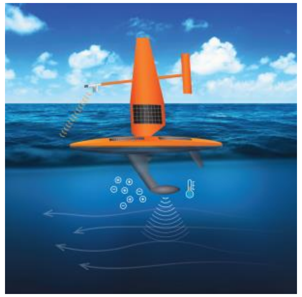
- Relevance of interface observations, e.g. Snow (cover, water equivalent, depth), sea ice (concentration, thickness), snow on sea ice, SST for NWP and reanalysis

- Development of consistent observation monitoring across the components

- Challenges of Earth System approach for NWP:
  - Observations availability and sustainability (e.g. snow, ocean)
  - Observations timeliness and consistency at different time scales for NRT & reanalysis
  - Time scale differences between the ES components → influences the coupling approach
  - Coupling through the observation operator, e.g. SST, snow surfaces, and opportunities to enhance the exploitation of satellite data

ECMWF

… and next steps



- Monitoring consistency: auto-alert/blocklist extended all obs types for land and ocean

- Enhance DA methodologies & exploitation of observations in each component,
  - Existing observations not yet assimilated (e.g. land surface temperature)
  - Explore new type of observations, including from the private sector (e.g. Saildrones) and future missions including Metop-SG, MTG, Copernicus Expansion CIMR and CRISTAL

- Transition to lower level (level 1) products assimilation: key for coupled assimilation to enhance assimilation of observations that are sensitive to the surface
  - Further work on skin temperature DA over ocean and extend to land
  - Investigate multivariate soil and vegetation analysis (consistent water and CO2)
  - Further developments on forward operator coupling, integrating ML/AI to tackle challenges of radiative transfer over complex surfaces in support of an all-surface approach

- Other components: atmospheric composition, river and flood forecast system (Copernicus Services CMEMS, CEMS, CAMS)

ECMWF

Special Collection Quarterly Journal of The Royal Meteorological Society
“Coupled Earth system data assimilation”

- In the context of the first Joint WCRP-WWRP Symposium on Data Assimilation and Reanalysis

- We invite contributions on coupled assimilation developments for research and operational applications.
  We welcome papers that address methodological aspects of coupled assimilation as well as scientific investigations on coupling degrees and impact studies.

- Submission deadline: 31 December 2022

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