Assimilation of water vapour, cloud and precipitation observations in extratropical cyclones
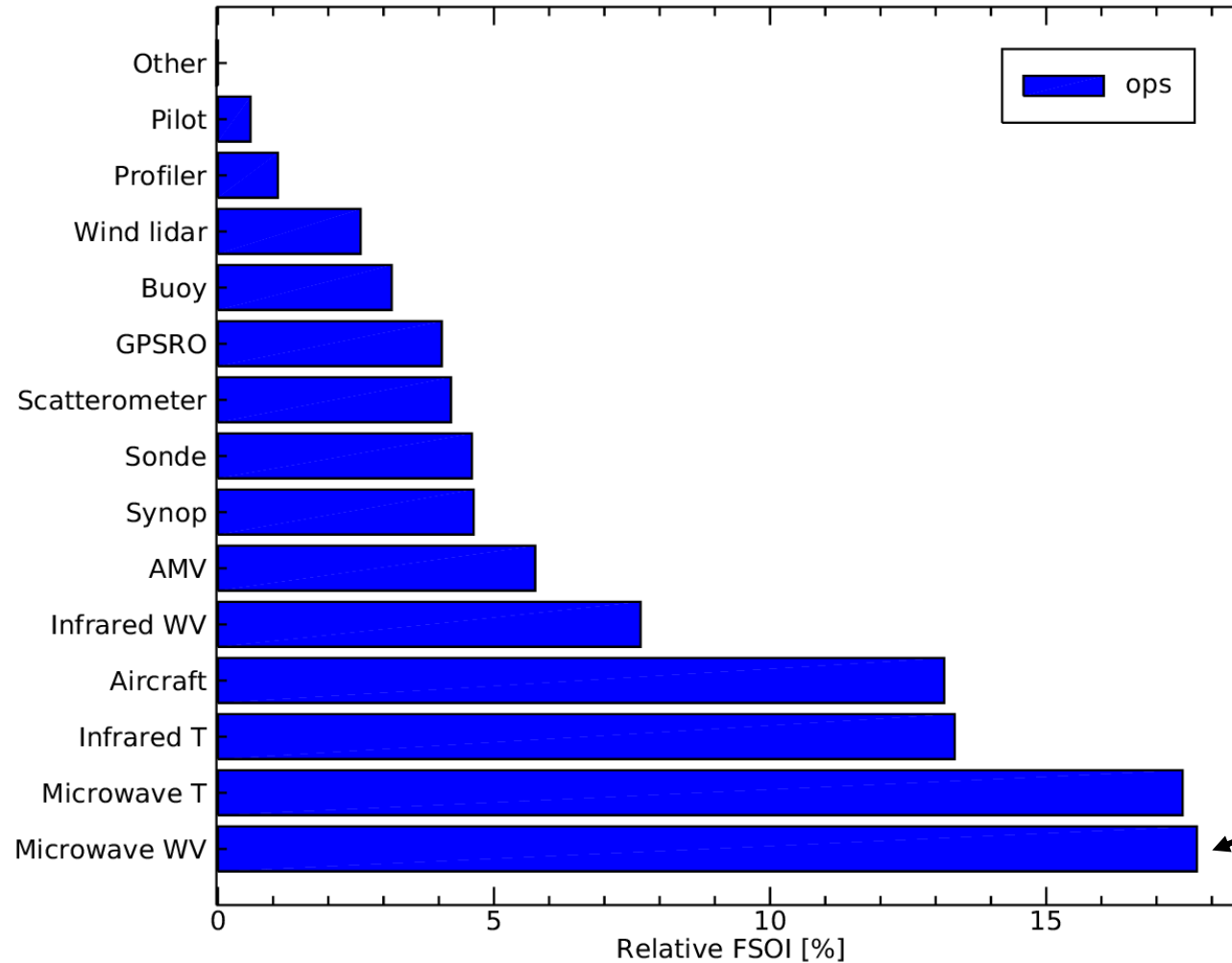
Alan Geer

ECMWF

Thanks to: Mark Rodwell, Katrin Lonitz, Cristina Lupu, Bruce Ingleby, FD
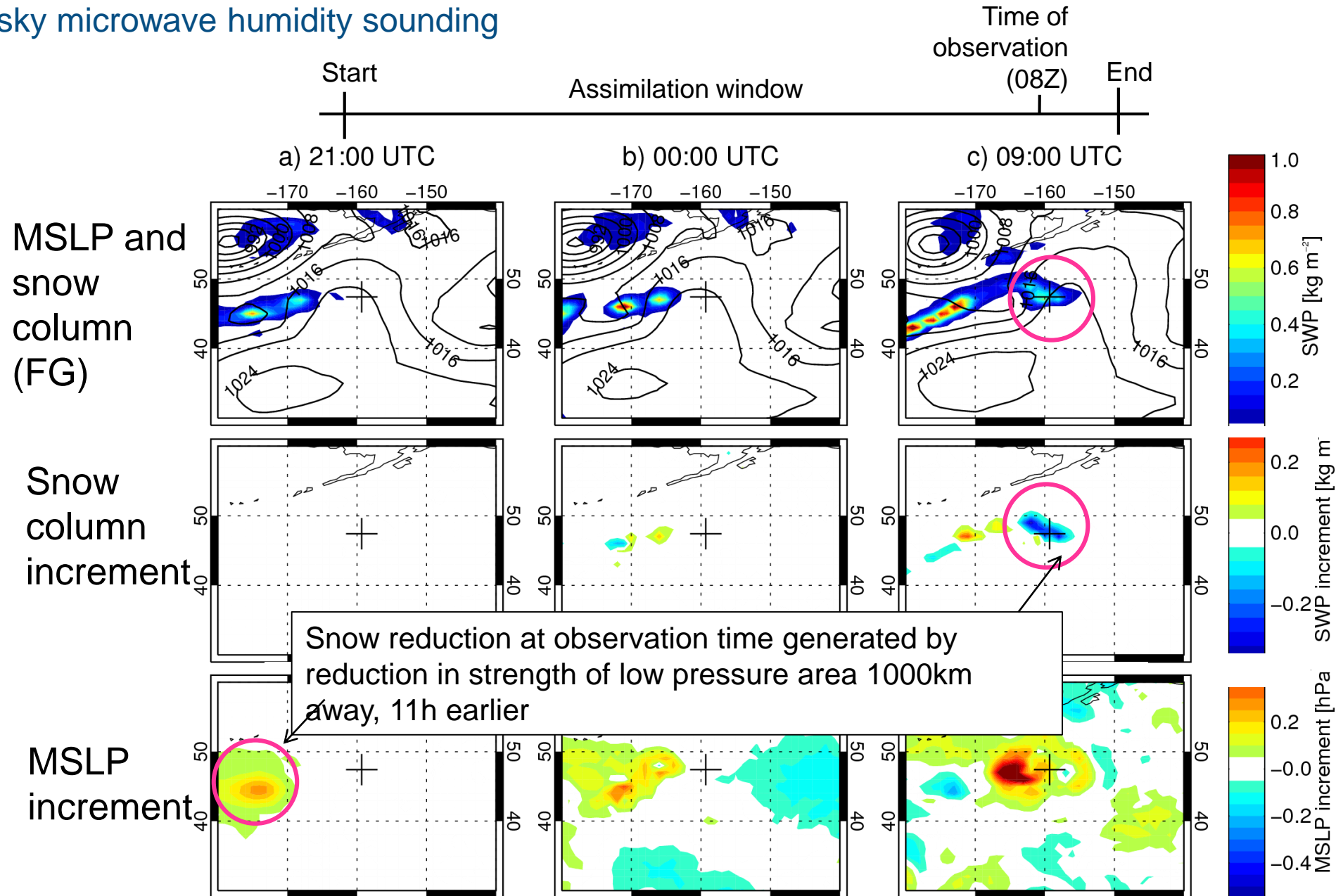
ECMWF

Relative impact on 24h forecast quality at ECMWF (relative FSOI, adds up to 100%)

1-Jan-2020 to 31-Jan-2020

Microwave WV: Water vapour, cloud and precipitation sensitive radiance observations from 13 satellite sensors, mostly assimilated in all-sky conditions

# 4D-Var tracer effect in single-observation experiment: all-sky microwave humidity sounding

Start

Assimilation window

Time of observation (08Z)

End

a) 21:00 UTC   b) 00:00 UTC   c) 09:00 UTC

MSLP and snow column (FG)

Snow column increment

Snow reduction at observation time generated by reduction in strength of low pressure area 1000km away, 11h earlier

MSLP increment

SWP [kg m^{-2}]

SWP increment [kg m^{-2}]

MSLP increment [hPa]

Relative impact on 24h forecast: satellite radiances

1-Jan-2020 to 31-Jan-2020

Microwave WV:
Water vapour, cloud and precipitation sensitive observations from 13 sensors, mostly assimilated in all-sky conditons

Humidity sounders:
Water vapour and frozen precipitation in mid to upper troposphere => dynamics through 4D-Var ("tracer" effect)

Microwave imagers:
Water vapour, liquid cloud and rain in lower troposphere
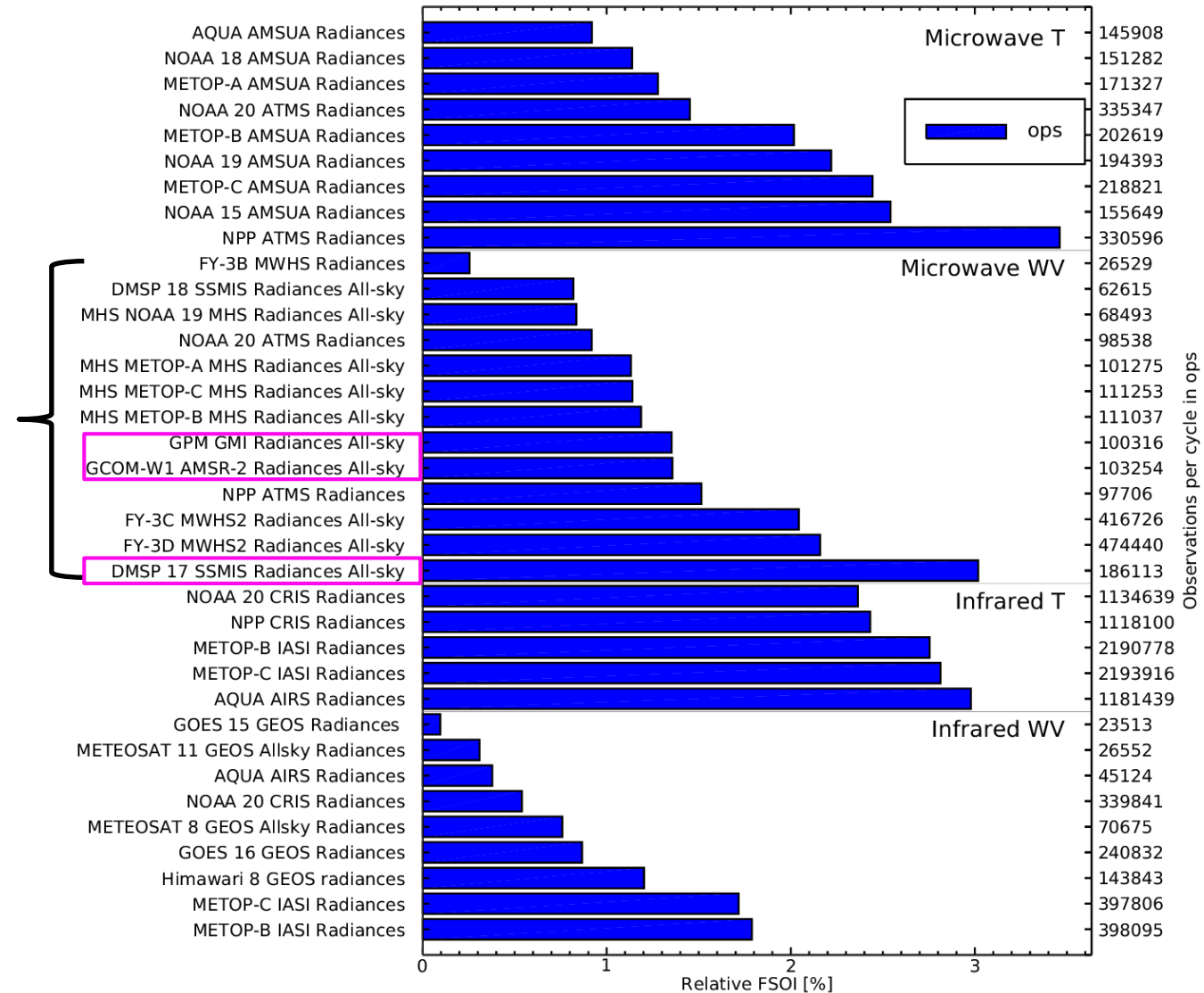
All-sky microwave imagers: a unique contribution from low-frequency microwave channels over ocean

- Currently assimilated at ECMWF:

  - NASA/JAXA Global Precipitation Mission (GPM) microwave imager (GMI)

  - JAXA GCOM-W2 Advanced Microwave Scanning Radiometer-2 (AMSR2)

  - US DoD Defense Meteorological Space Programme (DMSP) Special Sensor Microwave Imager Sounder (SSMIS)

- Other current sensors:

  - China FY-3D MWRI

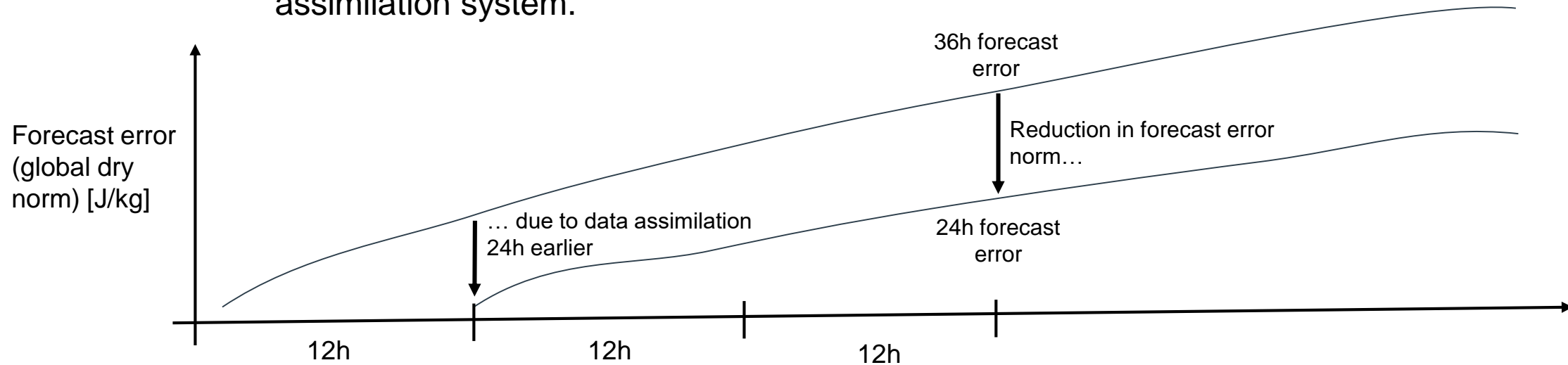 - Windsat

- Future sensors

  - EUMETSAT EPS-SG MWI

  - Copernicus CIMR

All-sky microwave imagers: a unique contribution from low-frequency microwave channels over ocean

Microwave imagers give their largest forecast impact from a small fraction of precipitating scenes. Why?

AMSR2, July-August 2016
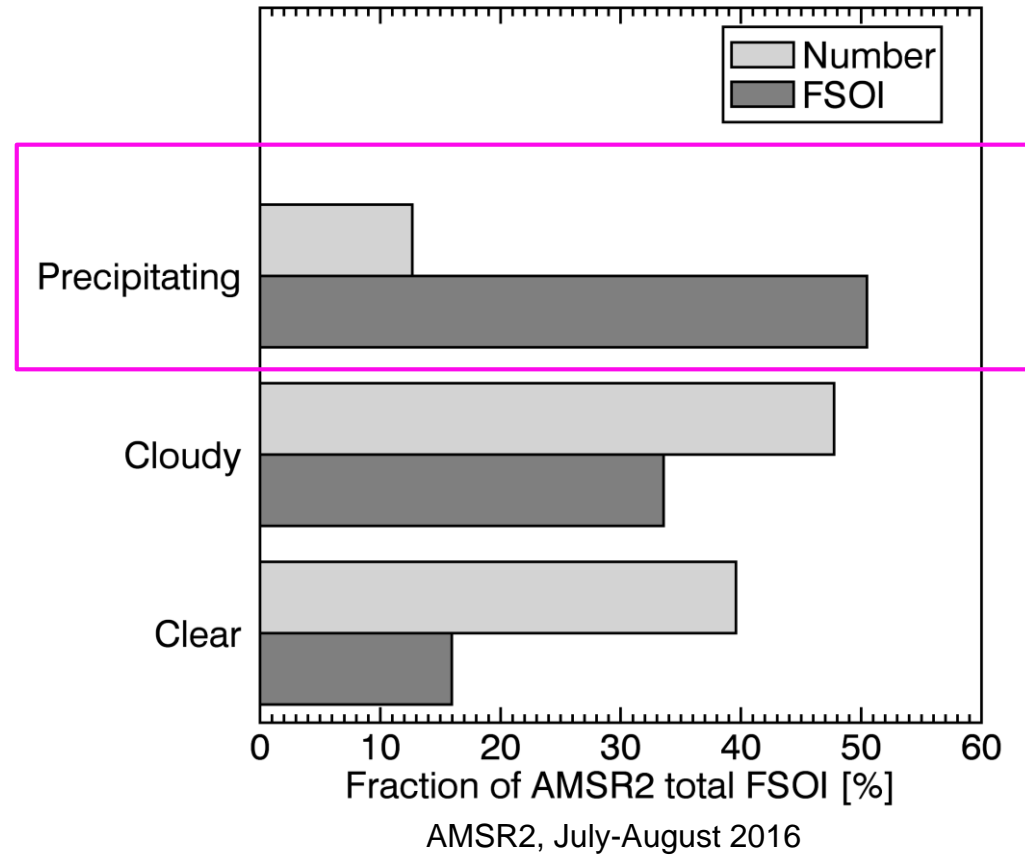
Forecast sensitivity to observation impact - FSOI – impact on what?

- Change in dry energy error norm:

  - Error norm of forecast errors (forecast – analysis), globally, on all vertical levels

    - Dry energy: total of kinetic energy (winds), static energy (temperature, surface P) - e.g. Rabier (1996)

  - 36h error norm – 24h error norm

- Propagated backwards in time using the adjoint forecast model

- Mapped onto individual observations using the "inverse" of the data assimilation system.

Forecast error (global dry norm) [J/kg]

36h forecast error

Reduction in forecast error norm…

… due to data assimilation 24h earlier

24h forecast error

12h   12h   12h

All-sky microwave imagers: contribution to forecast improvement is highly localised in time and space

2018-2019 winter season: FSOI (global) impact of GMI observations in the Atlantic.

Bad (but expected due to probabilistic nature of data assimilation)
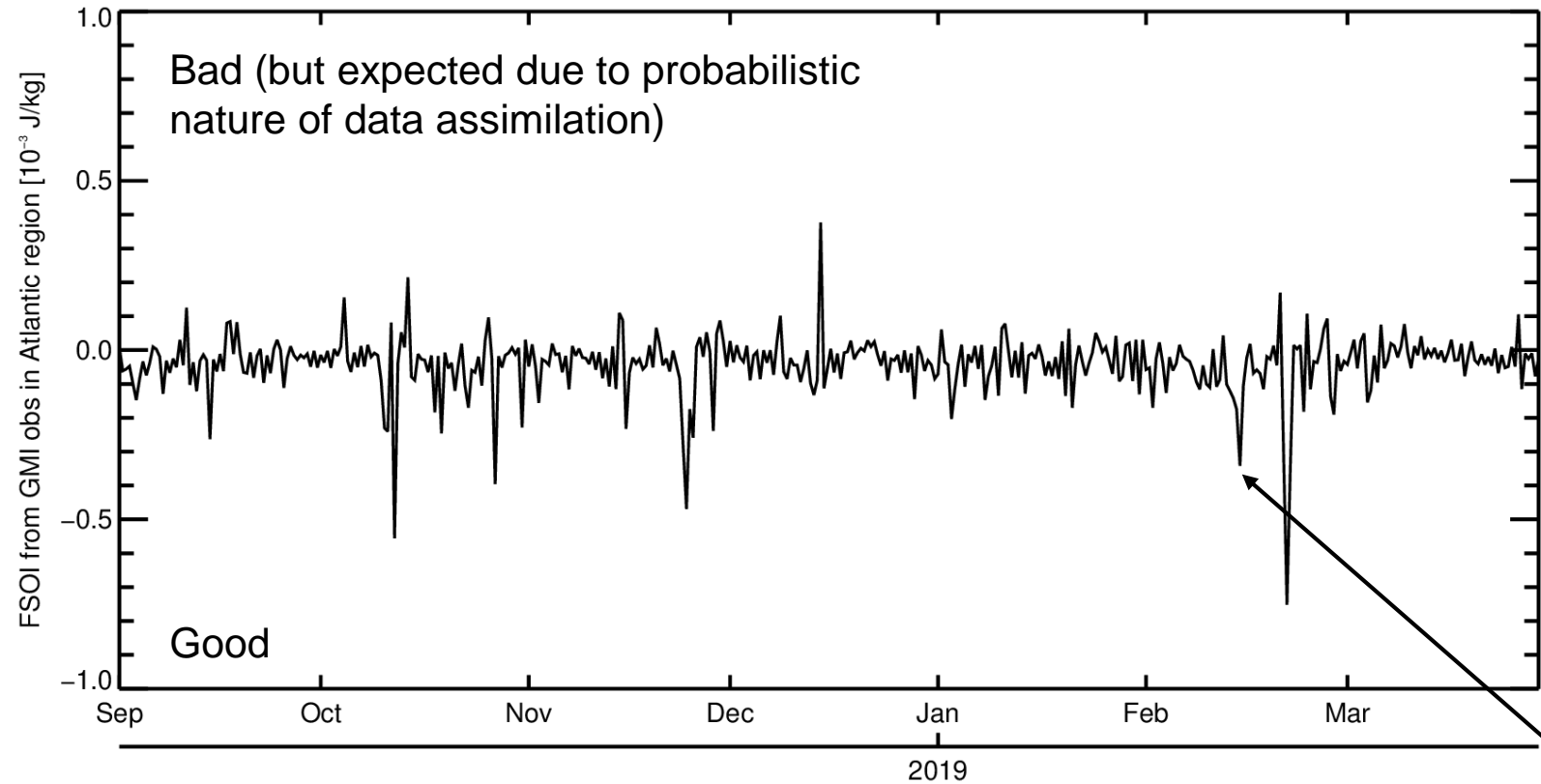
Good

Good impacts significantly outweigh bad, on average.

A few times a season, microwave imager data in the Atlantic is highly influential on the forecast:

Case study 15th February 2019

15th February 2019

WV (total column)

Line contours: mean sea level pressure in analysis (5 hPa contour spacing)
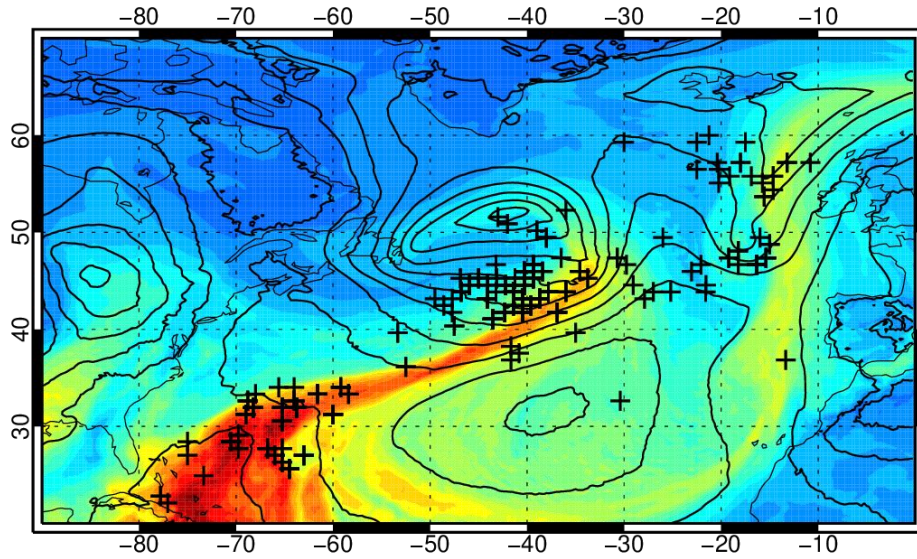
Crosses: Influential AMSR2 and GMI observations: with FSOI < -5×10^{-5} J/kg
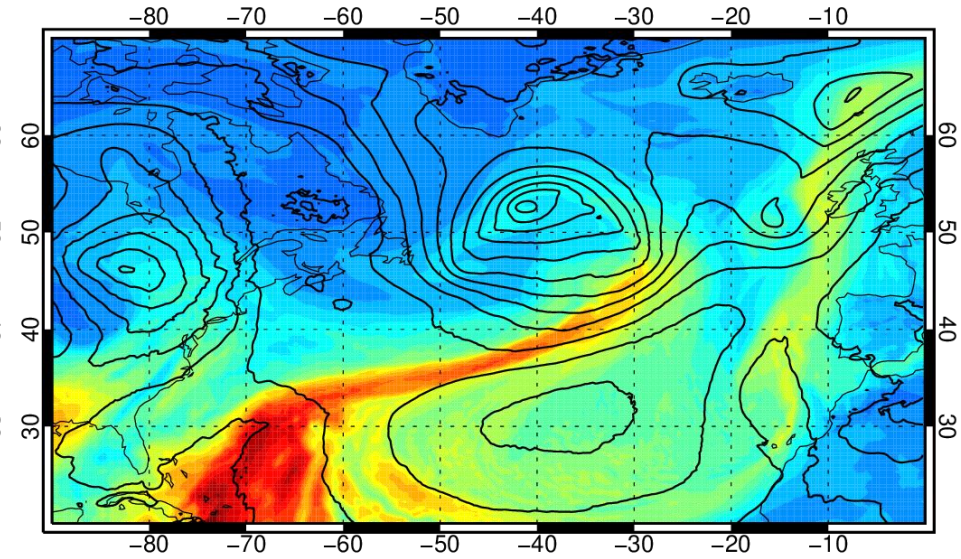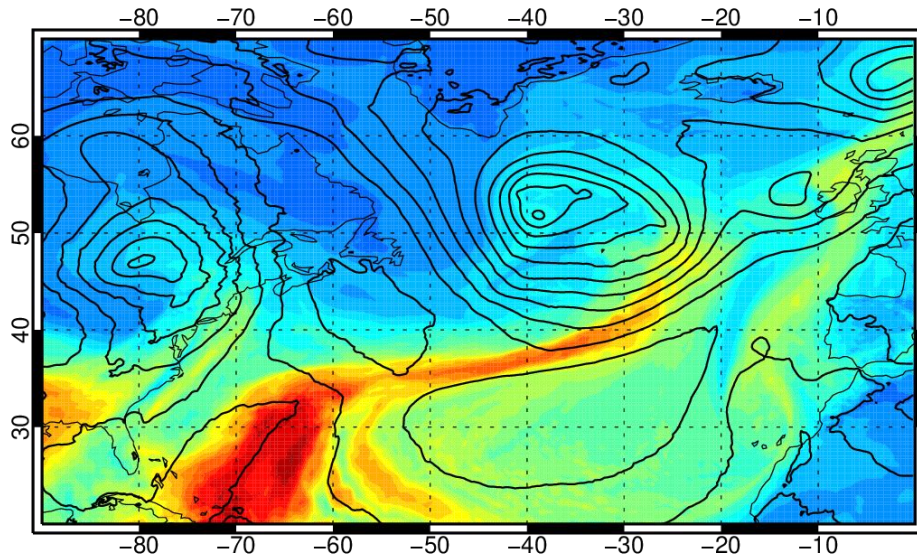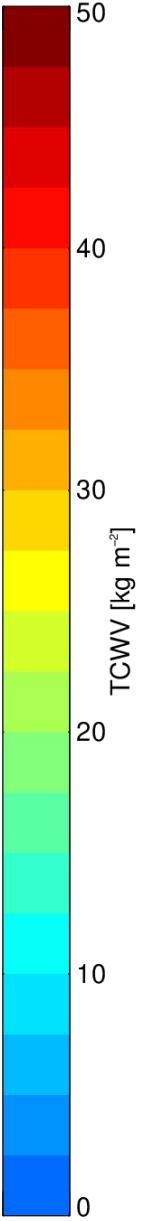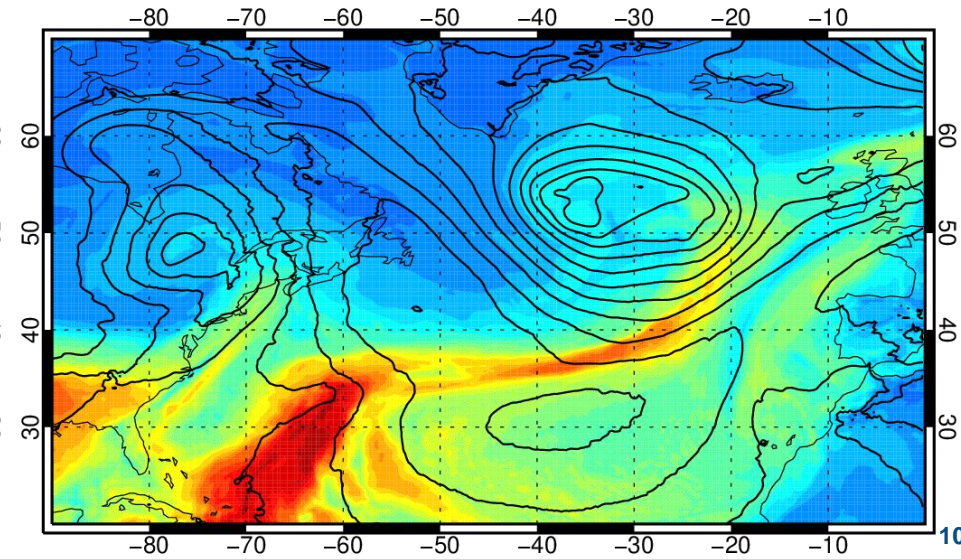
Analysis time window – deterministic data assimilation


Observations assimilated in 12h window (here 21 – 09 UTC)

Some forecast quantity

Background forecast

Evolved increment measured by change in FSOI error norm

Evolved increment

Evolved increment

True (control variable) increment

Analysis forecast

18 UTC   00 UTC   06 UTC   12 UTC   18 UTC   00 UTC

T+0   T+6   T+12   T+18   T+24

WV (total column)

Line contours: mean sea level pressure in analysis (5 hPa contour spacing)

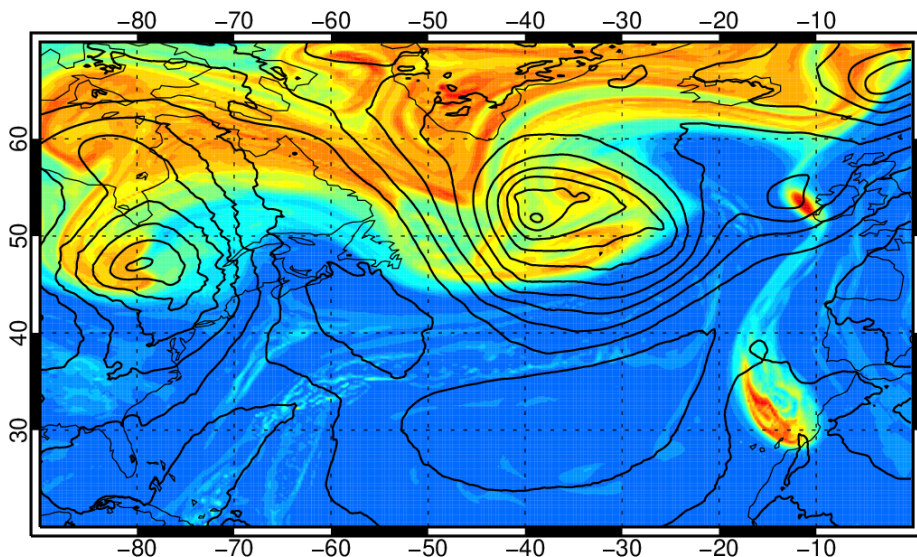**Crosses:** Influential AMSR2 and GMI observations: with FSOI < -5×10^{-5} J/kg


T+6   06:00:00 15−Feb−2019

T+12   12:00:00 15−Feb−2019

T+18   18:00:00 15−Feb−2019
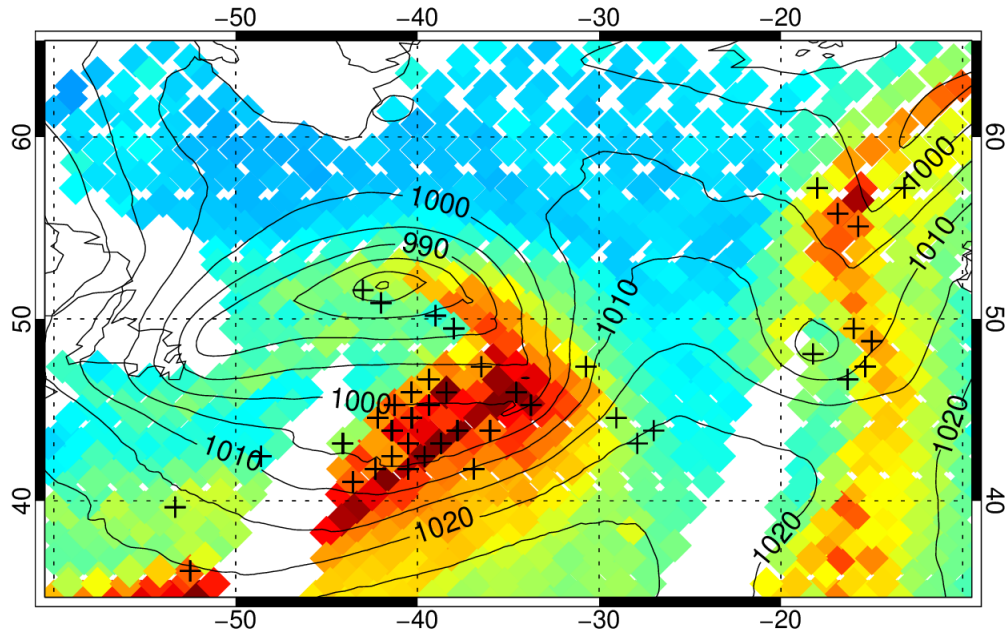
T+24   00:00:00 16−Feb−2019

TCWV [kg m^{-2}]
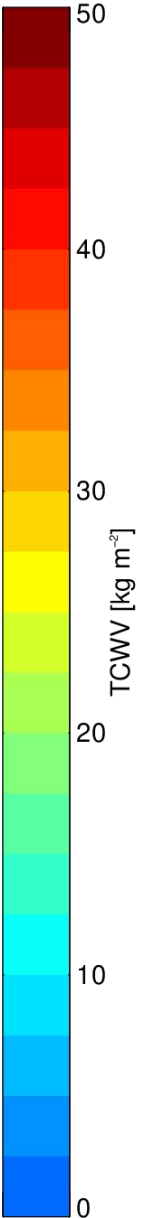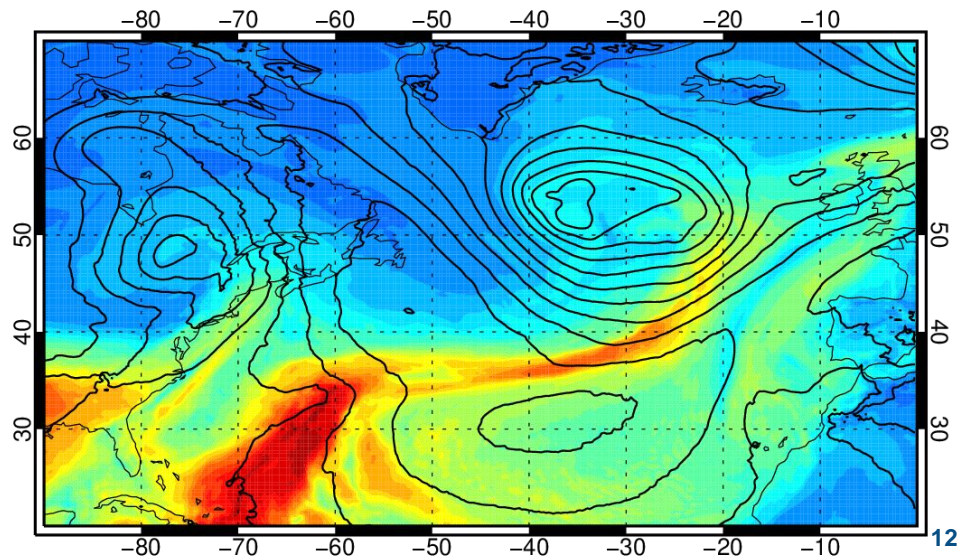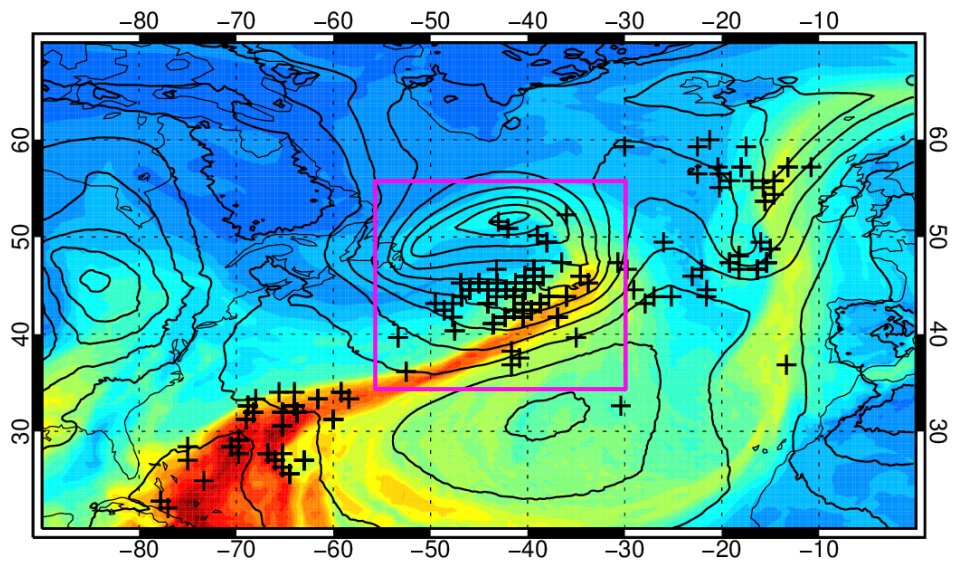
Line contours:
mean sea level
pressure in analysis
(5 hPa contour
spacing)

Crosses:
Influential AMSR2
and GMI
observations: with
FSOI < -5×10^{-5} J/kg

# Sensor impact (% of total FSOI) in pink box

Sensor	%
GCOM-W1 AMSR-2 Radiances All-sky	18.0
GPM GMI Radiances All-sky	14.6
METOP-A ASCAT	12.5
BUFR DRIFTING BUOYS	9.3
NOAA 20 ATMS Radiances Clear-sky	8.1
WIGOS AMDAR	6.5
DMSP 17 SSMIS Radiances All-sky	5.3
64 other sensor types	25.7

WV (total column)

Line contours: mean sea level pressure in analysis (5 hPa contour spacing)
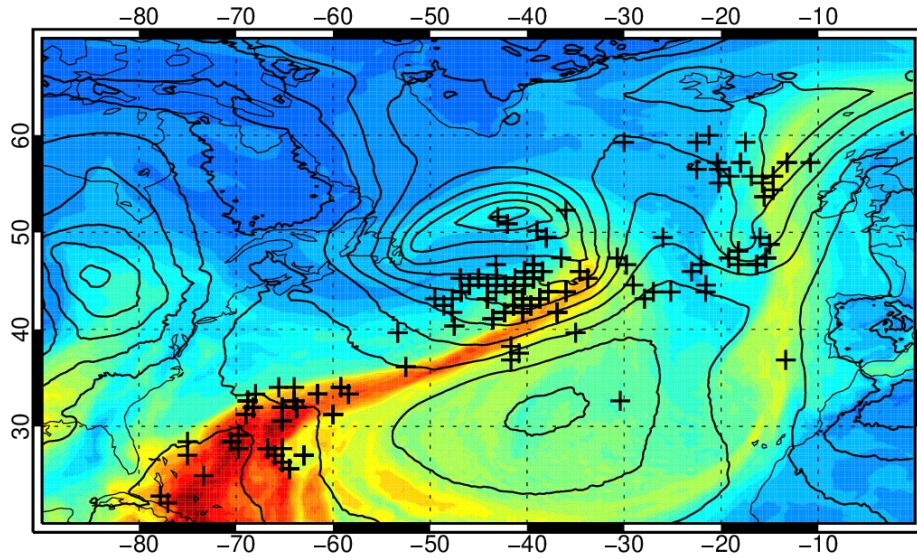
Crosses: Influential AMSR2 and GMI observations: with FSOI < -5×10⁻⁵ J/kg
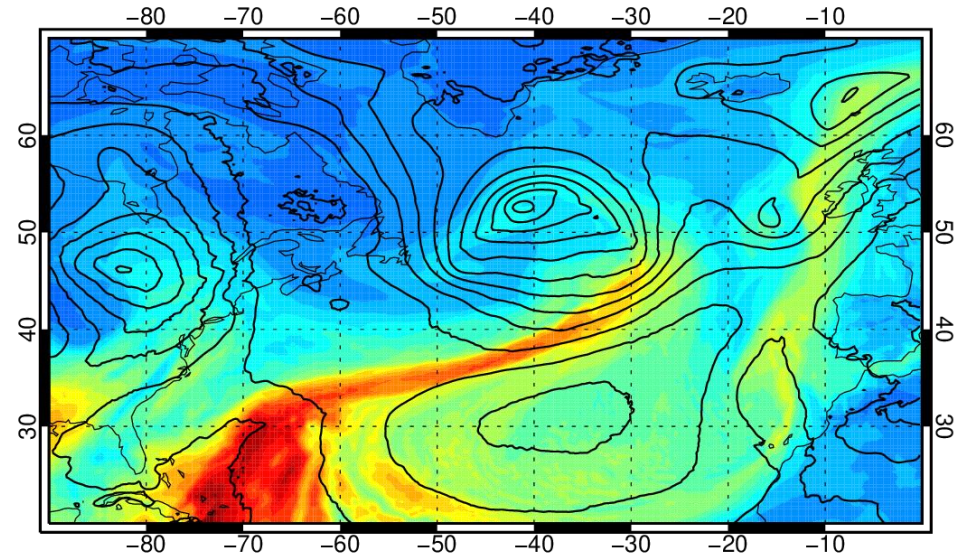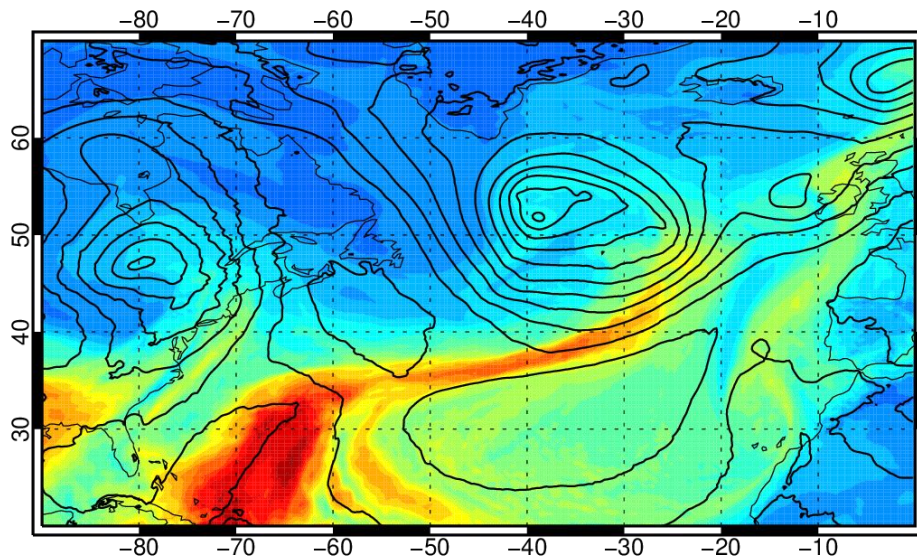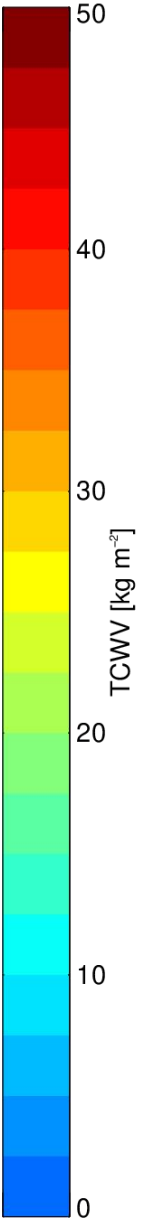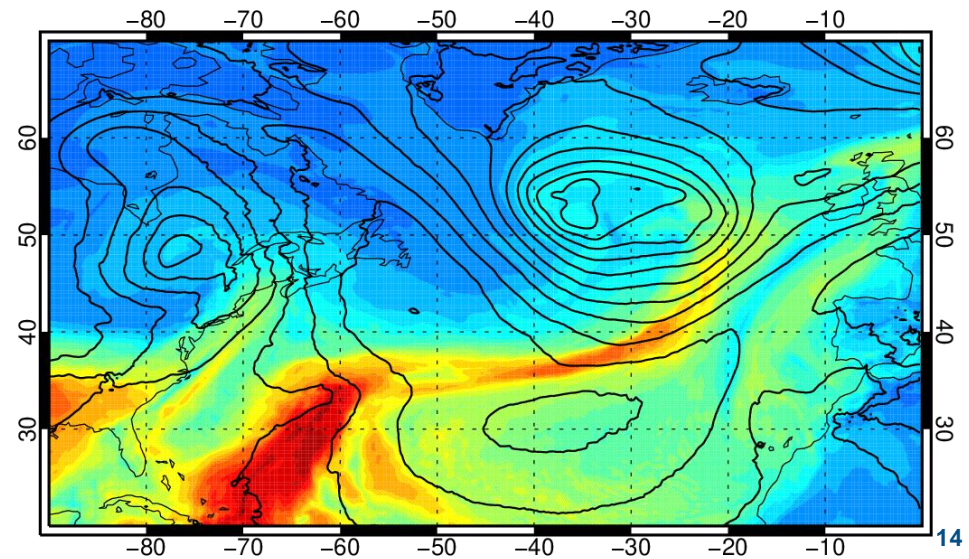
PV on 315K isentropic surface

Line contours: mean sea level pressure in analysis (5 hPa contour spacing)

Crosses: Influential AMSR2 and GMI observations: with FSOI < -5×10⁻⁵ J/kg

T+6   06:00:00 15–Feb–2019

T+12   12:00:00 15–Feb–2019

T+18   18:00:00 15–Feb–2019

T+24   00:00:00 16–Feb–2019

Potential vorticity – PVU [10^{-6} K m^2 g^{-1} s^{-1}]
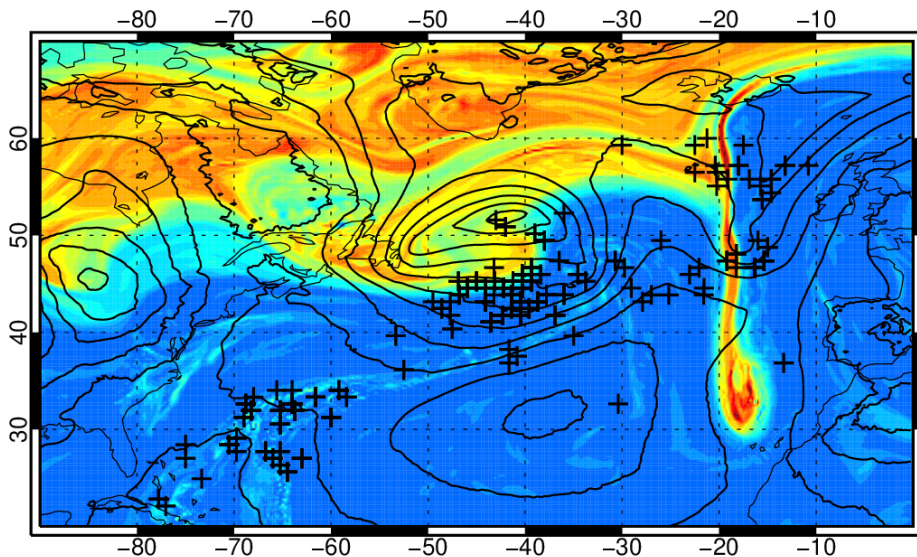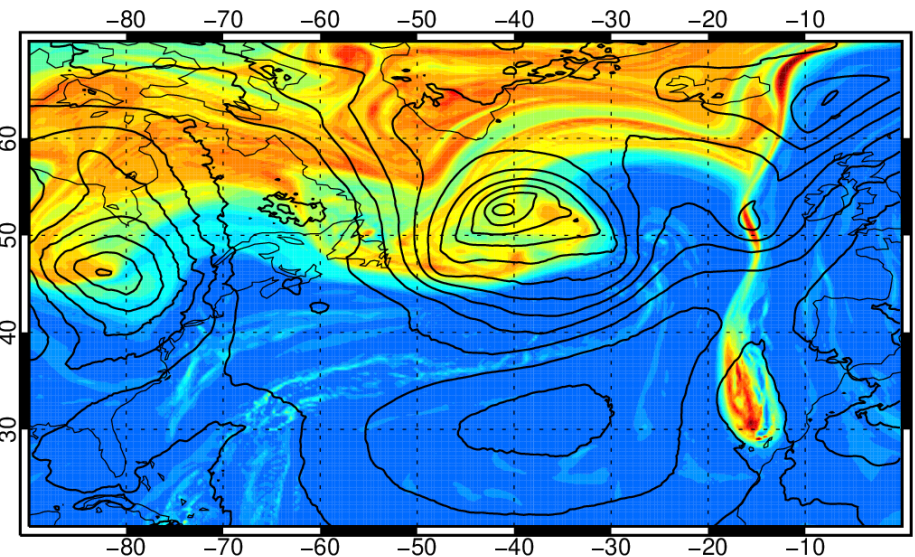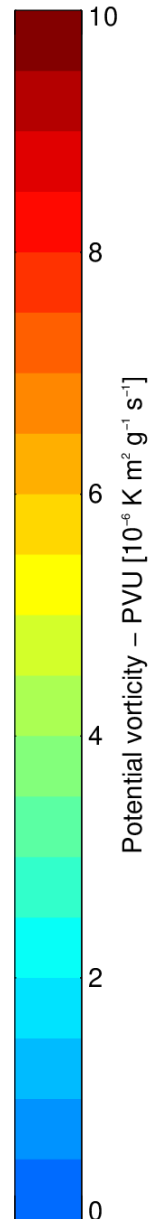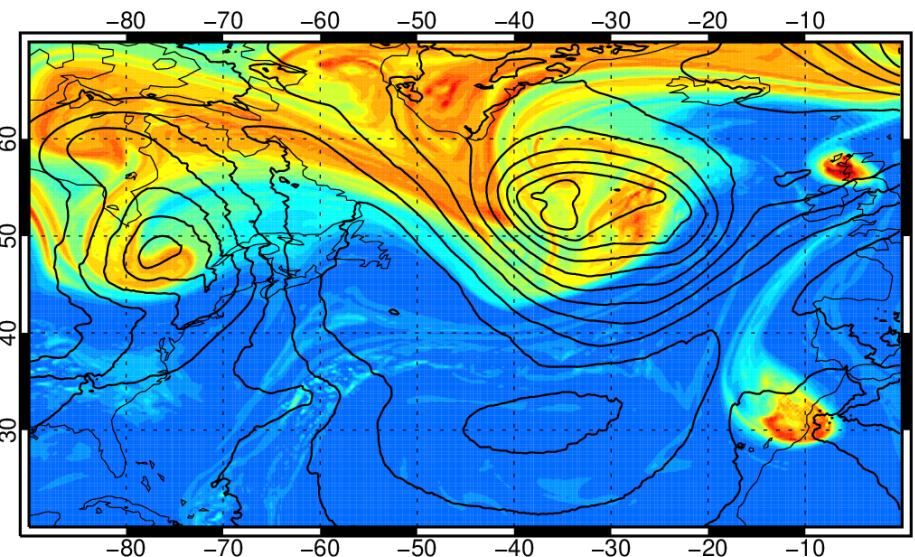
06:00 UTC
15th Feb
2019

Line contours:
mean sea level
pressure in analysis
(5 hPa contour
spacing)

Crosses:
Influential AMSR2
and GMI
observations: with
FSOI < -5×10^{-5} J/kg

PV

TCWV (water vapour)

TCLW (liquid cloud)

TCIW (ice cloud)
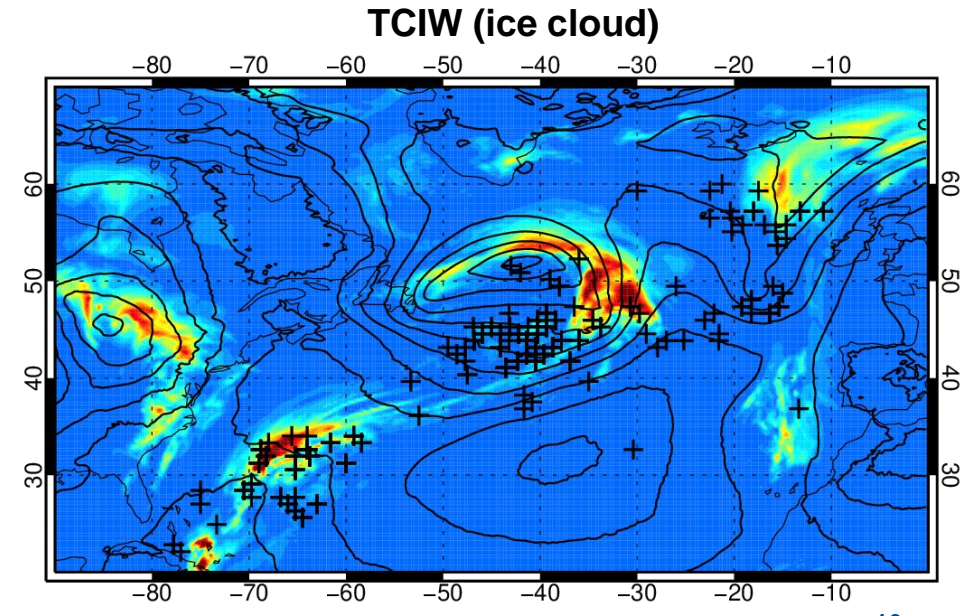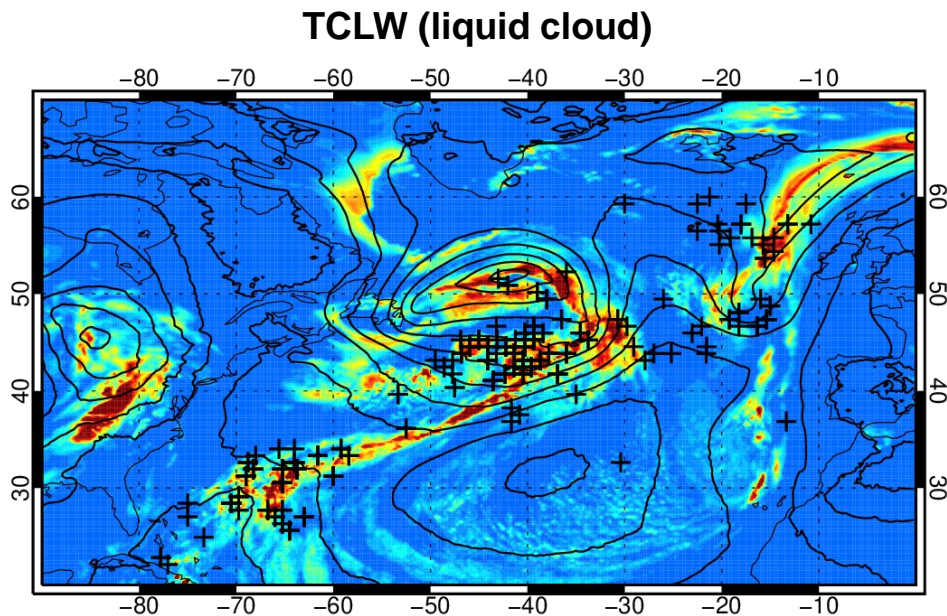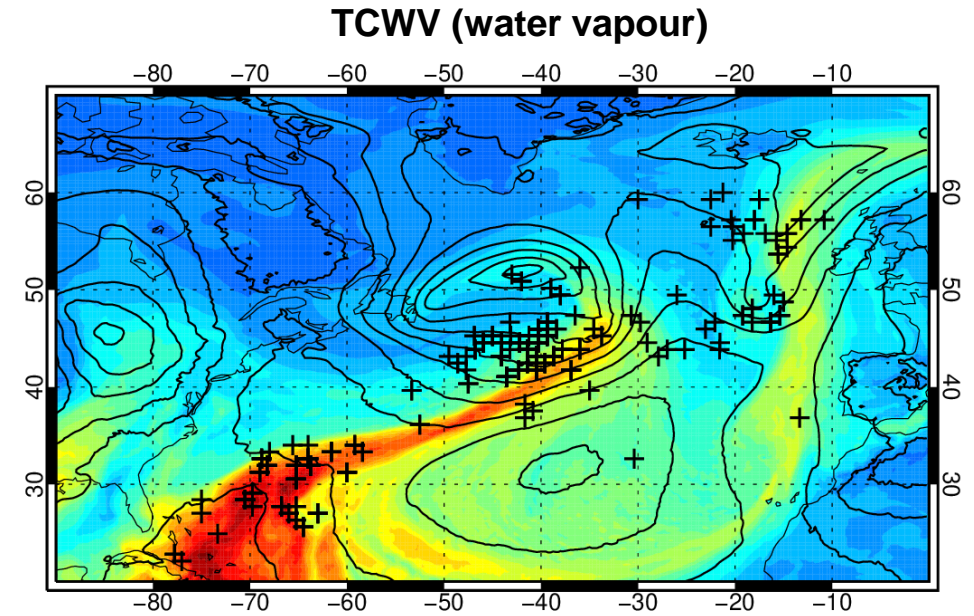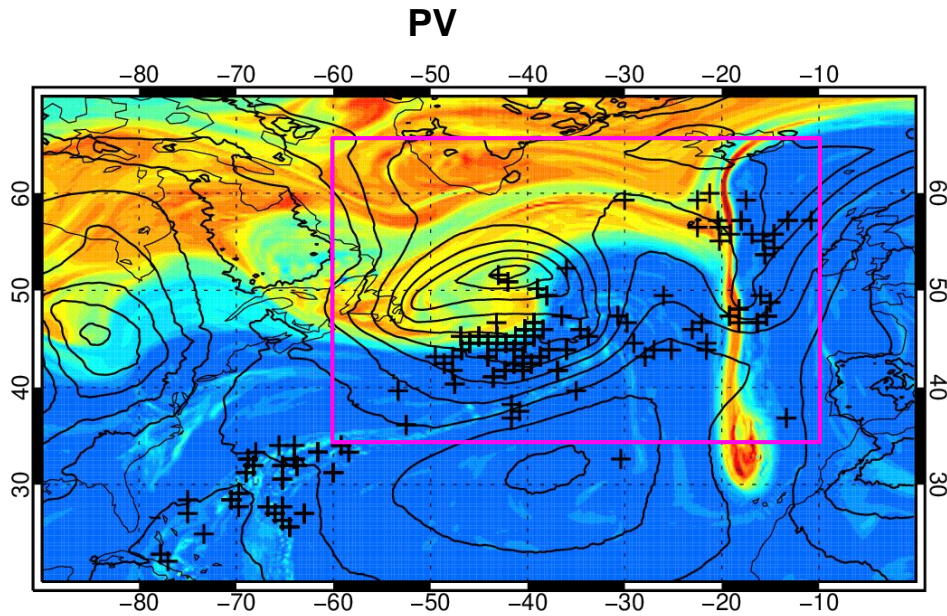
AMSR2 channel 9 (23.8 GHz, v-polarized: "24v")
Centre swath ~04:17 UTC 15th Feb 2019

Observed brightness temperature (TB)
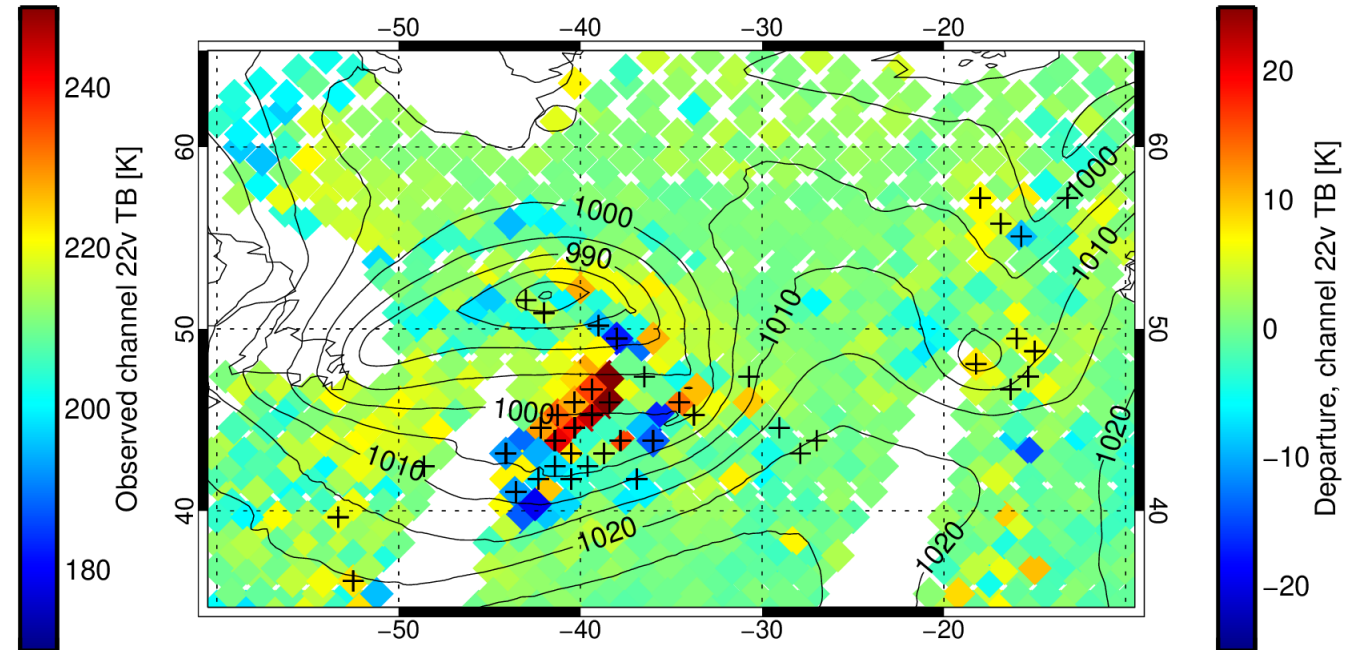
Departure (observation – background)
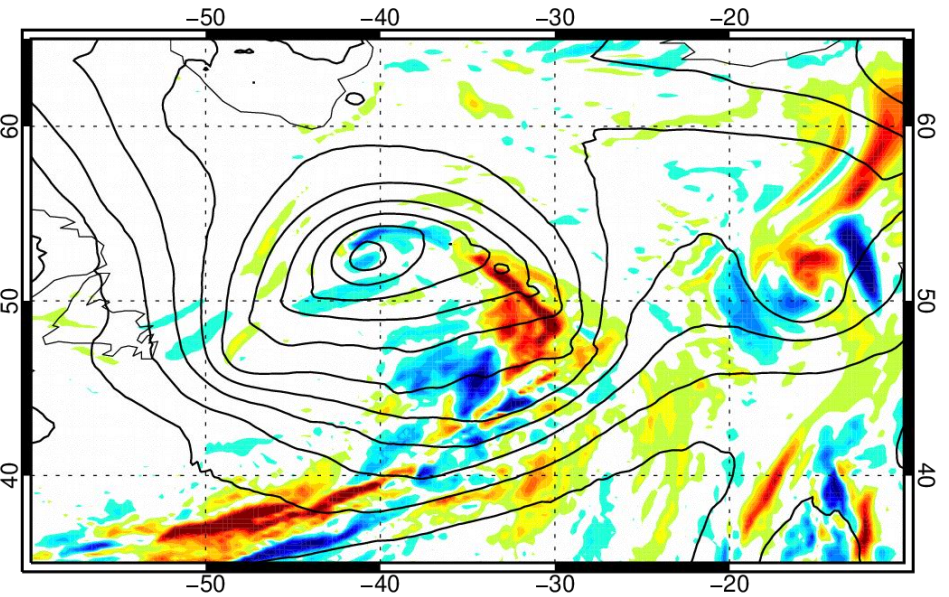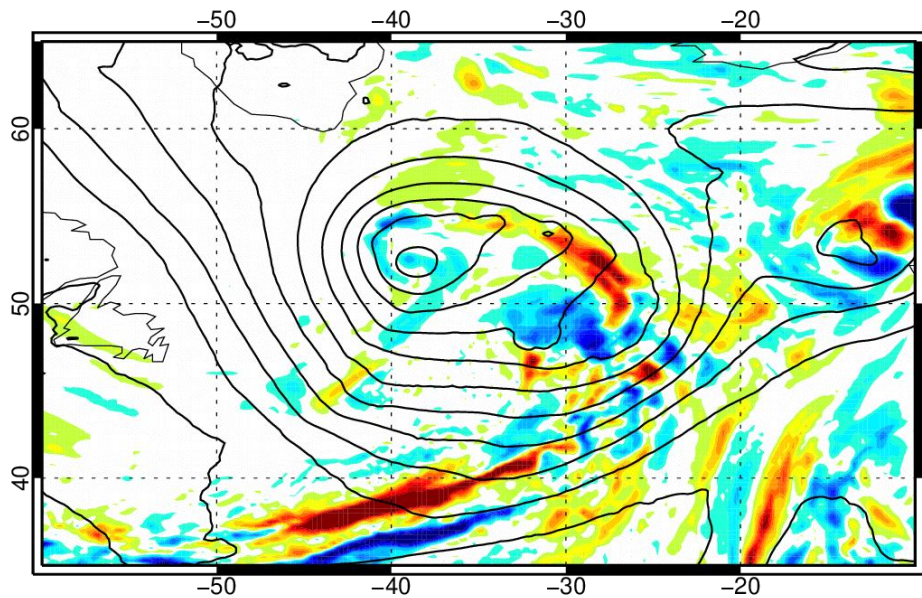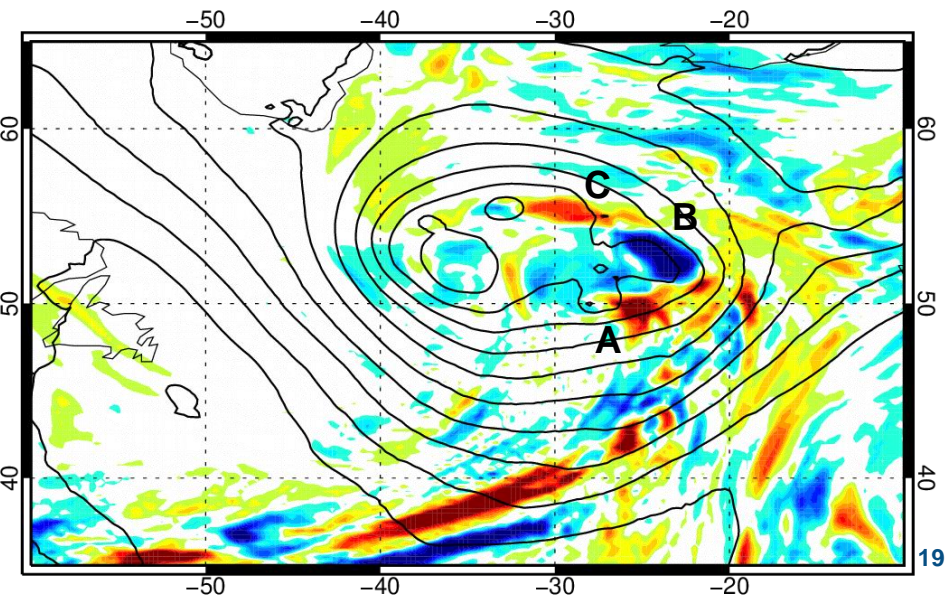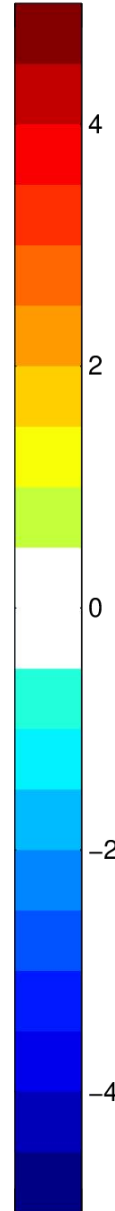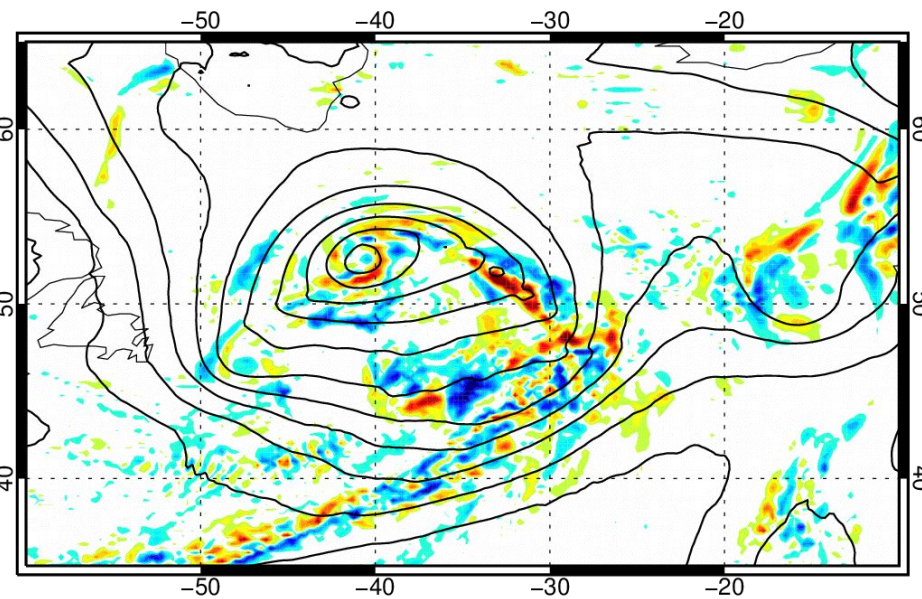
Line contours:
mean sea level pressure in forecast (5 hPa contour spacing) at 06:00

Crosses:
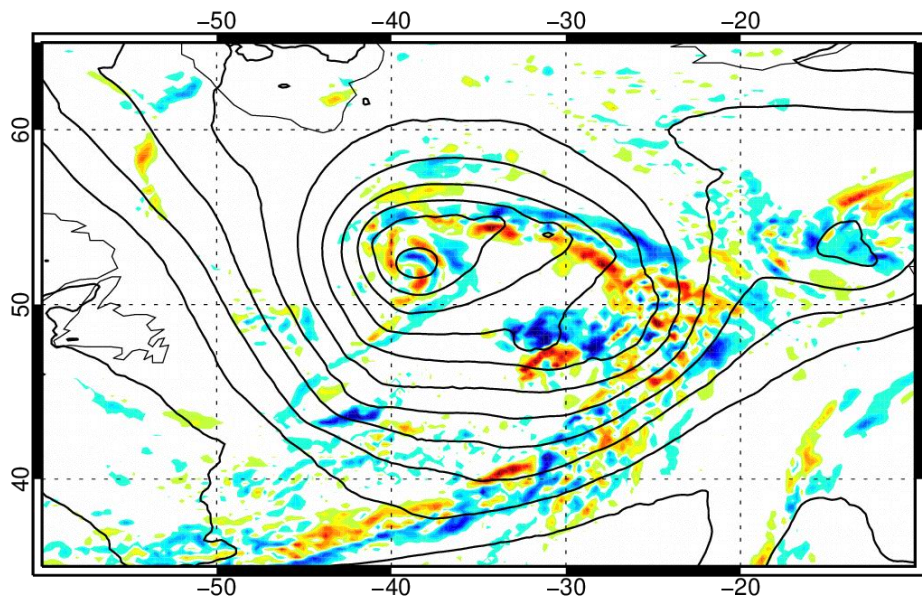Influential AMSR2 observations: with FSOI < -5×10^{-5} J/kg

GMI channel 5 (23.8 GHz, v-polarized: "24v")
Influential swath ~04:18 UTC 15th Feb 2019

Observed brightness temperature (TB)
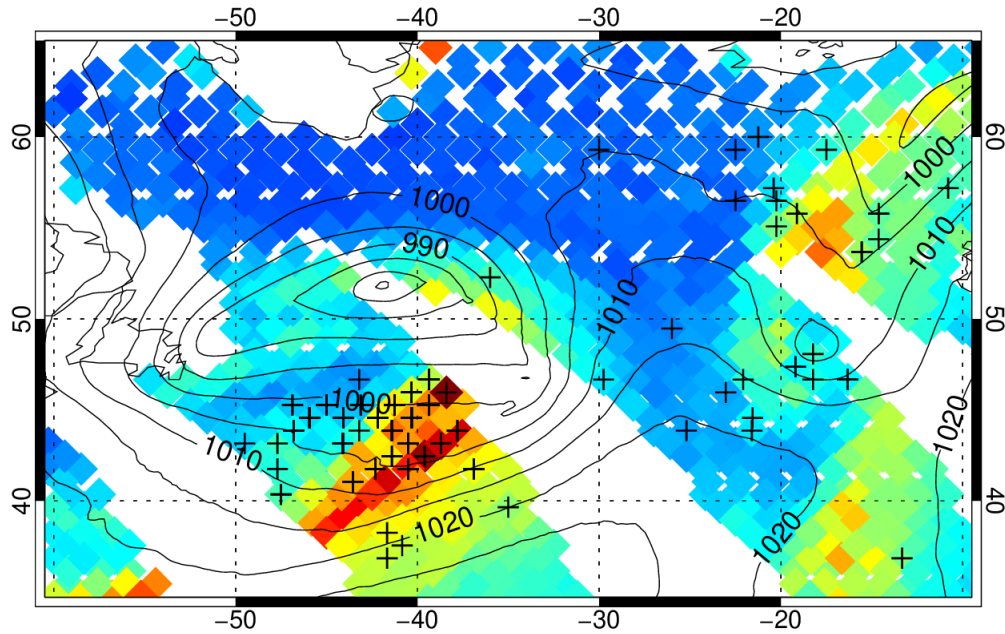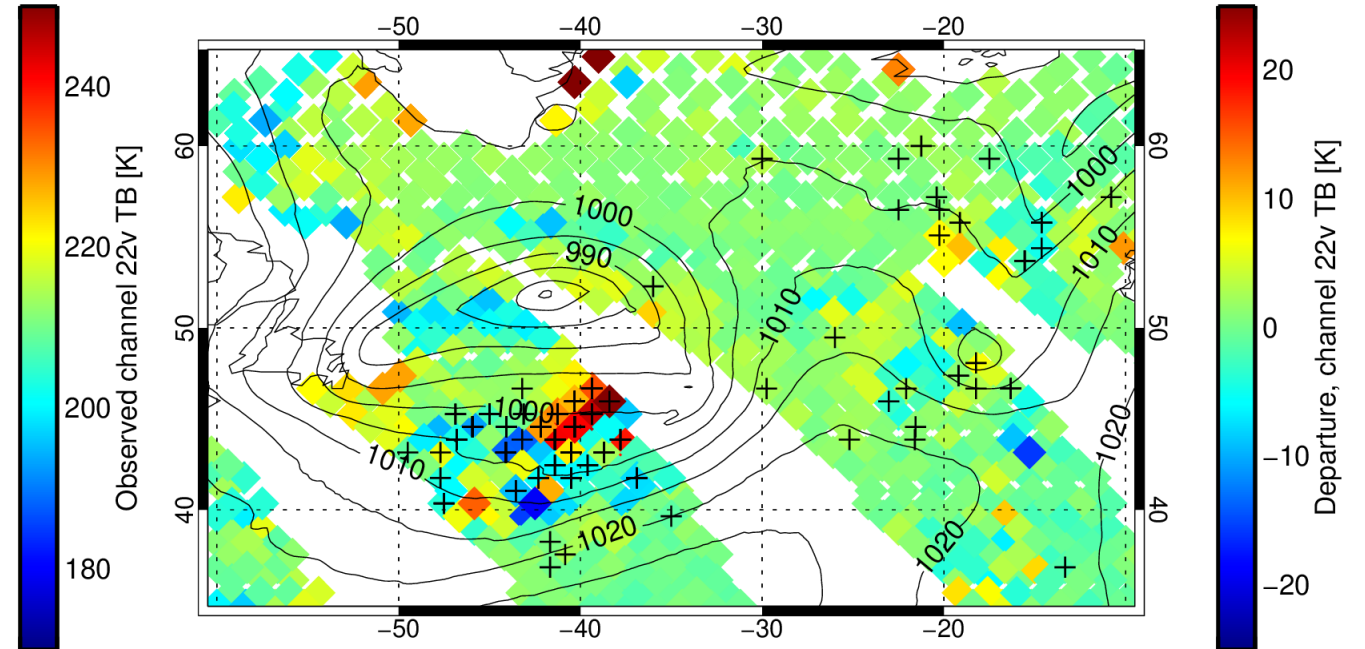
Departure (observation – background)

Line contours:
mean sea level pressure in forecast (5 hPa contour spacing) at 06:00

Crosses:
Influential GMI observations: with FSOI < -5×10^{-5} J/kg

18

WV (total column) increment

Line contours: mean sea level pressure in forecast (5 hPa contour spacing)

Crosses: Influential AMSR2 and GMI observations: with FSOI < -5×10⁻⁵ J/kg
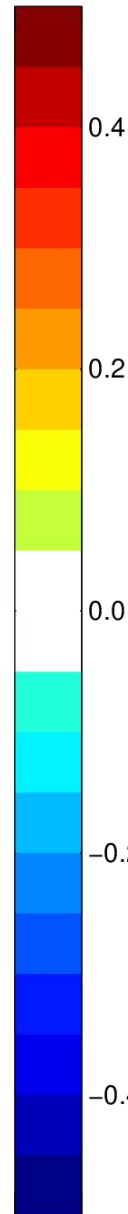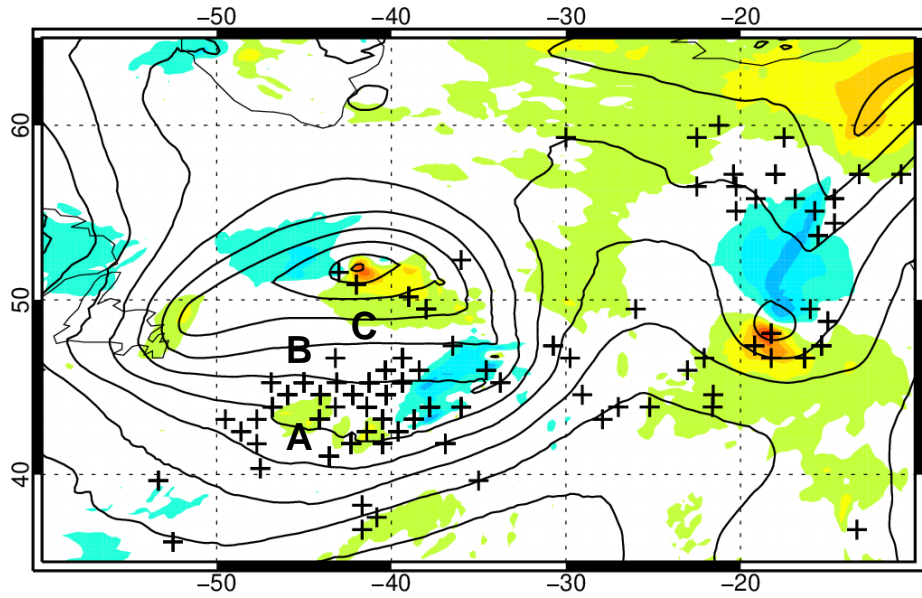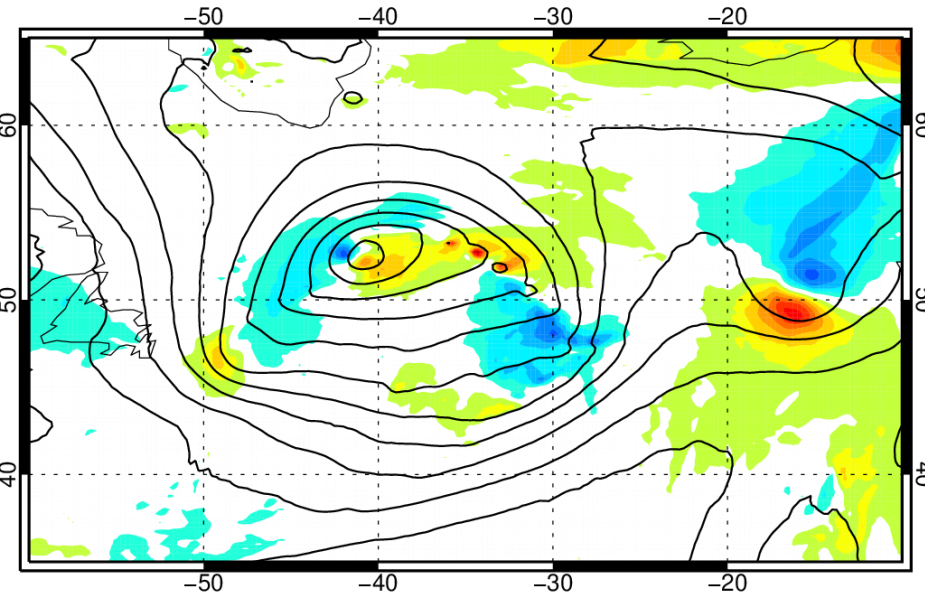
T+6   06:00:00 15-Feb-2019
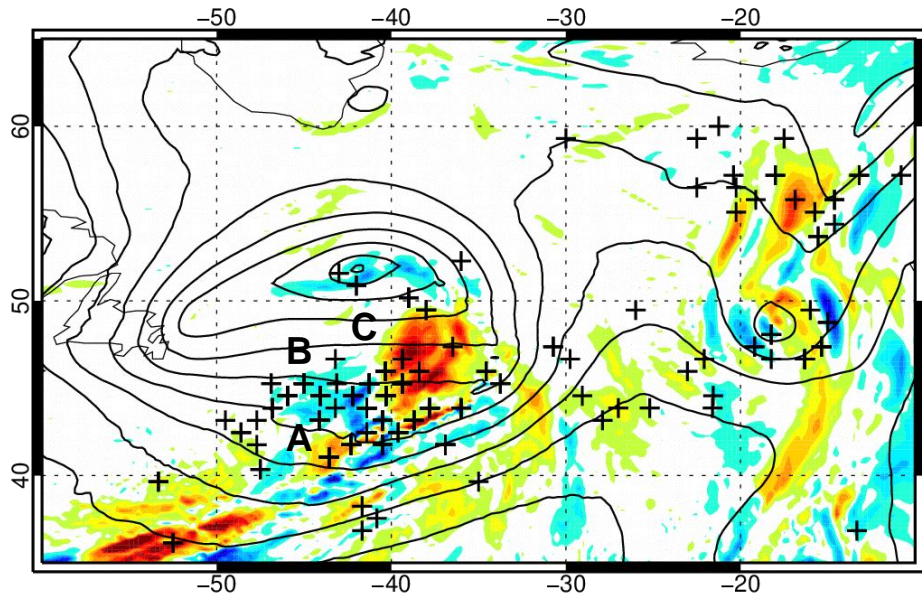
T+12   12:00:00 15-Feb-2019

T+18   18:00:00 15-Feb-2019

T+24   00:00:00 16-Feb-2019

TCWV increment [kg m⁻²]

Cloud water (total column) increment
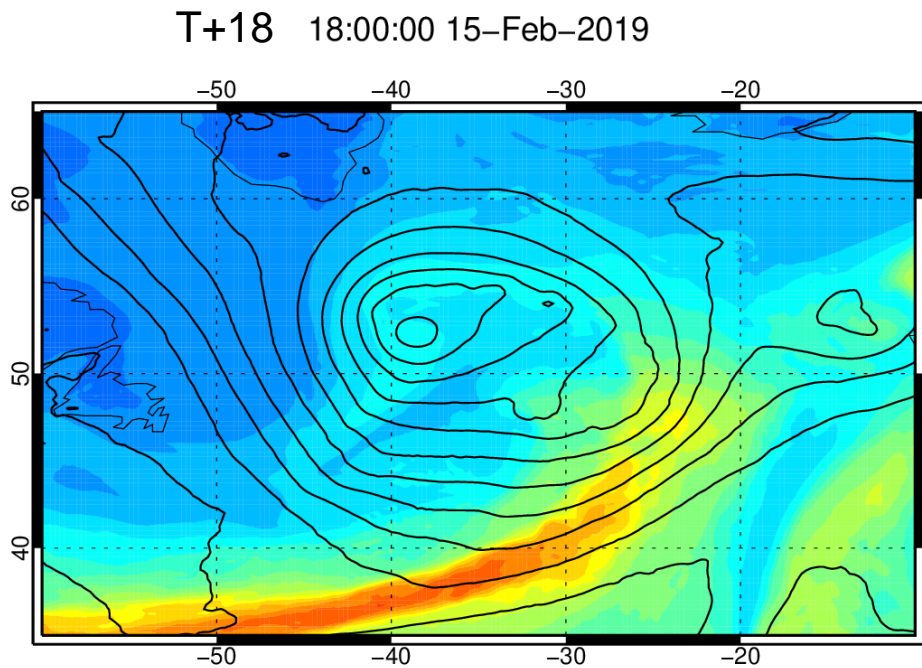
Line contours:
mean sea level pressure in forecast (5 hPa contour spacing)

Crosses:
Influential AMSR2 and GMI observations: with FSOI < -5×10^{-5} J/kg

T+6   06:00:00 15−Feb−2019
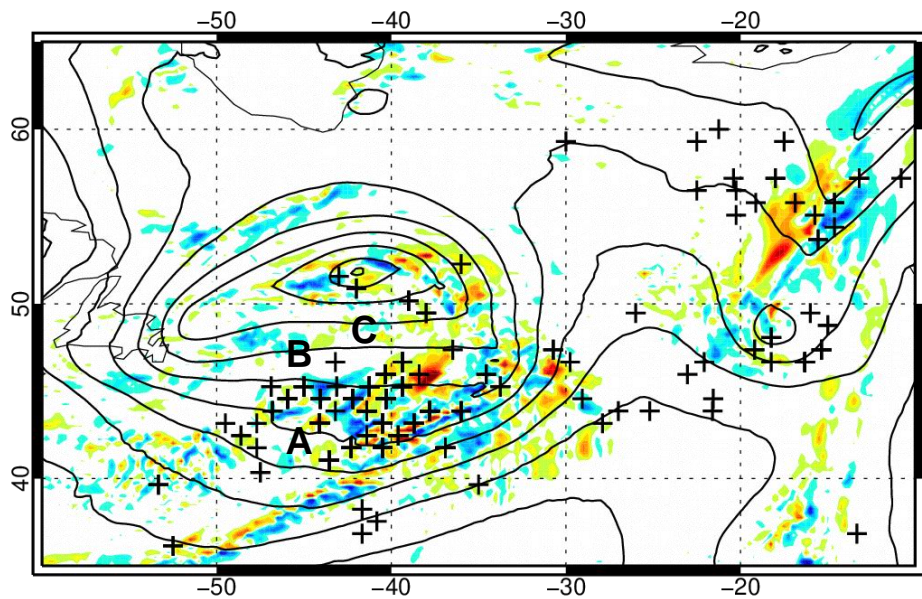
T+12   12:00:00 15−Feb−2019

T+18   18:00:00 15−Feb−2019

T+24   00:00:00 16−Feb−2019
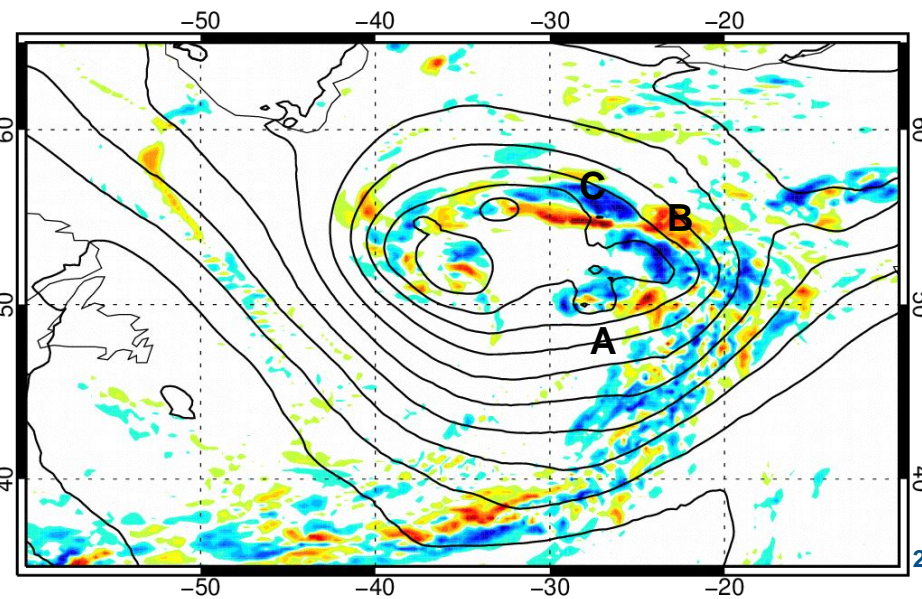
TCIW increment [kg m^{-2}]

Surface pressure increment

Line contours: mean sea level pressure in forecast (5 hPa contour spacing)
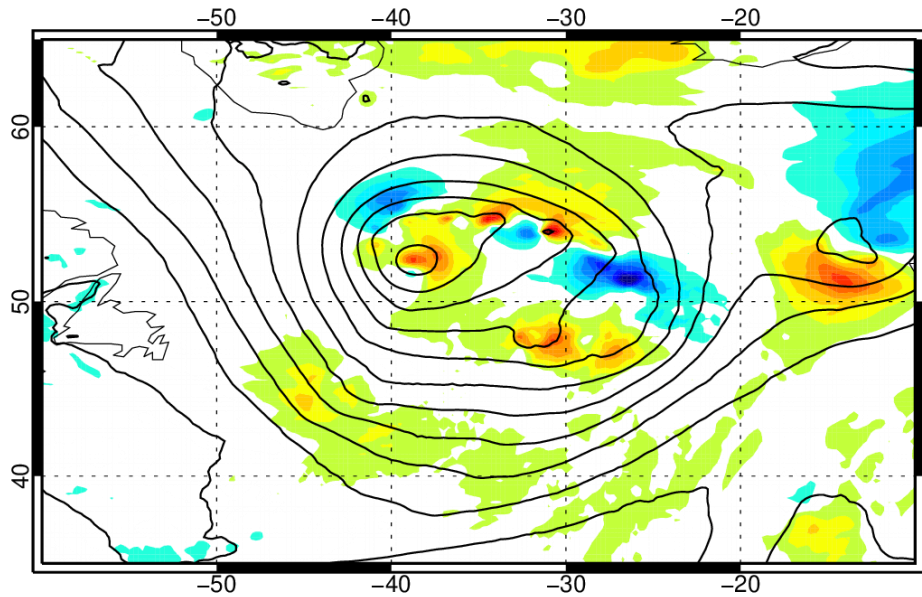
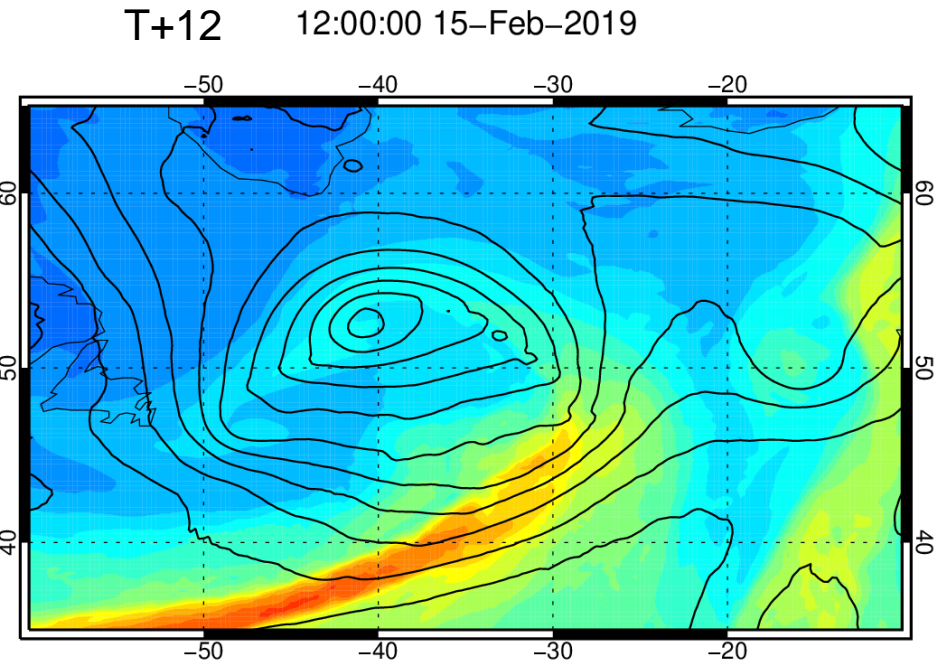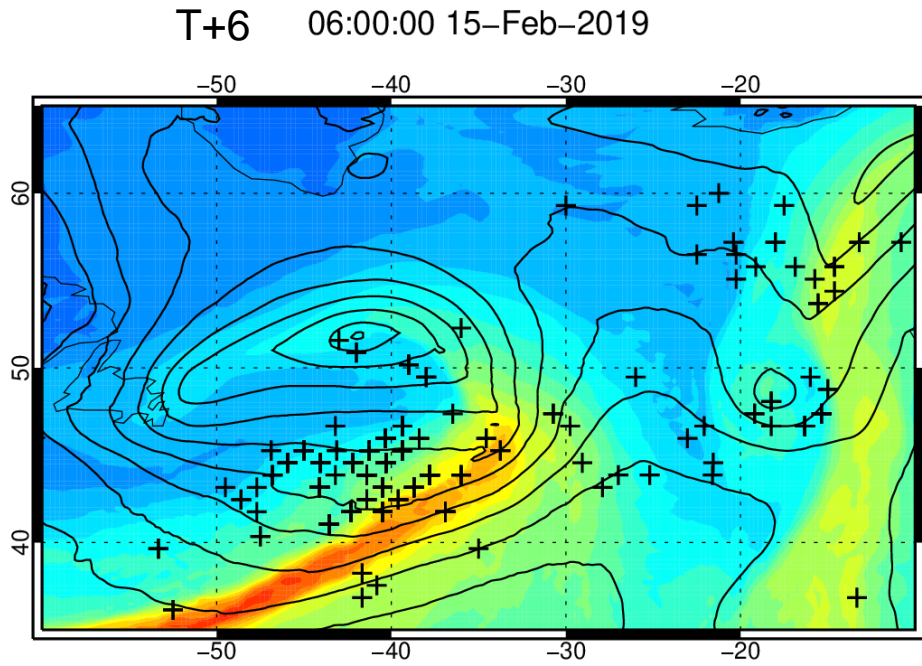**Crosses:** Influential AMSR2 and GMI observations: with FSOI < -5×10^{-5} J/kg
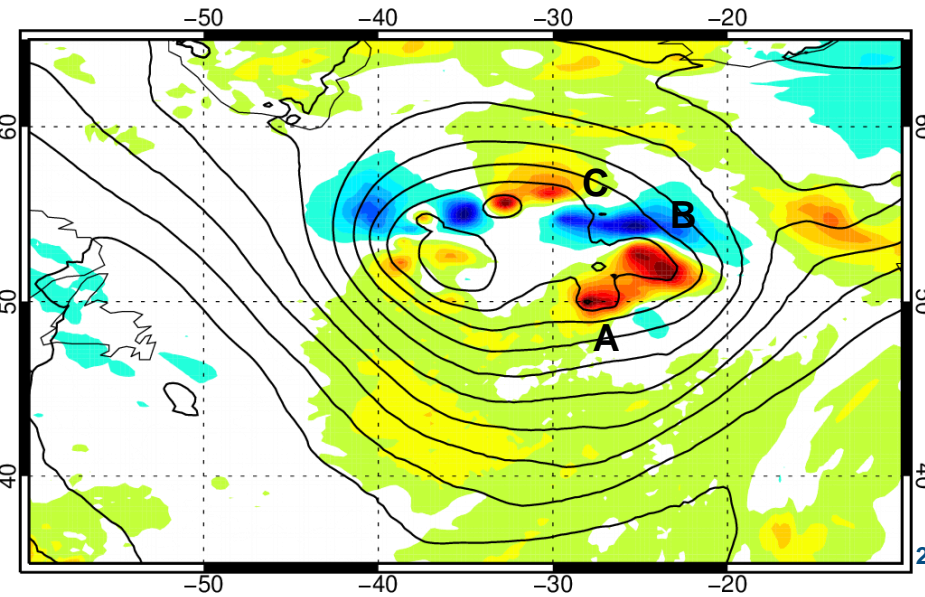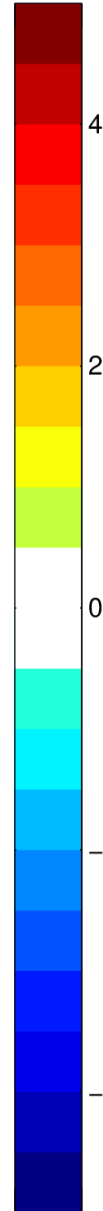
WV (total column) Forecast

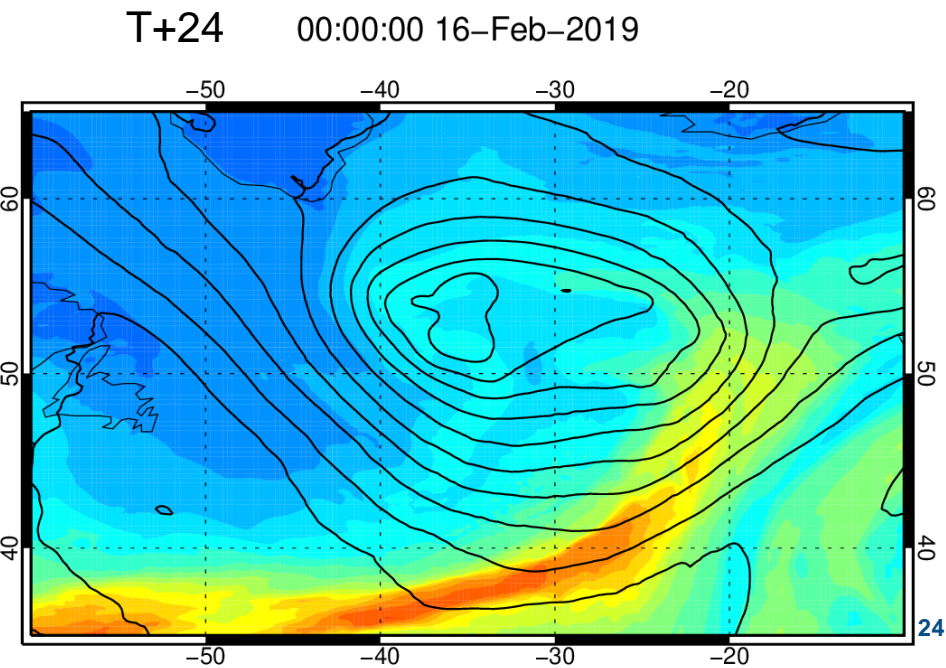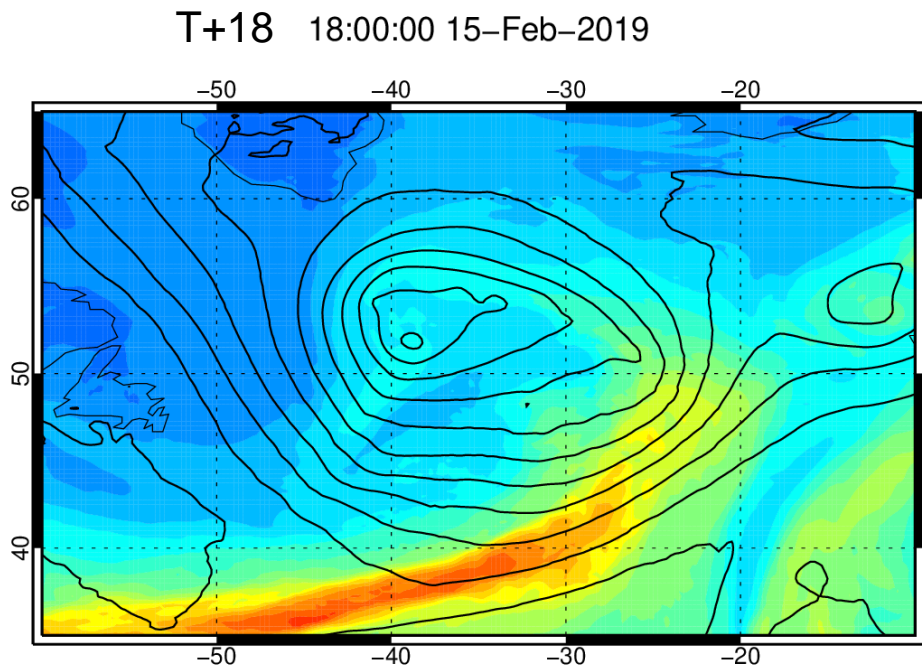**Line contours:** mean sea level pressure in forecast (5 hPa contour spacing)

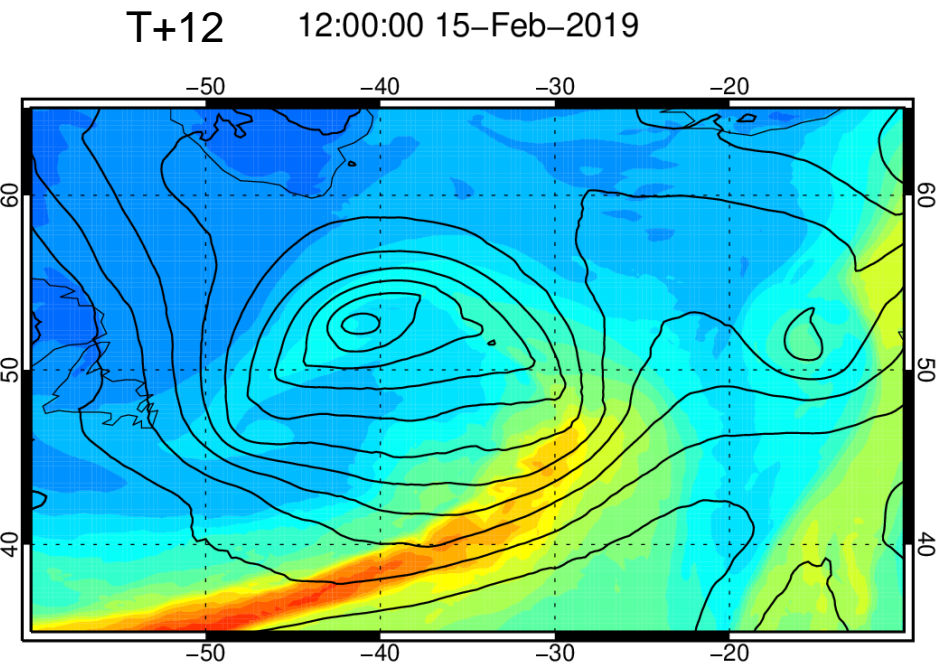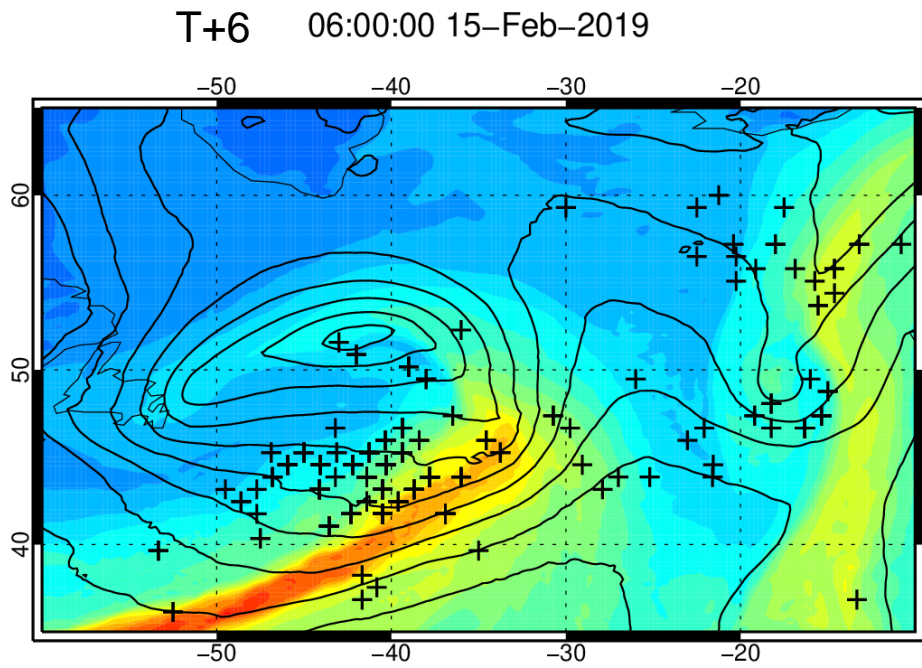**Crosses:** Influential AMSR2 and GMI observations: with FSOI < -5×10^{-5} J/kg
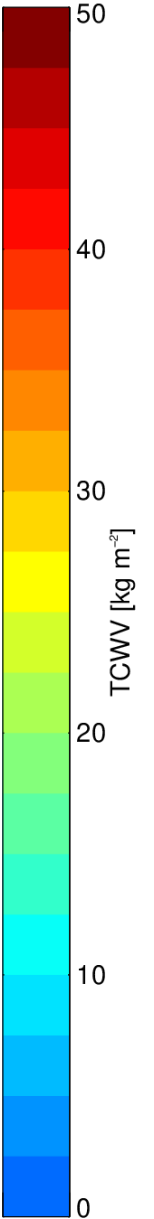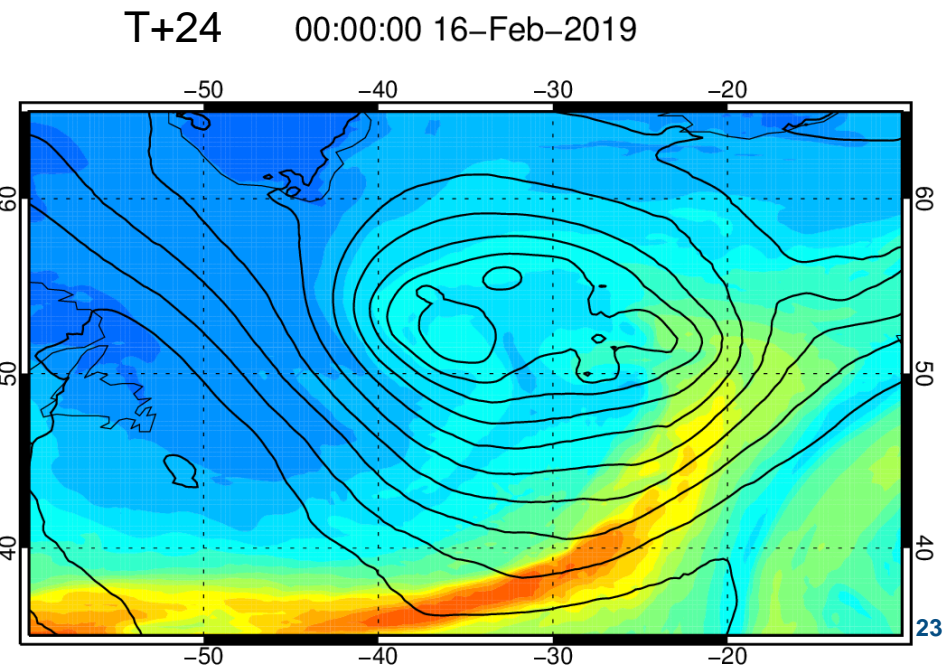
WV (total column) Analysis

Line contours: mean sea level pressure in analysis (5 hPa contour spacing)

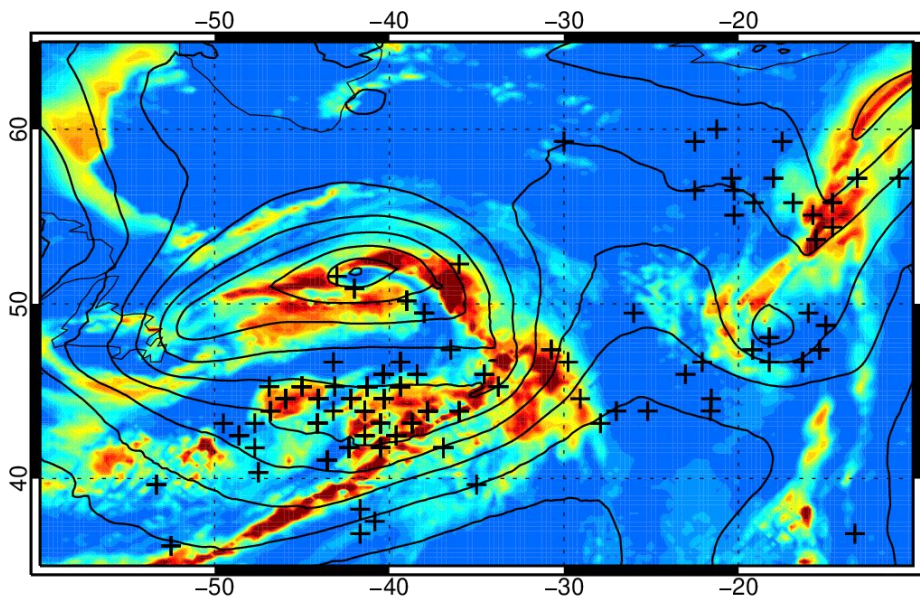**Crosses:** Influential AMSR2 and GMI observations: with FSOI < -5×10^{-5} J/kg
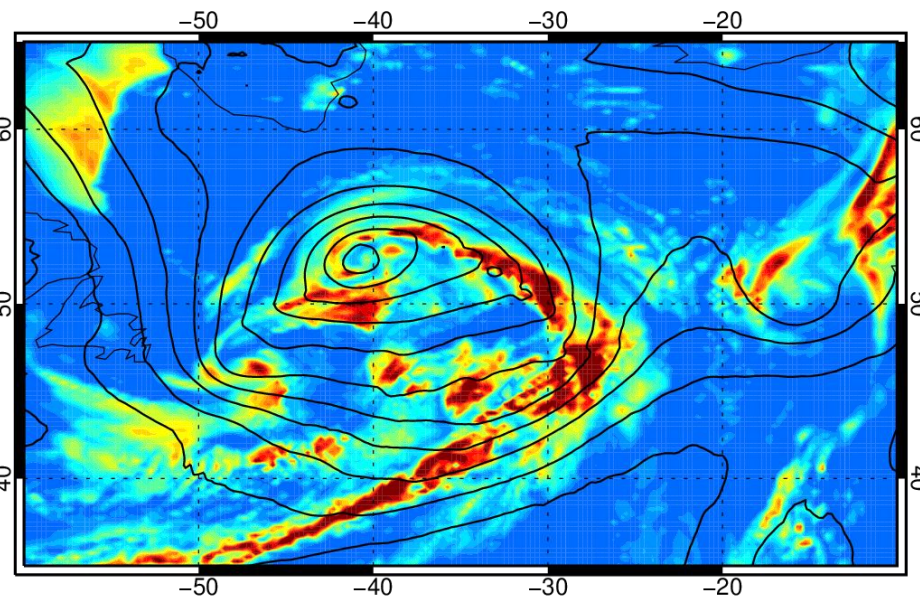
Cloud water (total column) Forecast

Line contours: mean sea level pressure in forecast (5 hPa contour spacing)

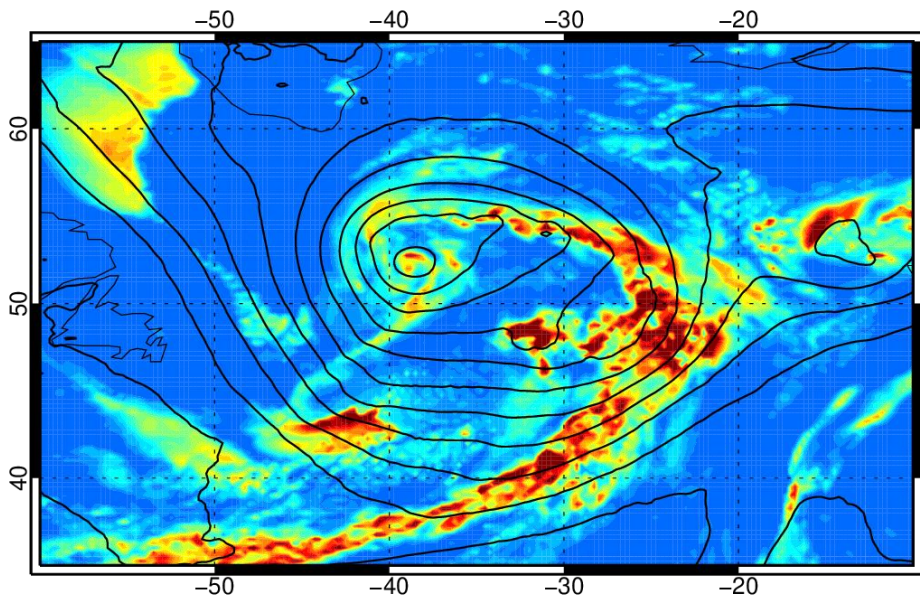**Crosses:** Influential AMSR2 and GMI observations: with FSOI < -5×10^{-5} J/kg
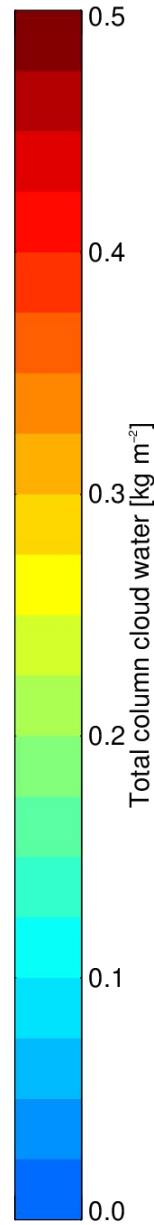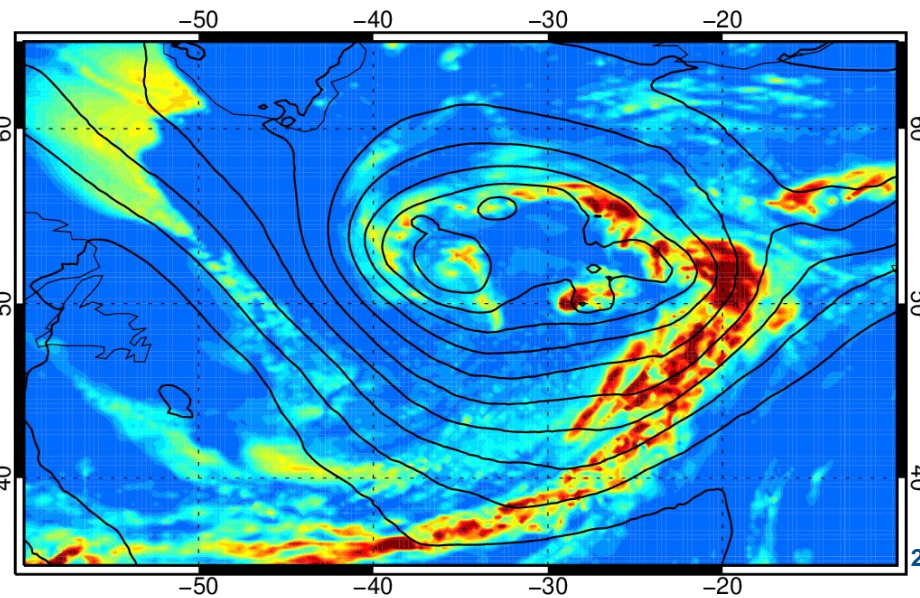

T+6   06:00:00 15–Feb–2019

T+12   12:00:00 15–Feb–2019

T+18   18:00:00 15–Feb–2019

T+24   00:00:00 16–Feb–2019

Total column cloud water [kg m^{-2}]

25

Cloud water (total column) Analysis

Line contours: mean sea level pressure in analysis (5 hPa contour spacing)

Crosses: Influential AMSR2 and GMI observations: with FSOI < -5×10⁻⁵ J/kg

Cloud ice (total column) Forecast

Line contours: mean sea level pressure in forecast (5 hPa contour spacing)

Crosses: Influential AMSR2 and GMI observations: with FSOI < -5×10^{-5} J/kg

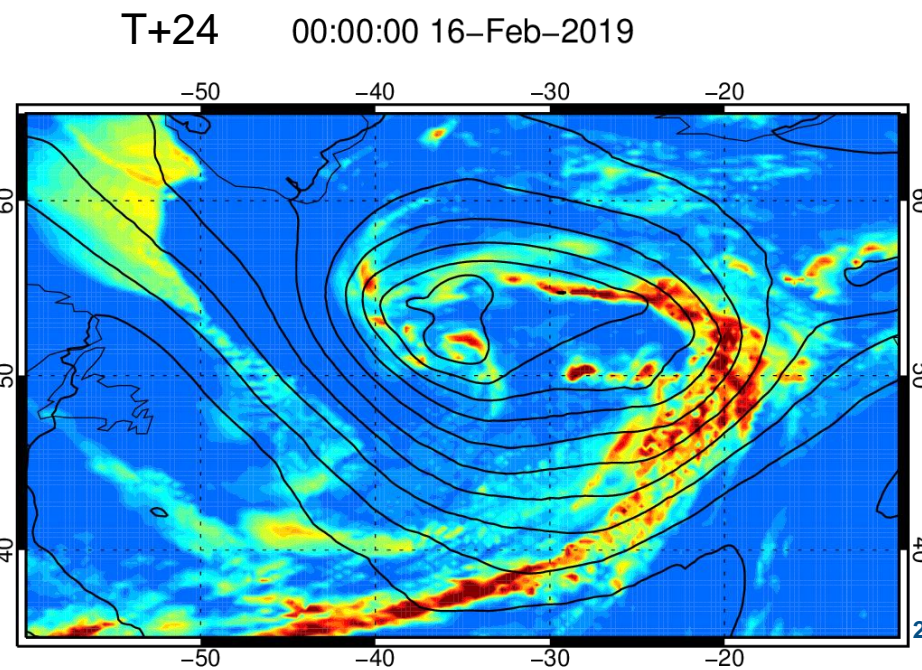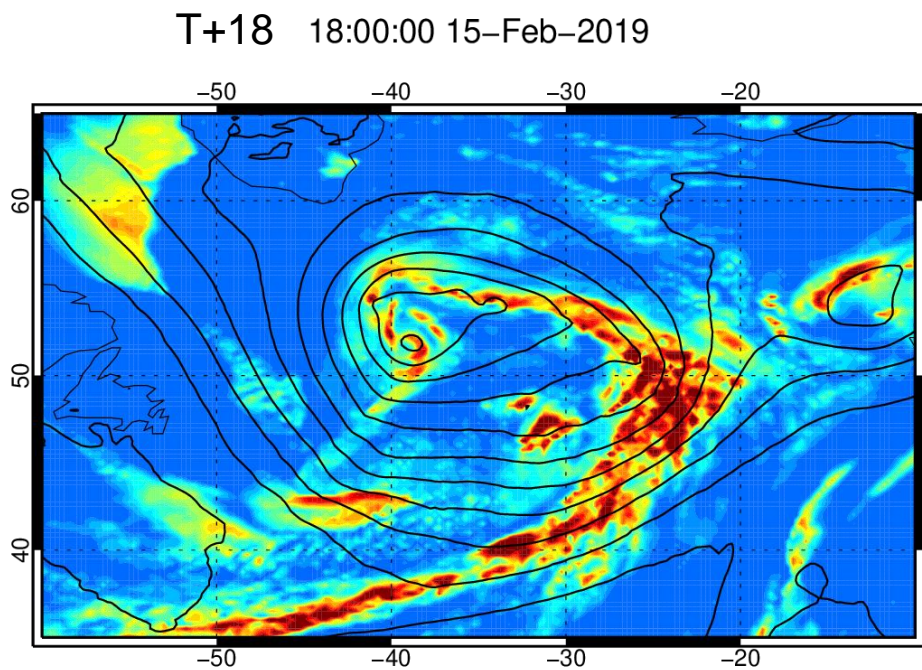T+6   06:00:00 15–Feb–2019

T+12   12:00:00 15–Feb–2019

T+18   18:00:00 15–Feb–2019

T+24   00:00:00 16–Feb–2019

Total column cloud water [kg m^{-2}]
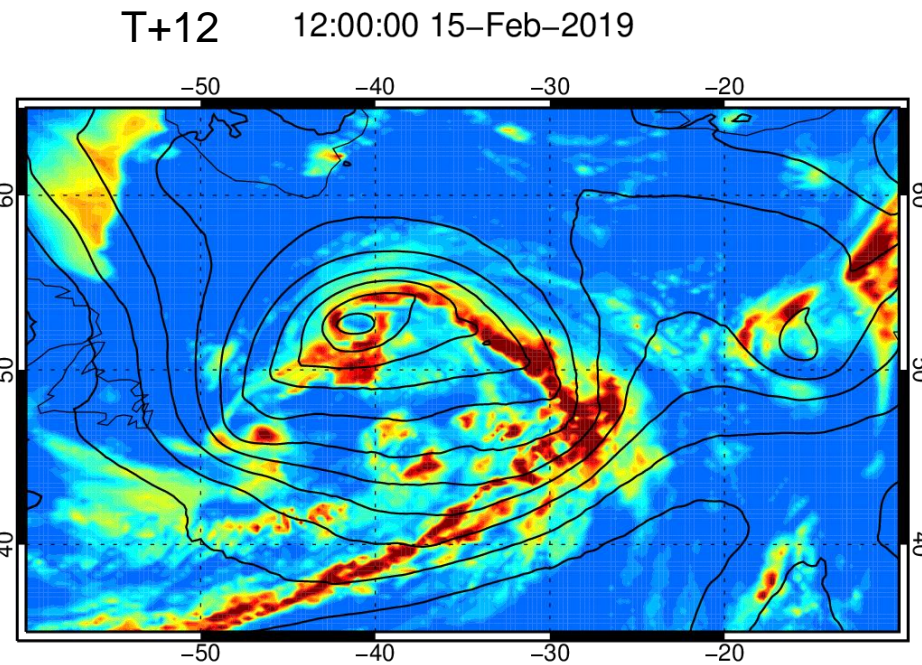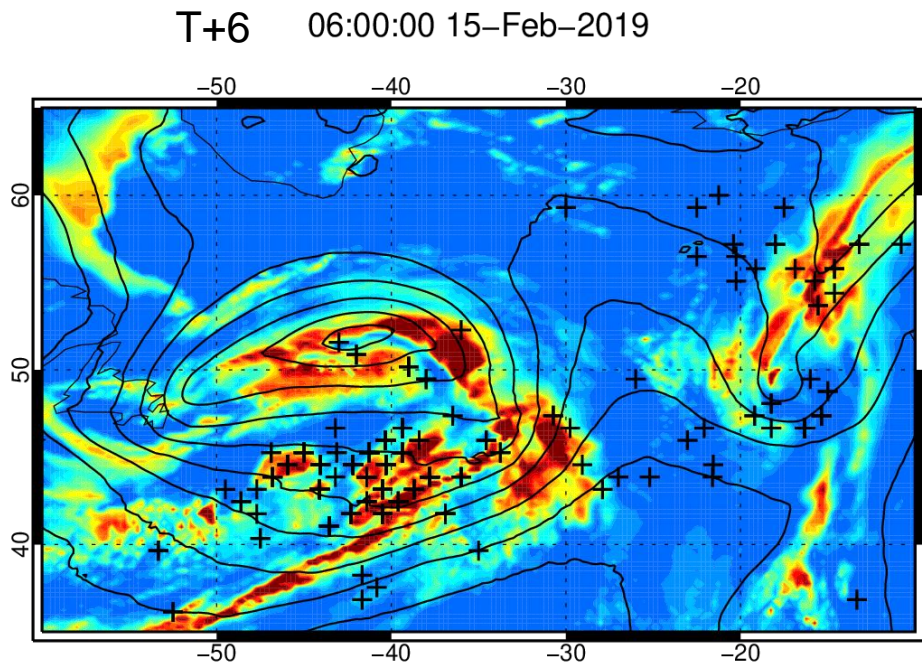
Cloud ice (total column) Analysis

Line contours: mean sea level pressure in analysis (5 hPa contour spacing)

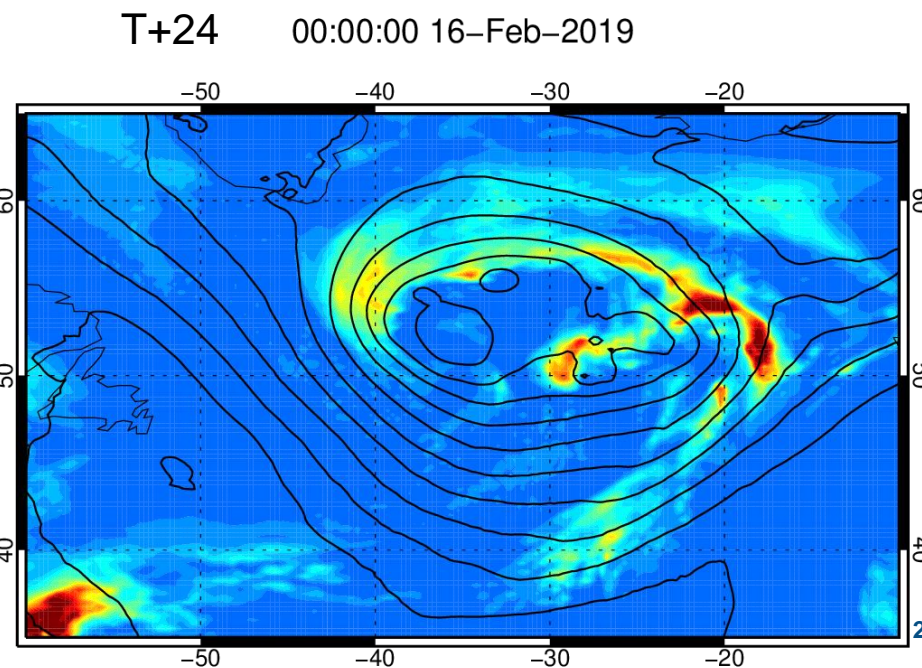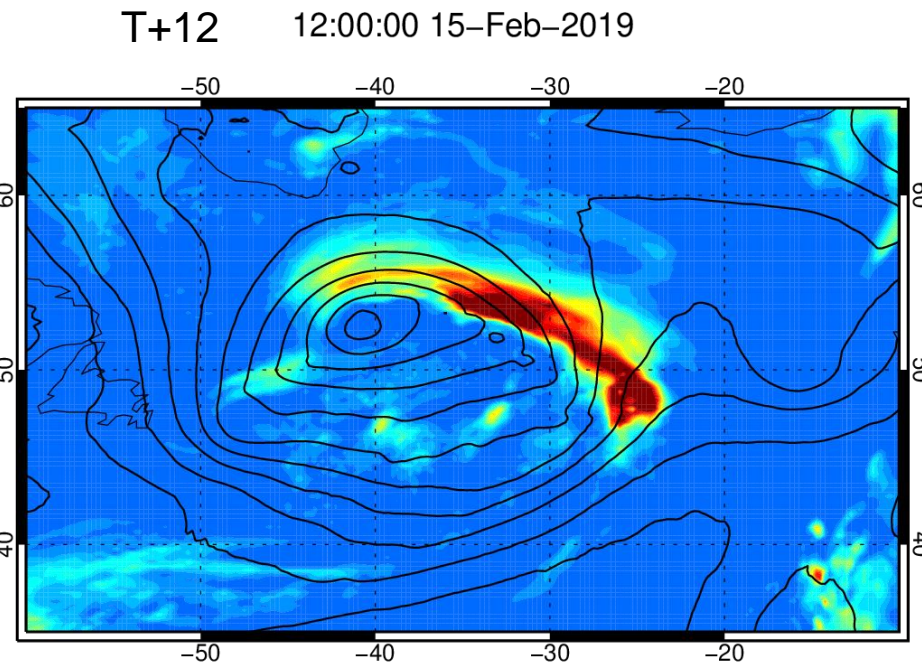**Crosses:** Influential AMSR2 and GMI observations: with FSOI < -5×10^{-5} J/kg

T+6   06:00:00 15–Feb–2019

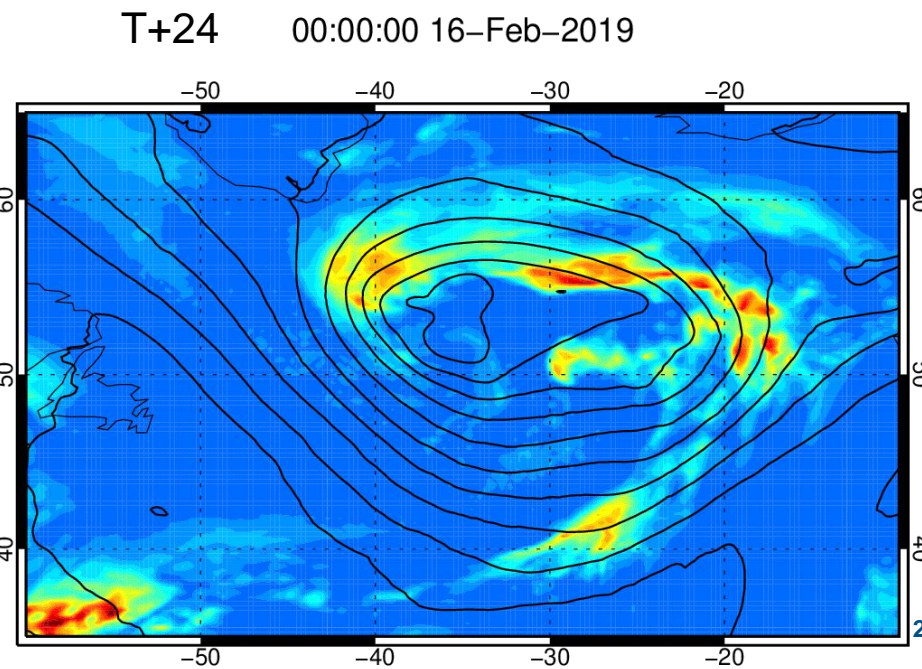T+12   12:00:00 15–Feb–2019

T+18   18:00:00 15–Feb–2019

T+24   00:00:00 16–Feb–2019

Total column cloud water [kg m^{-2}]
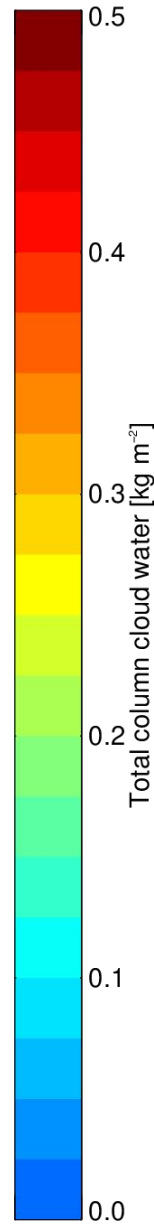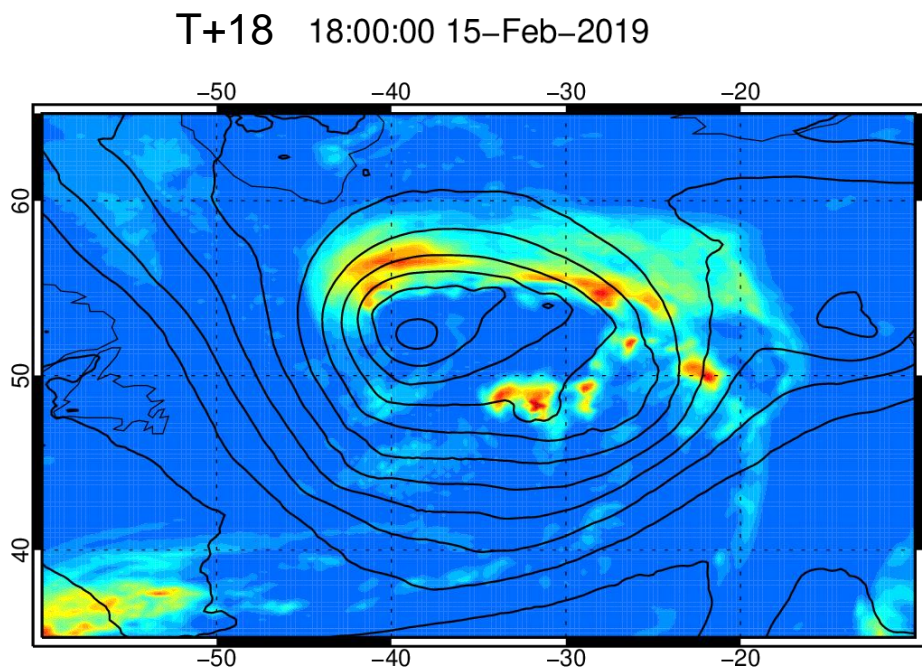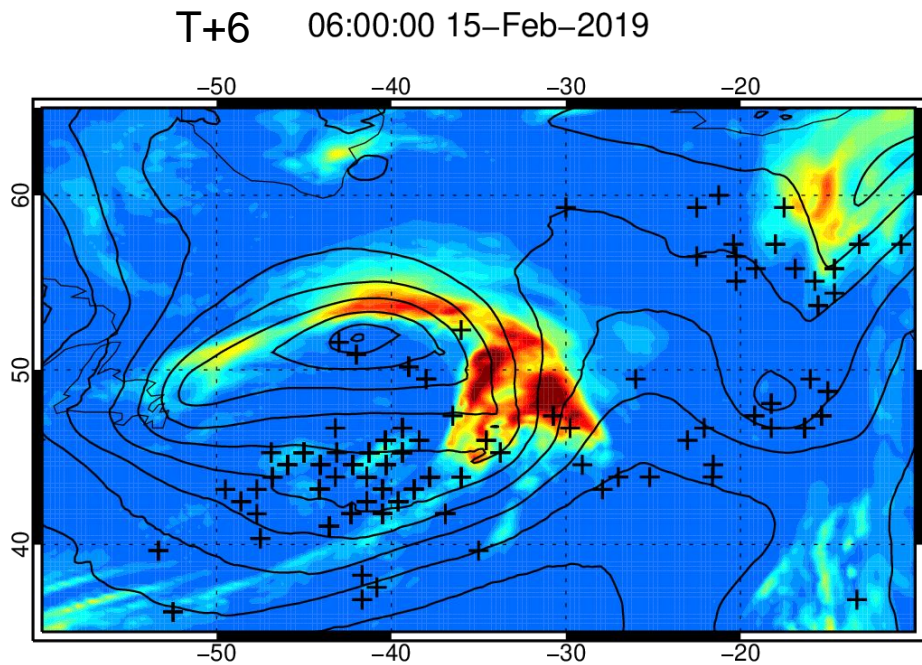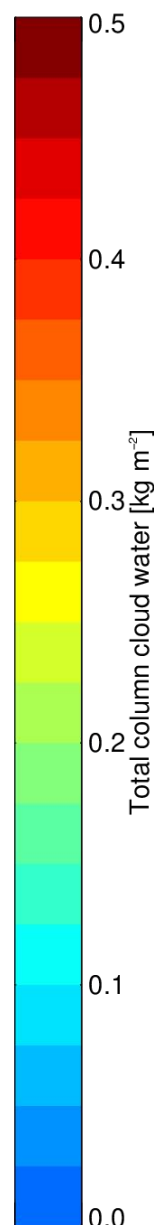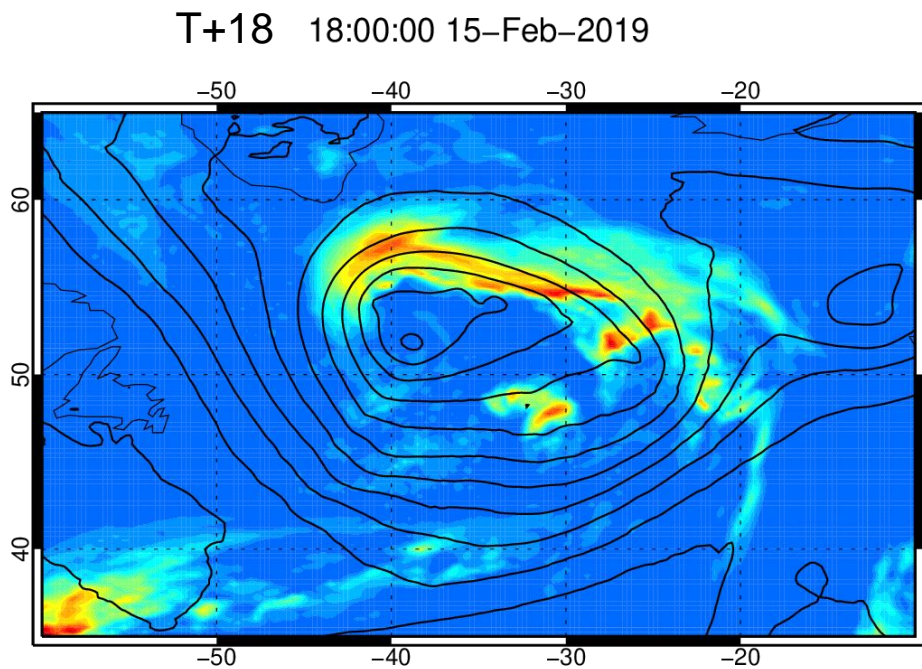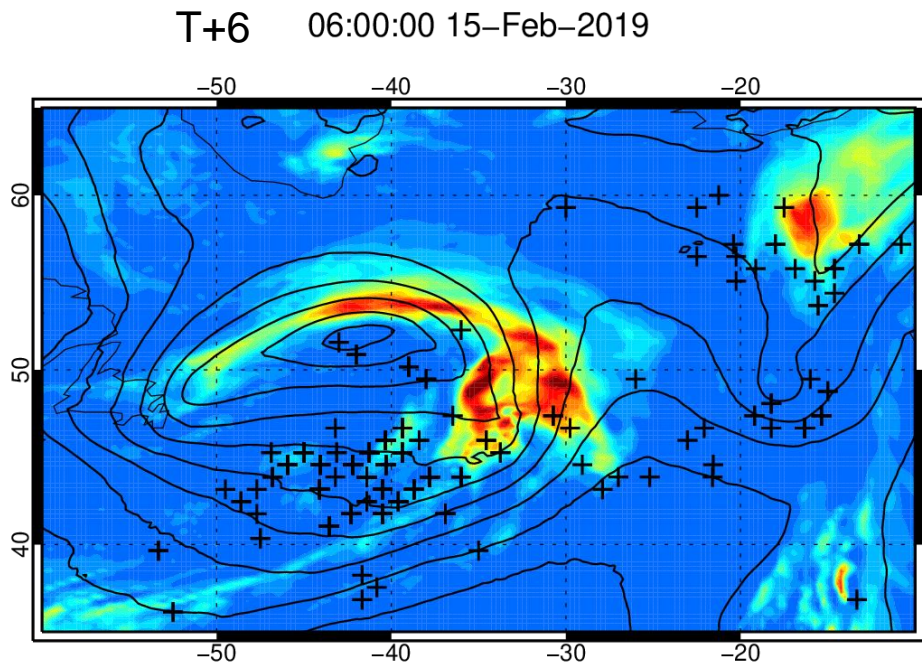
Summary: 15th February

- In 4D-Var assimilation, all variables are interdependent and hard to disentangle, e.g.:
  - Dynamical (e.g surface pressure) observations change cloud amount
  - Cloud and water vapour observations change surface pressure
  - Increments come not just from GMI and AMSR2, but the full global observing system!
- Errors in sub-12h forecasts (judged by the increments):
  - Surface pressure errors are smaller (e.g. 1-2 hPa in a 30hPa deep cyclone = 3-7%)
  - Cloud errors are large (e.g. 0.5 kg/m2 in 0.5 kg/m2 cloud field = 100%)
  - Does this give scope for cloud and precipitation observations to better constrain the forecast?
    - Provisional answer: yes, if the clouds are predictable within the 4D-var window
- FSOI picks up an important correction to a developing instability in the inflow / jet of the cyclone in the 24h forecast:
  - Surface pressure oscillation = (gravity?) wave instability with large errors (e.g. 5 hPa in a 50hPa deep cyclone = 10%)

Other cases

ECMWF

Other cases

2019-2020 winter season: FSOI (global) impact of GMI observations in the Atlantic.

18th September 2019: cyclogenesis

ECMWF

GMI channel 5 (23.8 GHz, v-polarized: "24v")
18th Sep 2019

Observed brightness temperature (TB)

Departure (observation – background)

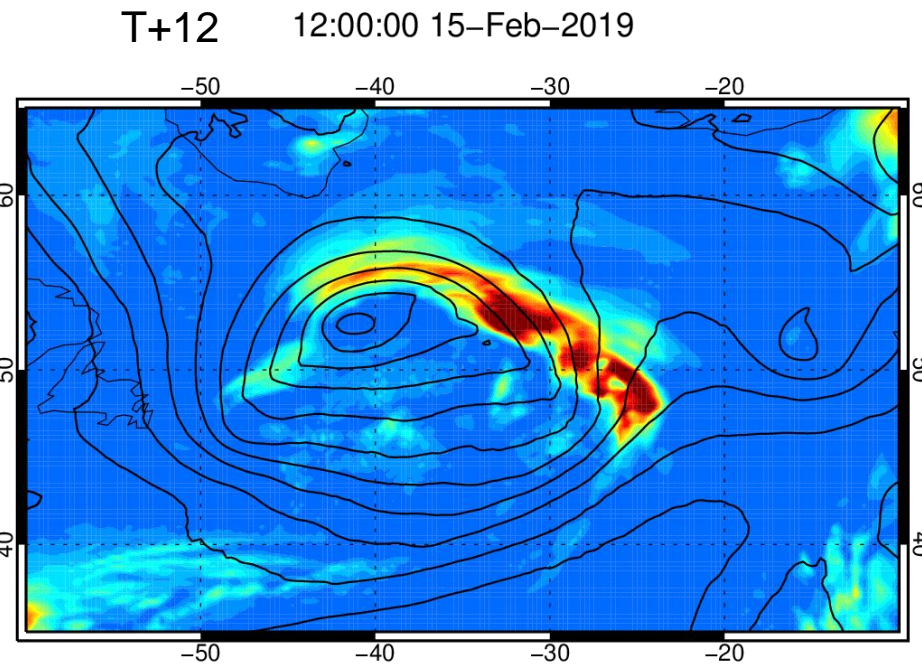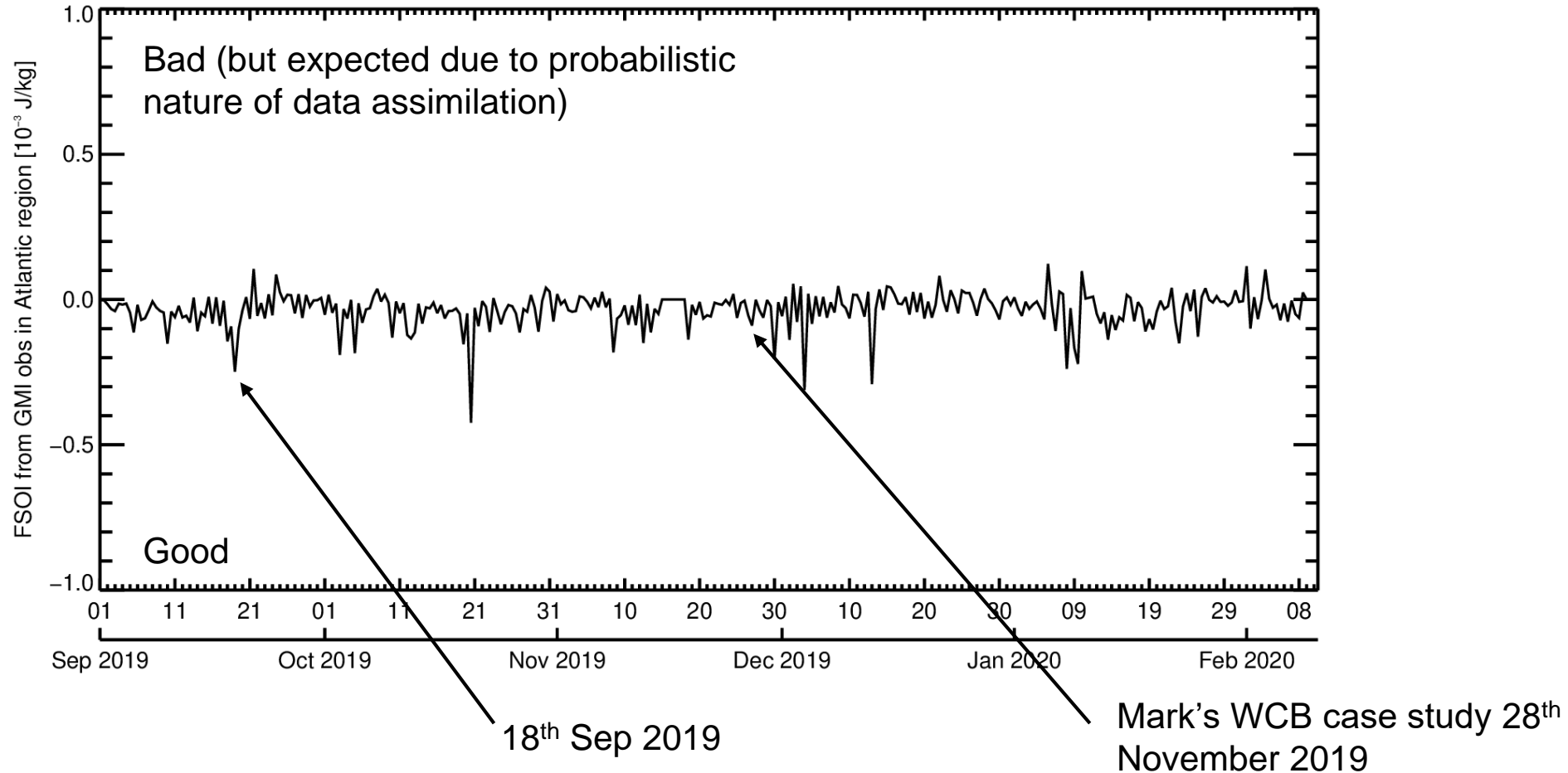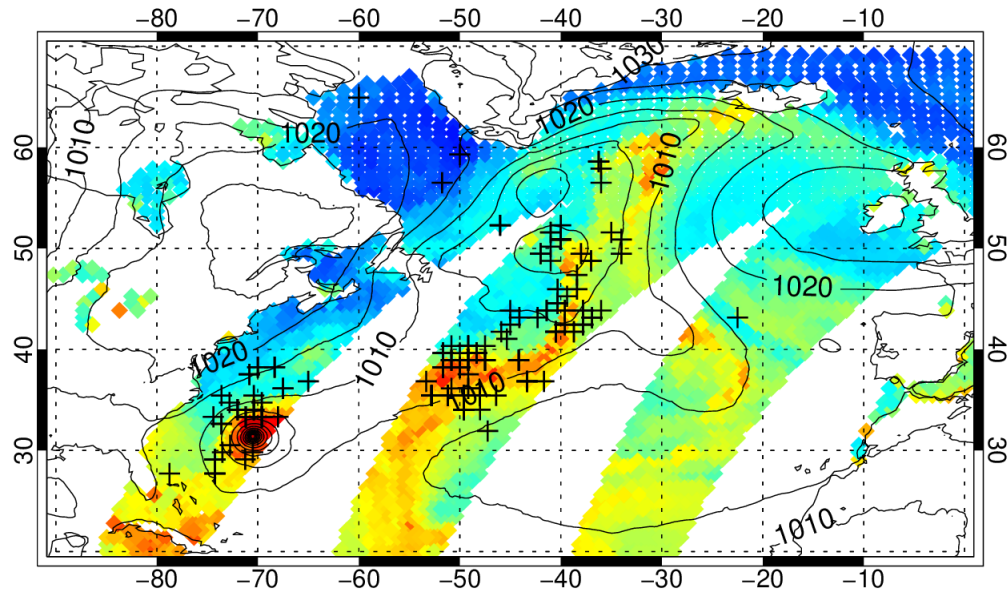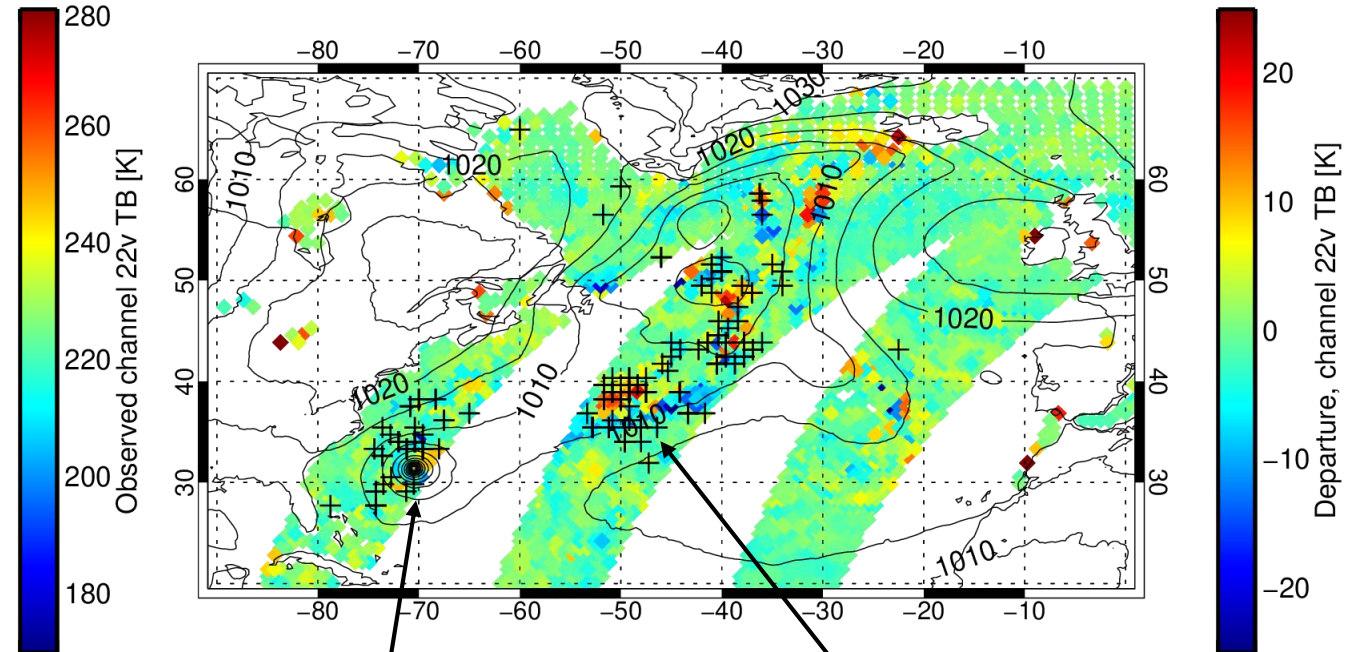**Line contours:** mean sea level pressure in forecast (5 hPa contour spacing)

Crosses: Influential GMI observations: with FSOI < -5×10⁻⁵ J/kg
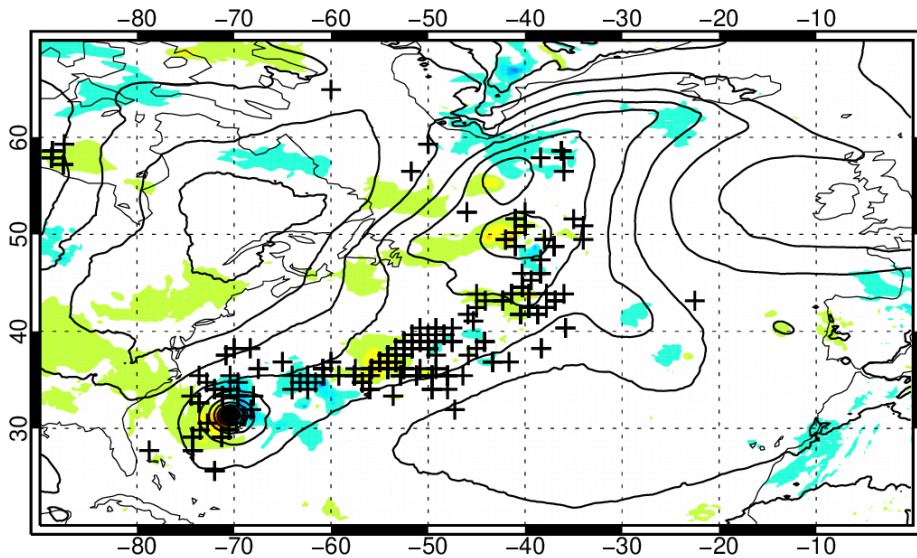
Hurricane Humberto approaching Bermuda

Cylogenesis (our focus)
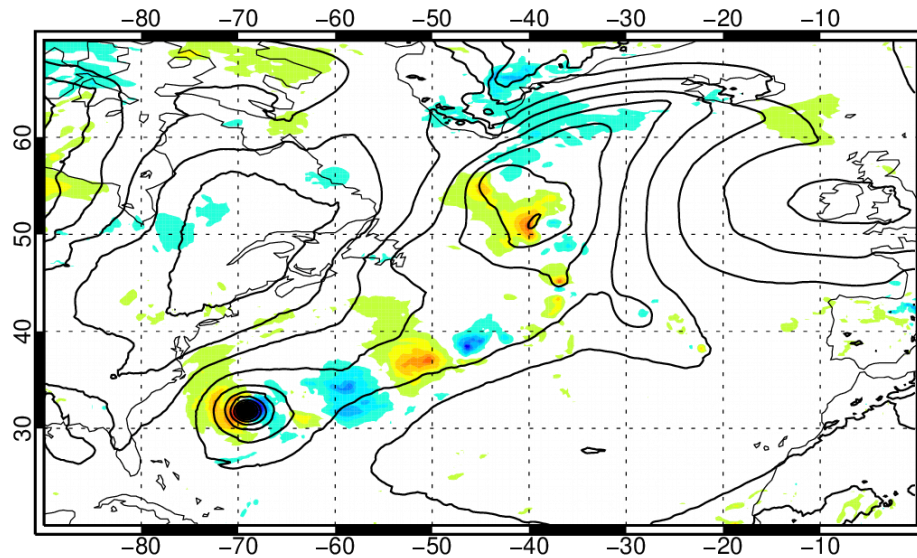
Surface pressure (at mean sea-level) increment

Line contours: mean sea level pressure in forecast (5 hPa contour spacing)

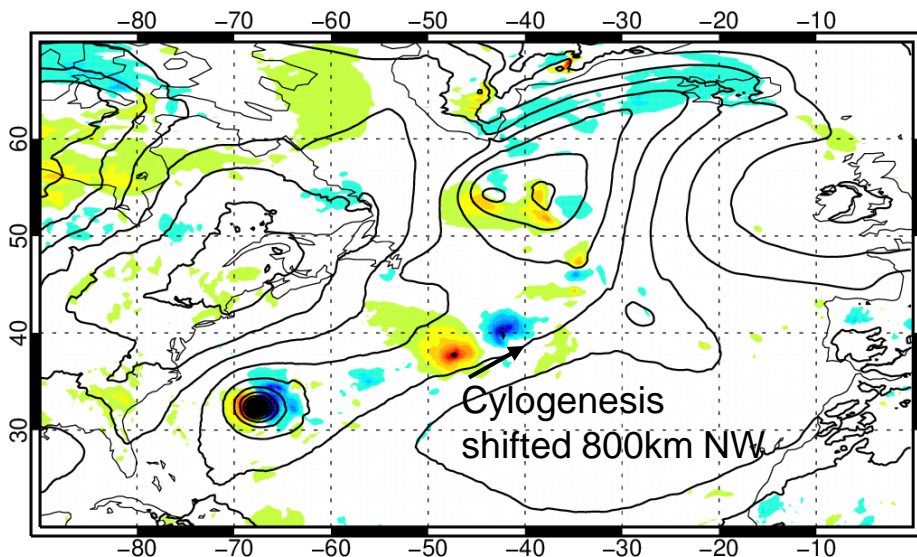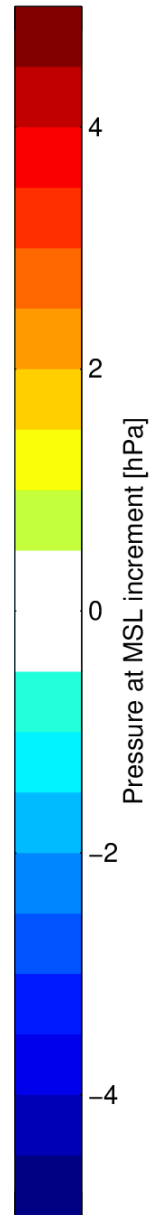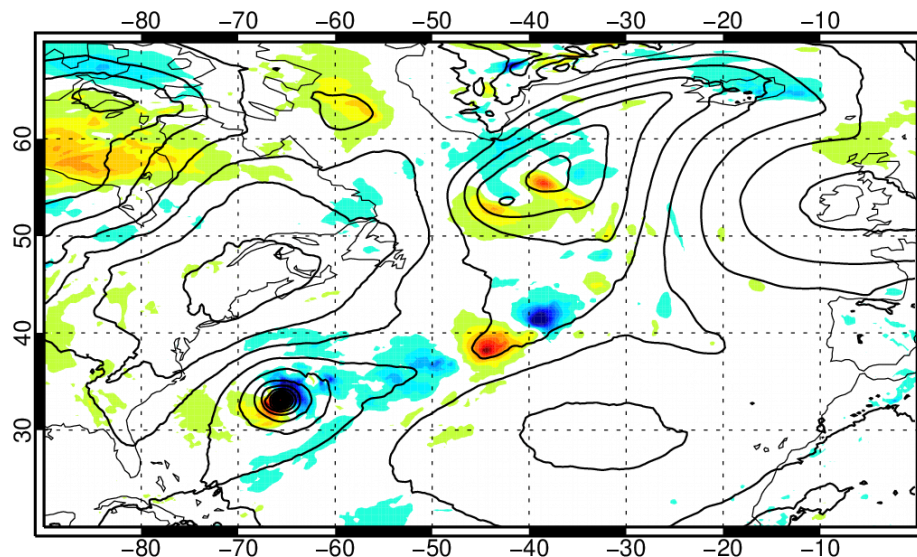**Crosses:** Influential AMSR2 and GMI observations: with FSOI < -5×10^{-5} J/kg

T+6   06:00:00 18–Sep–2019

T+12   12:00:00 18–Sep–2019

T+18   18:00:00 18–Sep–2019

T+24   00:00:00 19–Sep–2019

Cylogenesis shifted 800km NW
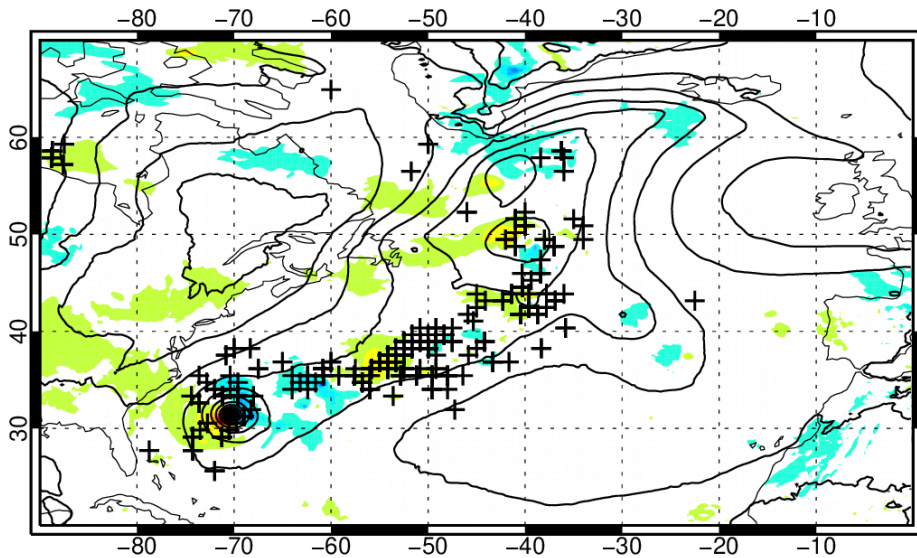
Pressure at MSL increment [hPa]

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Surface pressure (at mean sea-level) increment

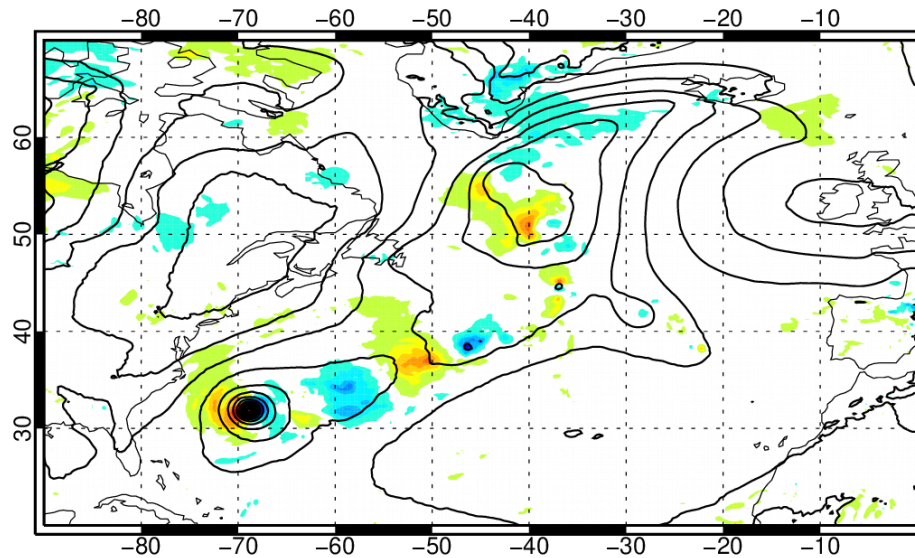**Line contours:** mean sea level pressure in analysis (5 hPa contour spacing)

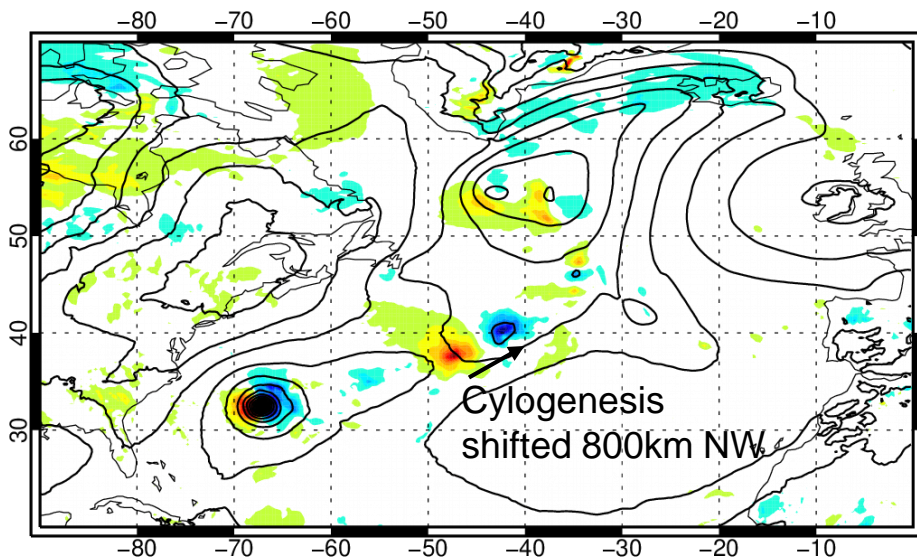**Crosses:** Influential AMSR2 and GMI observations: with FSOI < -5×10⁻⁵ J/kg

T+6   06:00:00 18–Sep–2019

T+12   12:00:00 18–Sep–2019

T+18   18:00:00 18–Sep–2019

Cylogenesis shifted 800km NW

T+24   00:00:00 19–Sep–2019

Pressure at MSL increment [hPa]

Surface pressure (at mean sea-level) increment

Line contours: mean sea level pressure in forecast (5 hPa contour spacing)

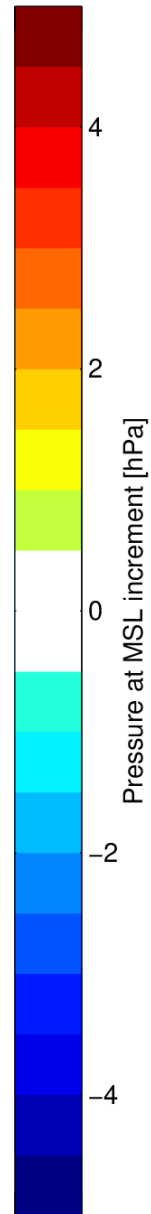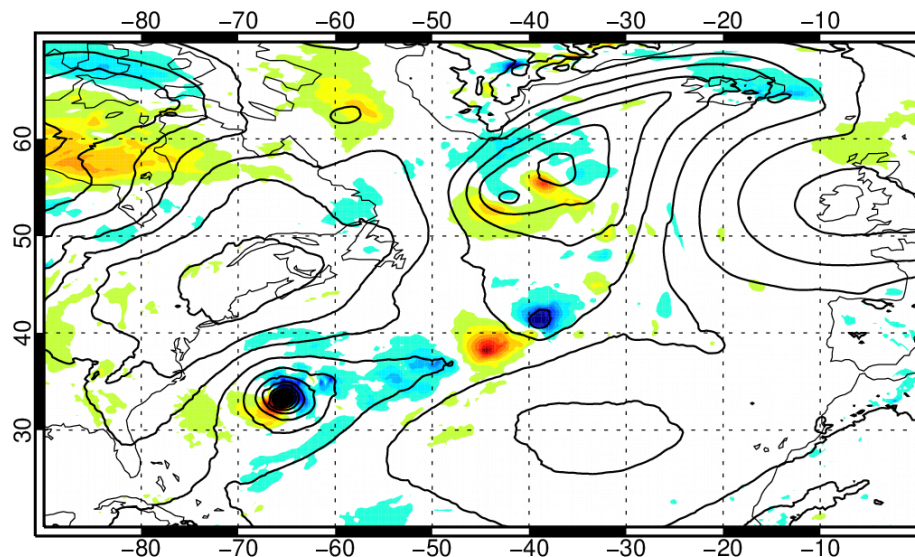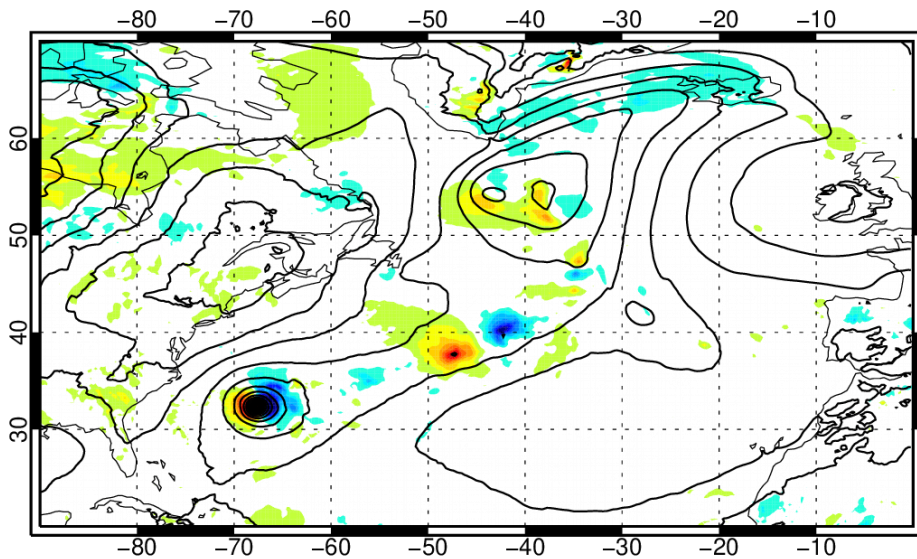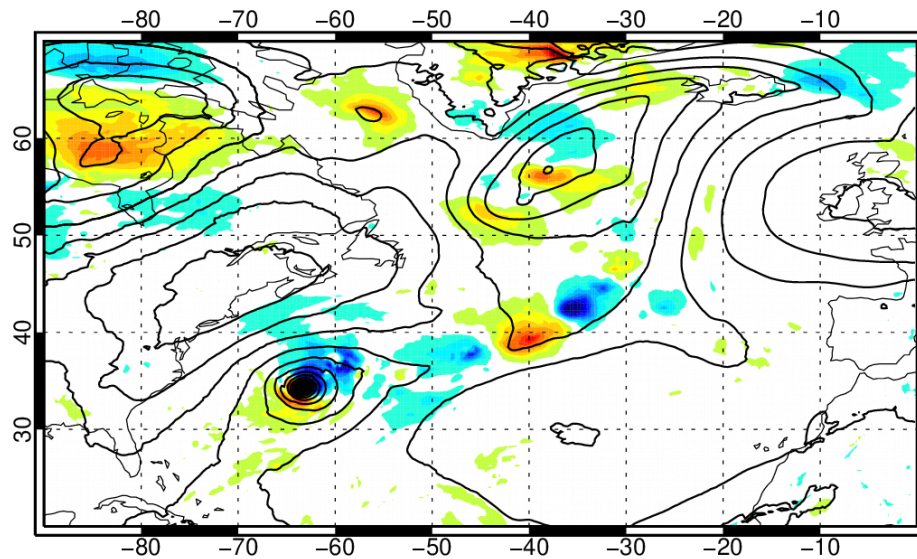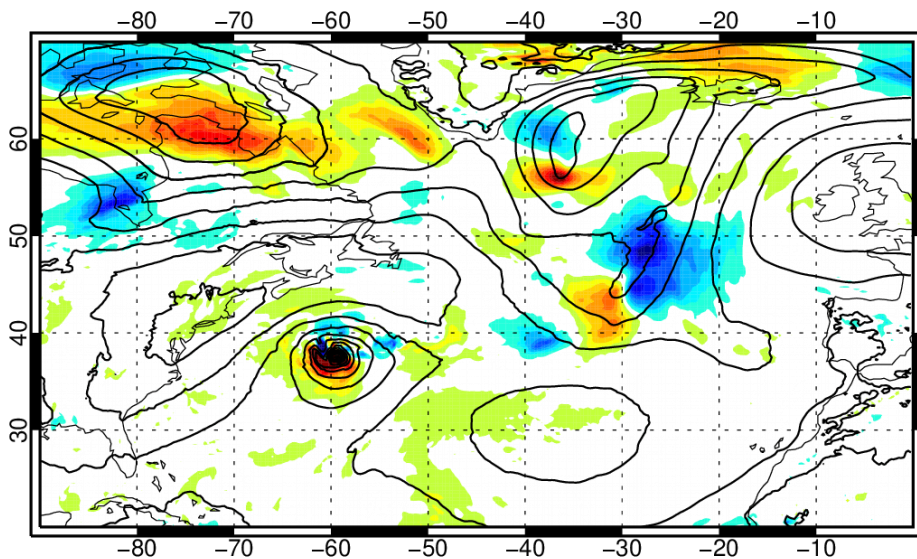**Crosses:** Influential AMSR2 and GMI observations: with FSOI < -5×10^{-5} J/kg

T+18   18:00:00 18–Sep–2019

T+30   06:00:00 19–Sep–2019

T+42   18:00:00 19–Sep–2019

T+54   06:00:00 20–Sep–2019

Pressure at MSL increment [hPa]

Surface pressure (at mean sea-level) increment

Line contours: mean sea level pressure in analysis (5 hPa contour spacing)

Crosses: Influential AMSR2 and GMI observations: with FSOI < -5×10^{-5} J/kg

T+18   18:00:00 18–Sep–2019

T+30   06:00:00 19–Sep–2019

T+42   18:00:00 19–Sep–2019

T+54   06:00:00 20–Sep–2019

Pressure at MSL increment [hPa]

37

28th November 2019: warm conveyor belt

Surface pressure (at mean sea-level) increment

Line contours: mean sea level pressure in forecast (5 hPa contour spacing)

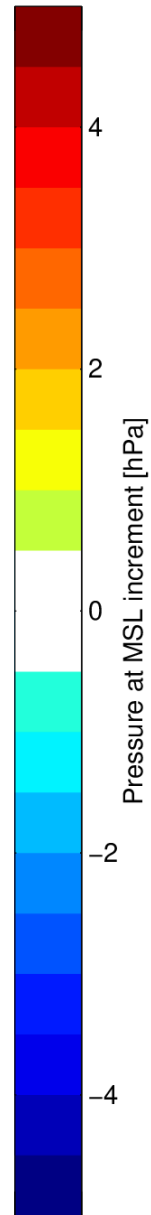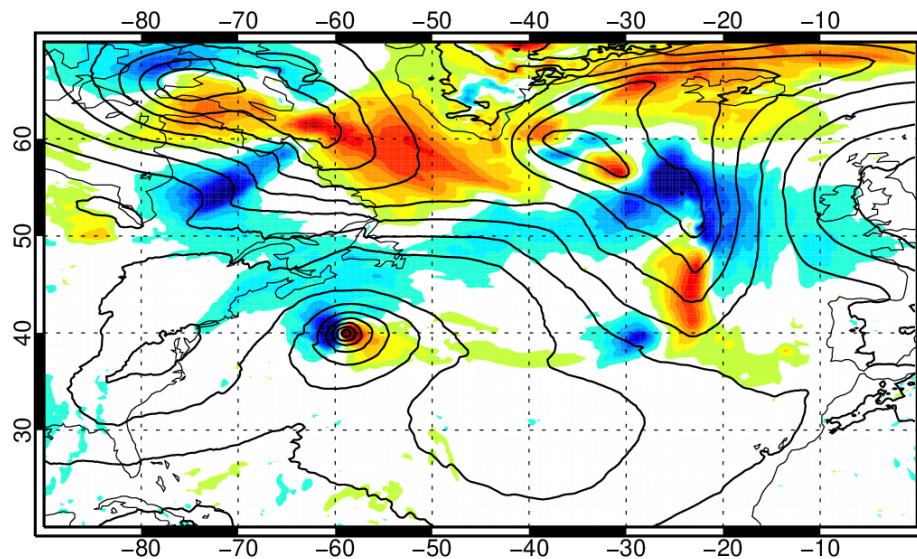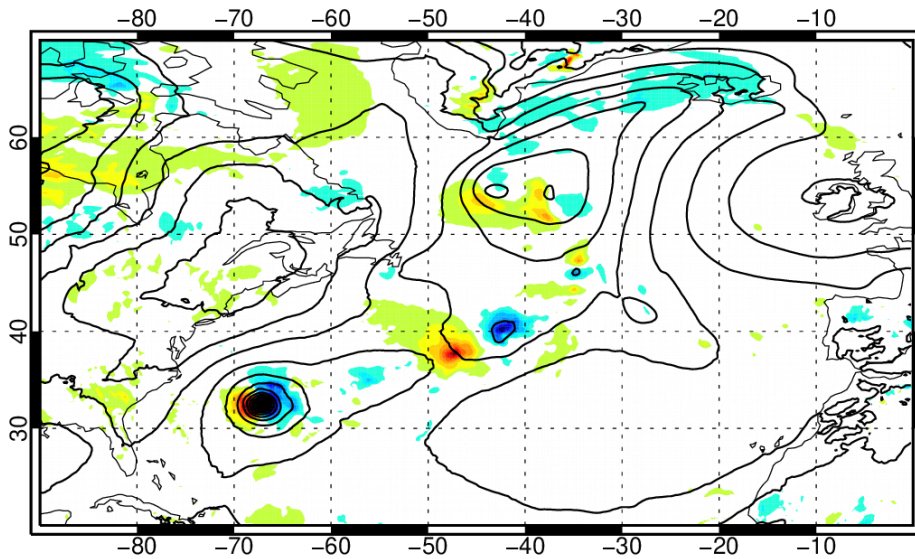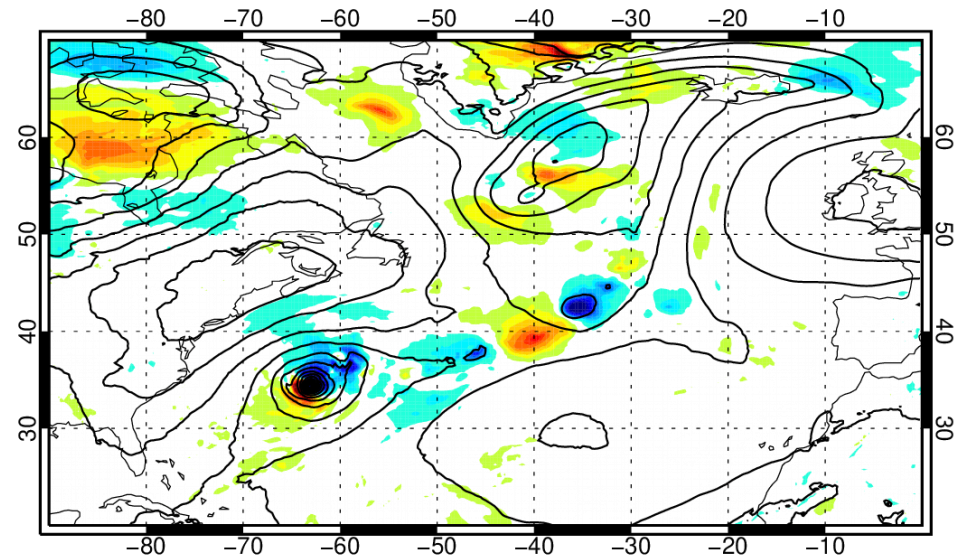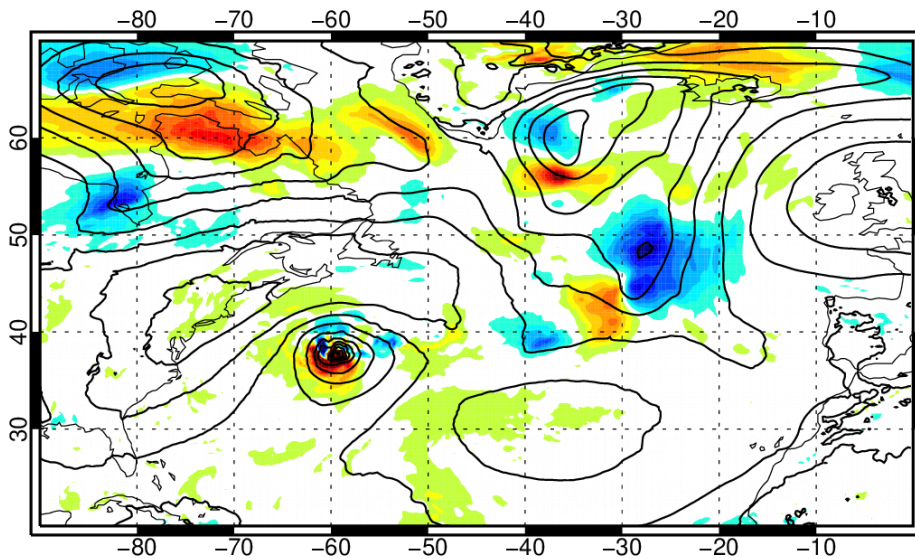**Crosses:** Influential AMSR2 and GMI observations: with FSOI < -5×10^{-5} J/kg

T+6   18:00:00 28–Nov–2019

T+12   00:00:00 29–Nov–2019

T+18   06:00:00 29–Nov–2019

T+24   12:00:00 29–Nov–2019

TCWV [kg m^{-2}]

Line contours: mean sea level pressure in forecast (5 hPa contour spacing)

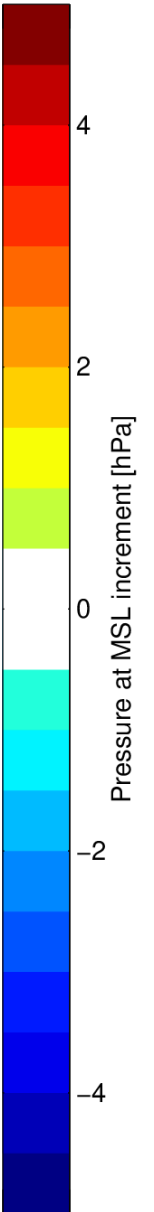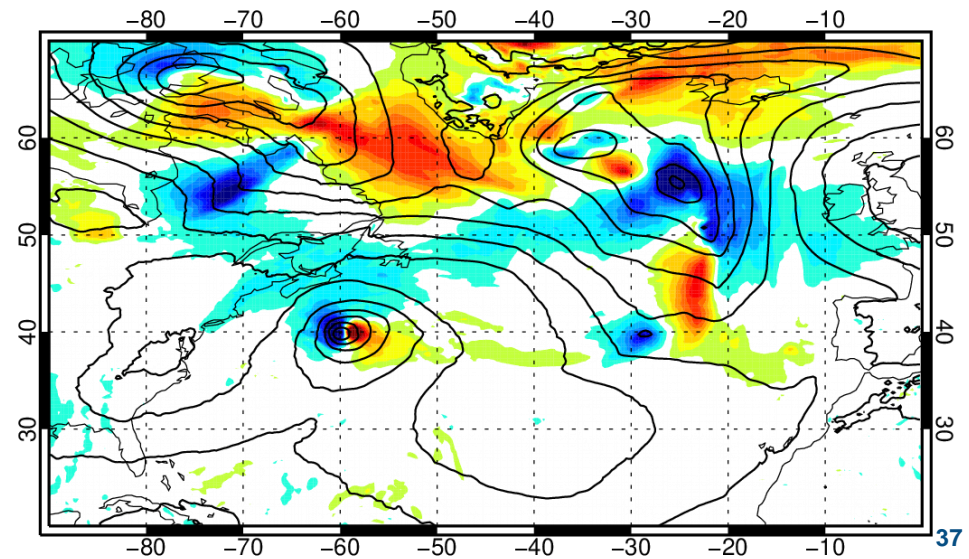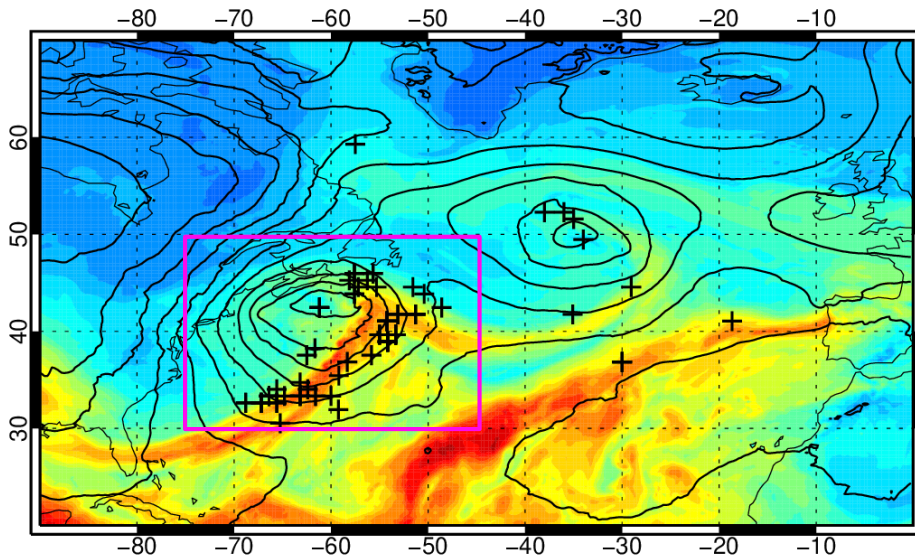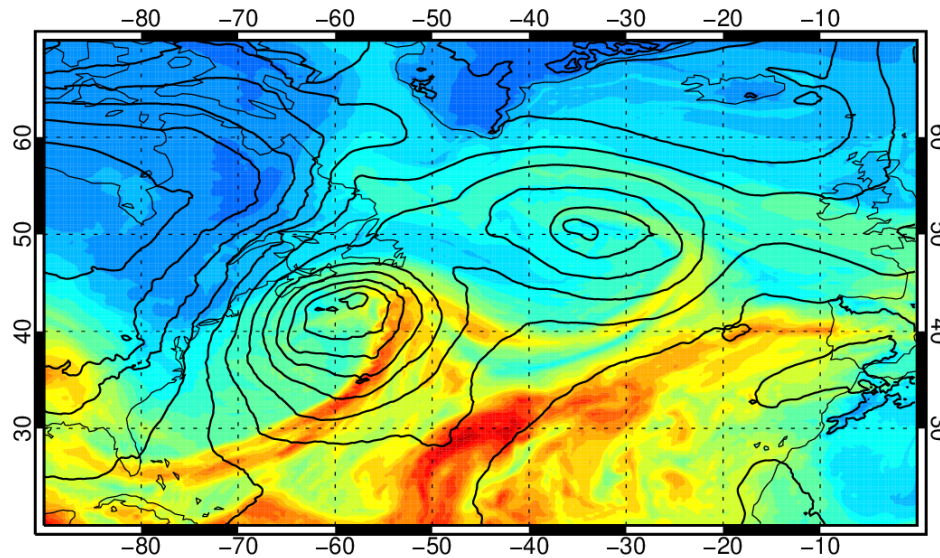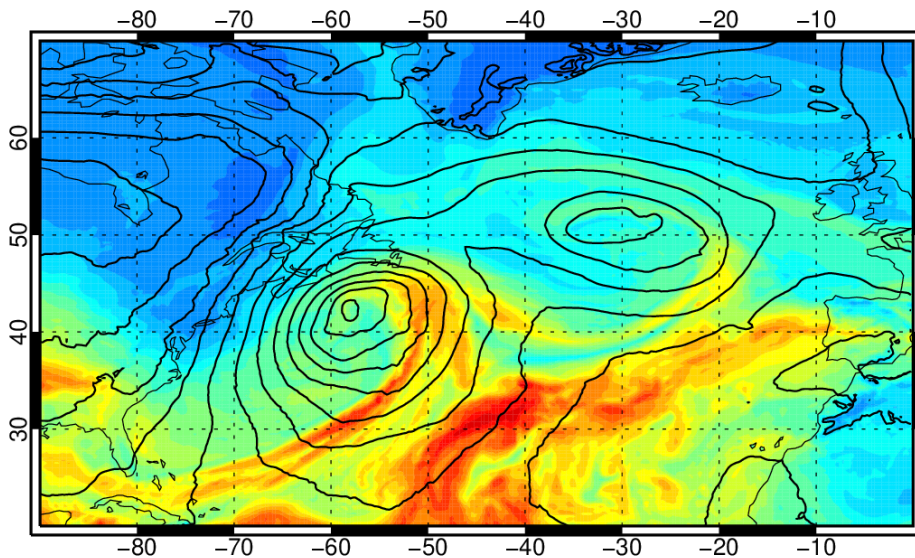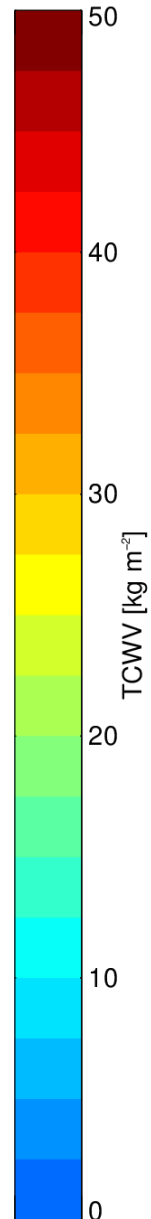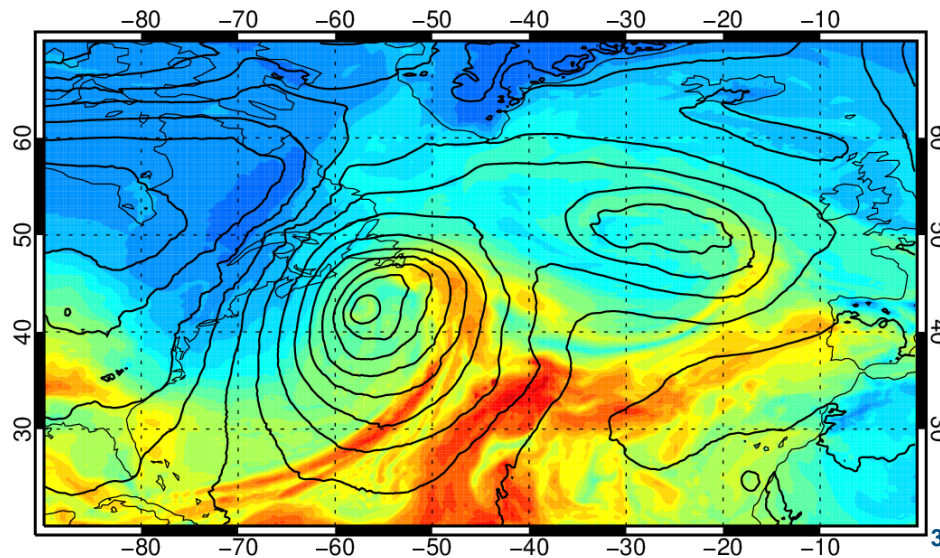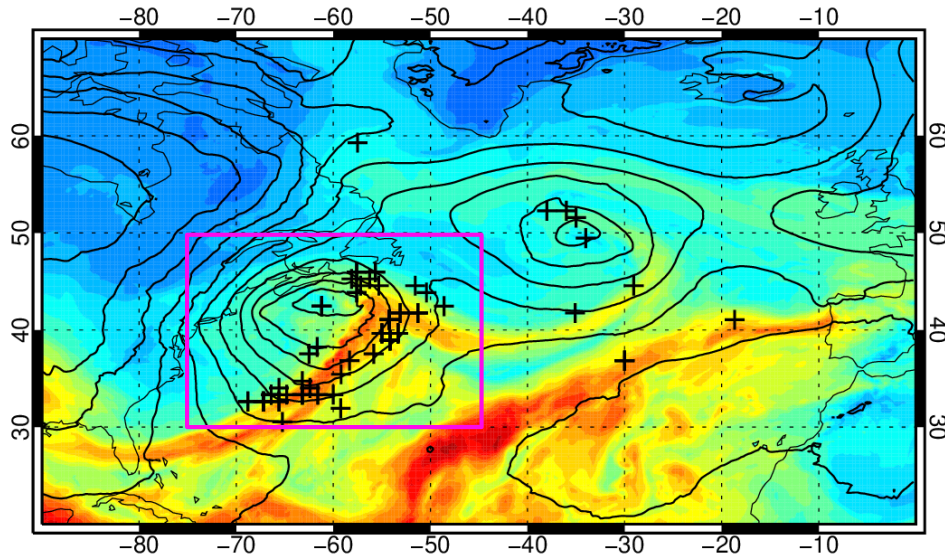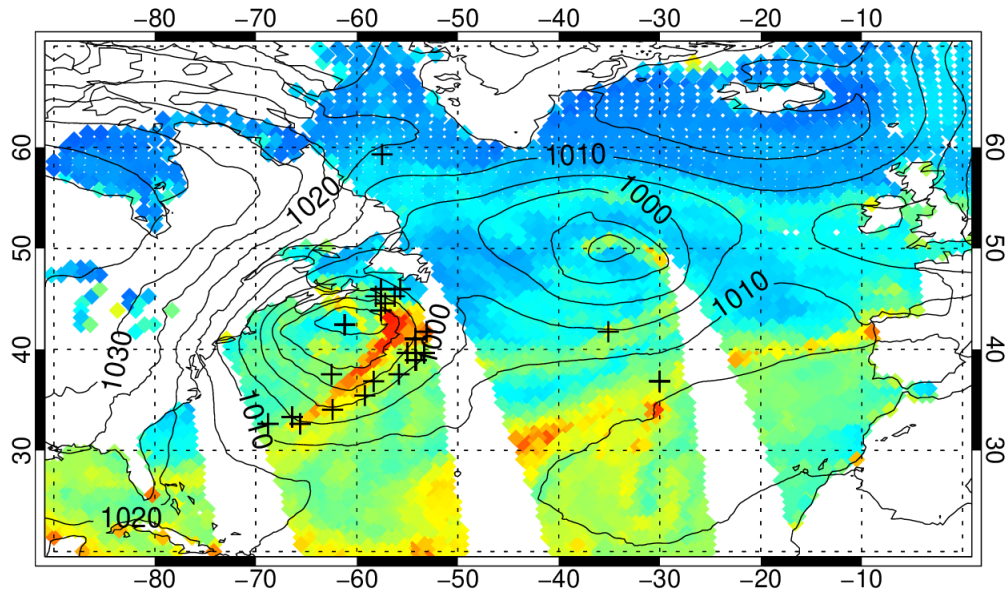**Crosses:** Influential AMSR2 and GMI observations: with FSOI < -5×10^{-5} J/kg

All on average very good data (7% of global FSOI) but not in this area on this day (Random error? Model systematic error?)

Sensor impact (% of total FSOI) in pink box

Sensor	%
Automatic SHIP	+56.1
GOES 16 AMV	+50.3
GCOM-W1 AMSR-2 Radiances All-sky	+43.2
NPP ATMS Radiances	+32.0
NPP CRIS Radiances	+21.2
65 other sensor types	+44.7
DMSP 18 SSMIS Radiances All-sky	-14.0
FY-3B MWHS Radiances	-16.1
MHS NOAA 19 MHS Radiances All-sky	-22.8
DMSP 17 SSMIS Radiances All-sky	-31.9
BUFR DRIFTING BUOYS	-62.9

AMSR2 channel 9 (23.8 GHz, v-polarized: "24v")
~16:00 UTC 28th November 2019

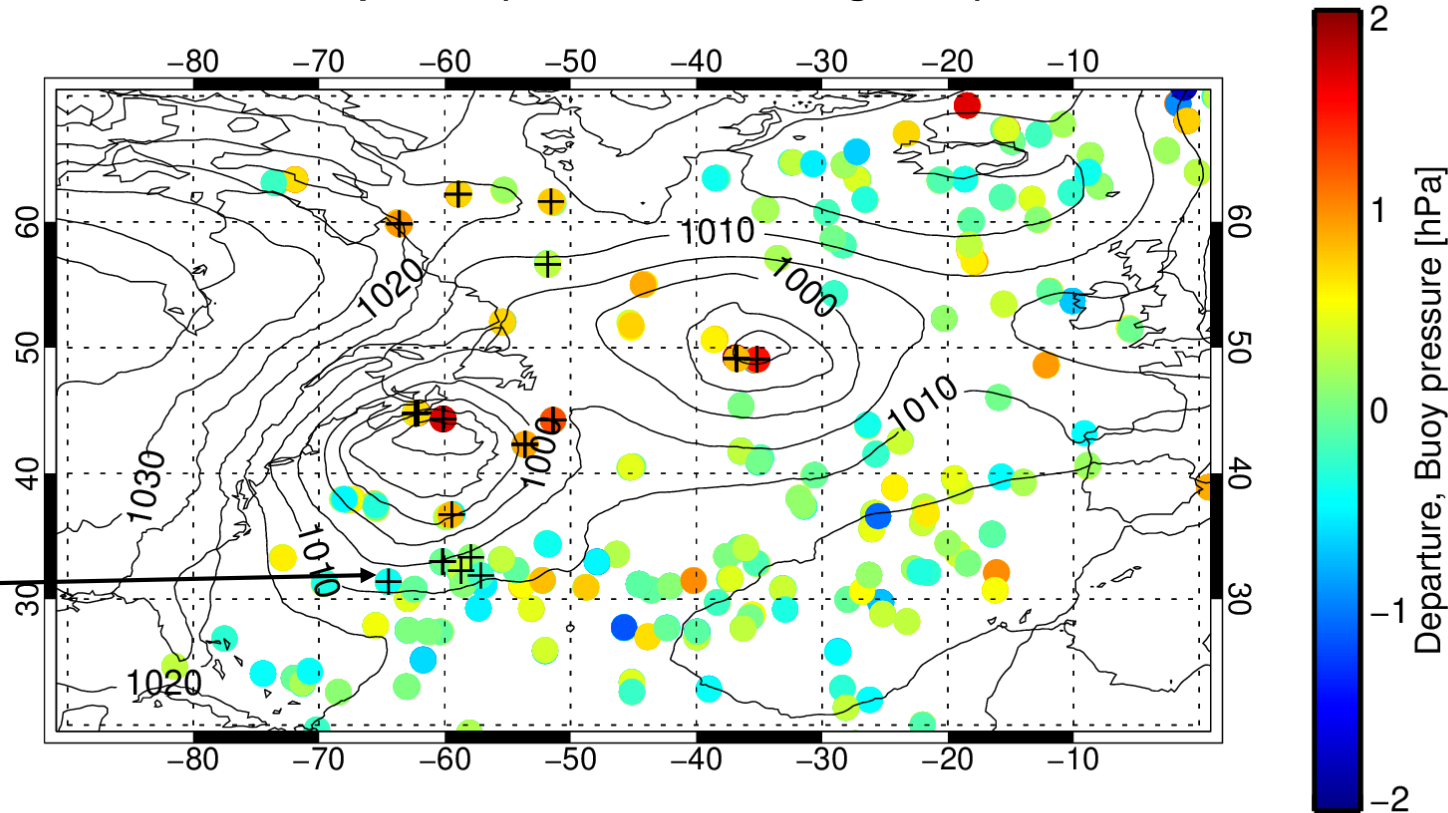**Observed brightness temperature (TB)**
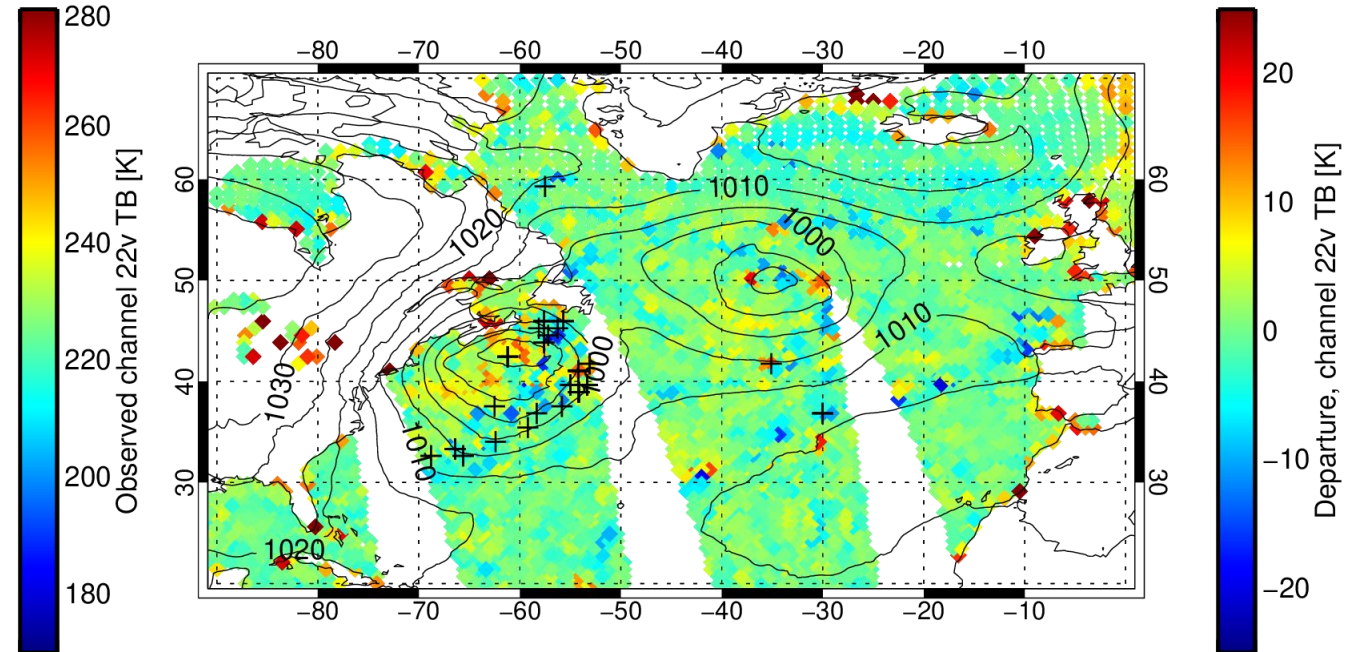
Departure (observation – background)

Line contours:
mean sea level pressure in forecast (5 hPa contour spacing)

Crosses:
Influential AMSR2 observations: with FSOI < -5×10⁻⁵ J/kg

BUFR drifting buoy
09 – 21 UTC 28th November 2019

Departure (observation – background)

Observations that seem to oppose the beneficial forecast correction. Multiple hourly buoy observations overlaid.
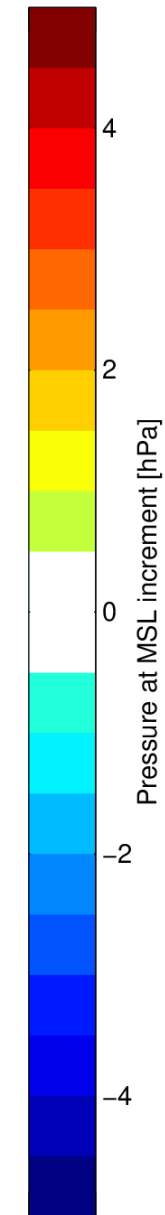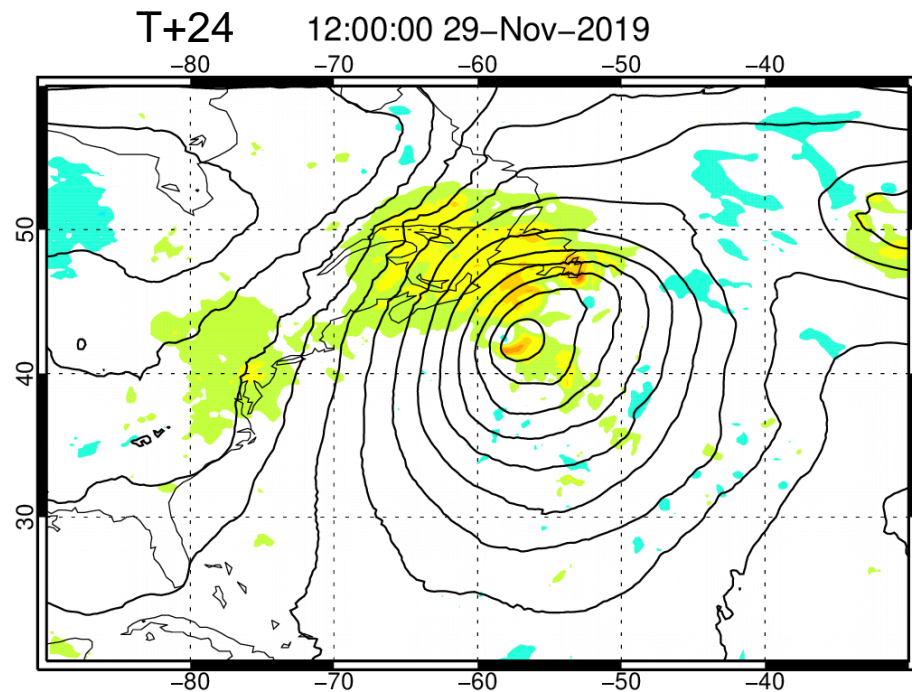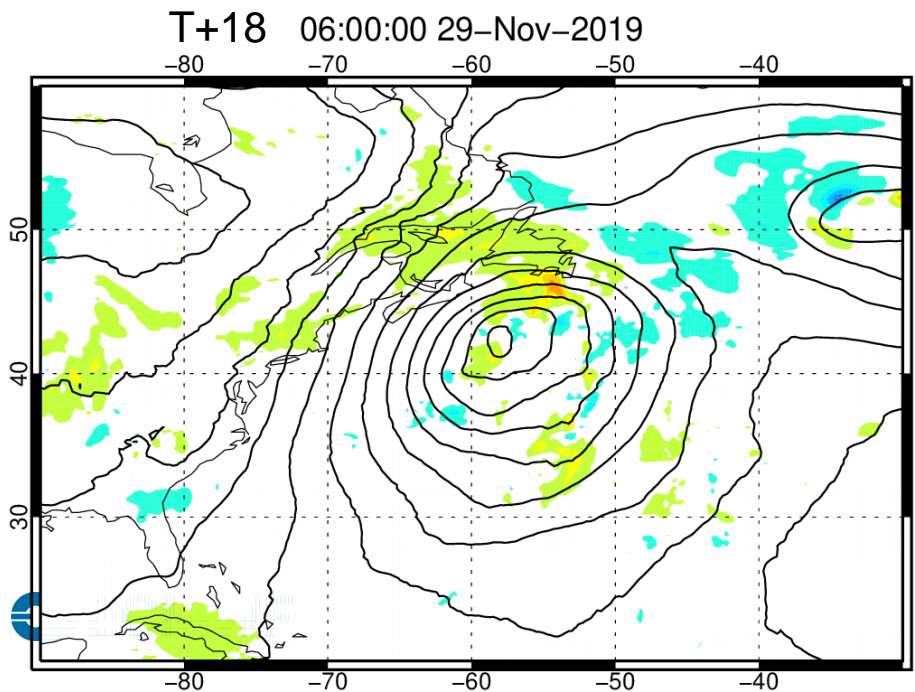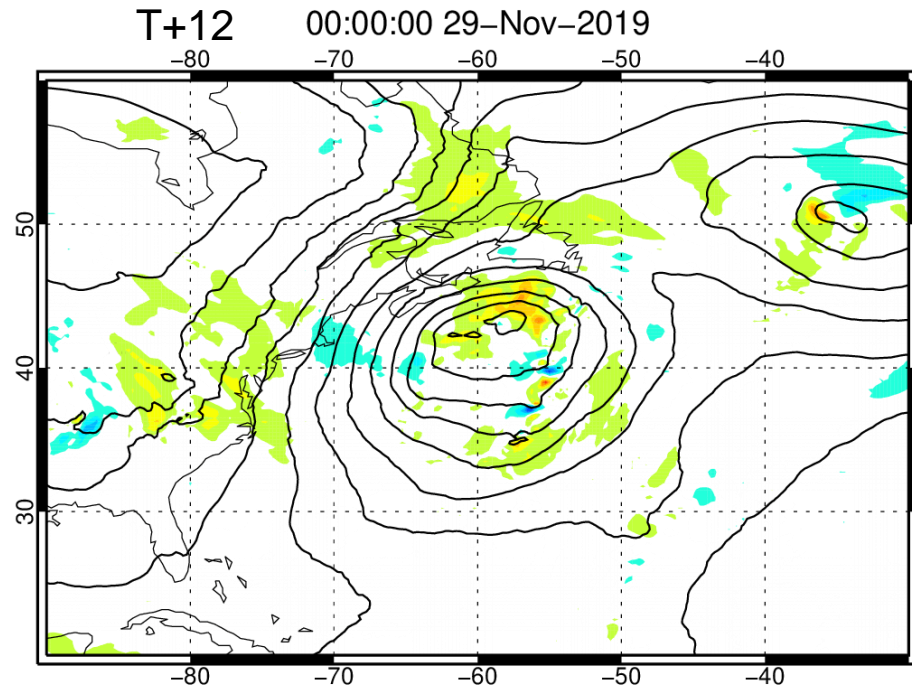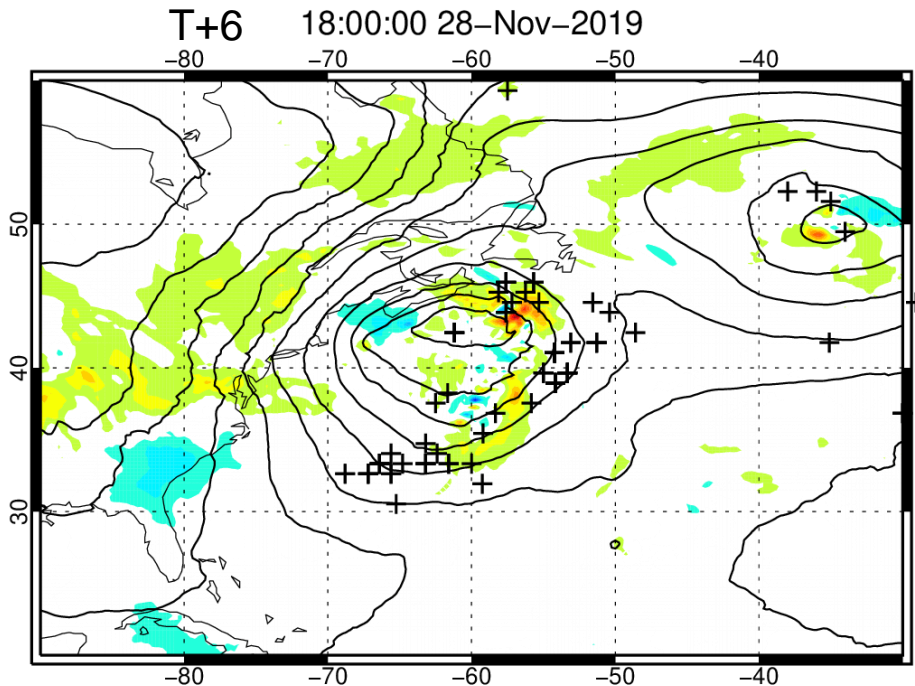
Line contours:
mean sea level pressure in forecast (5 hPa contour spacing)

Crosses:
Influential buoy observations: with FSOI > +5×10^{-5} J/kg

Surface pressure increment

Line contours: mean sea level pressure in forecast (5 hPa contour spacing)

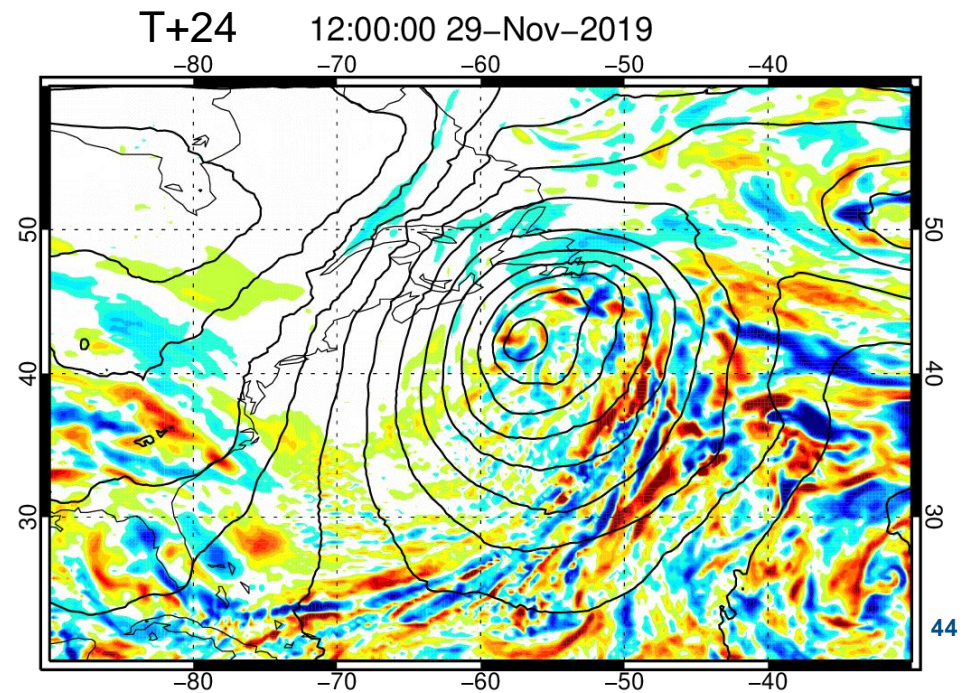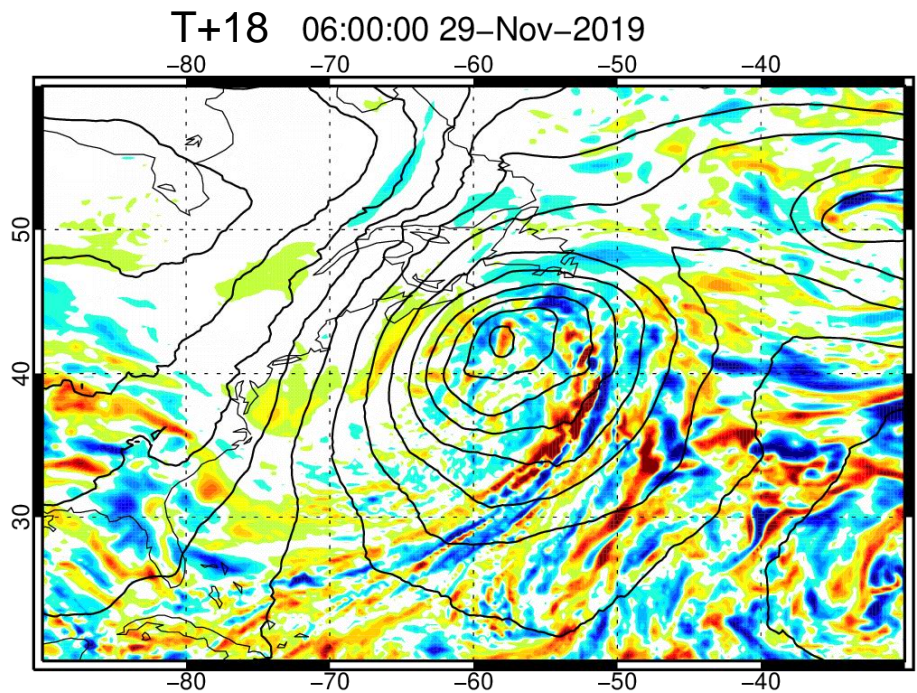**Crosses:** Influential AMSR2 and GMI observations: with FSOI < -5×10^{-5} J/kg

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WV (total column) increment

Line contours: mean sea level pressure in forecast (5 hPa contour spacing)
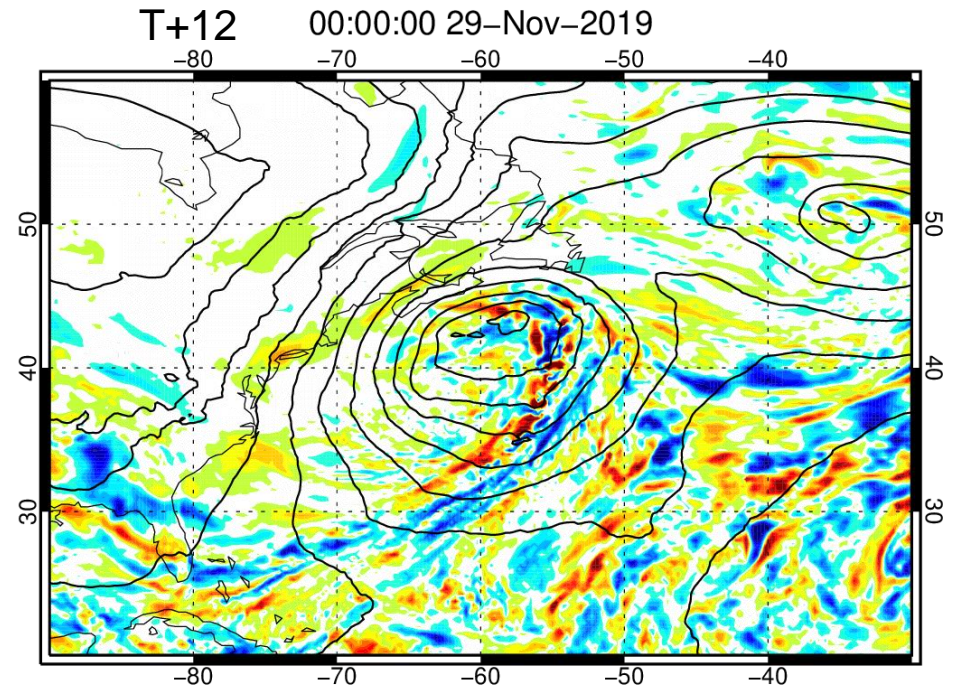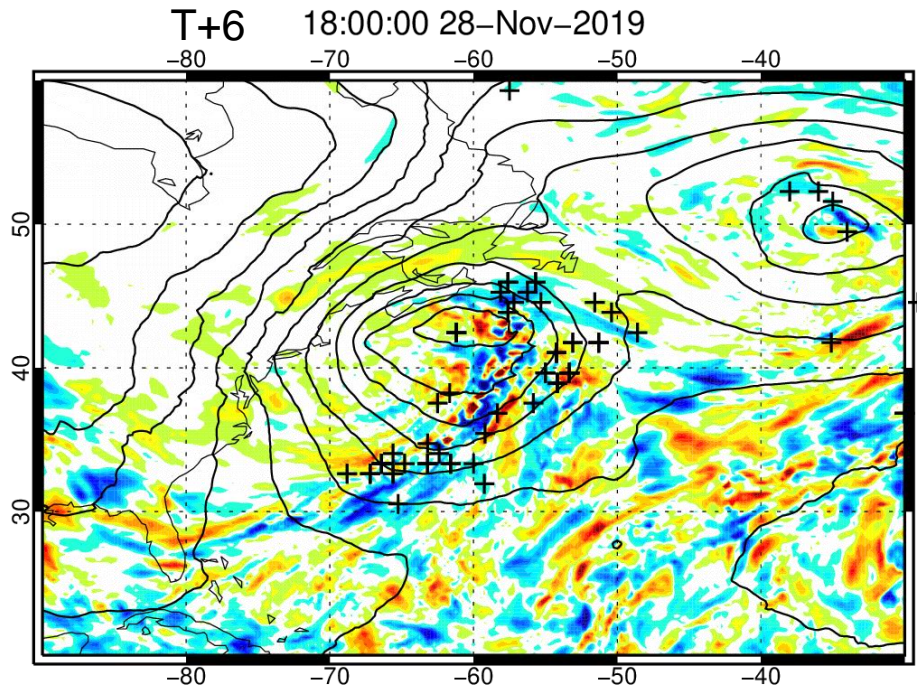
Crosses: Influential AMSR2 and GMI observations: with FSOI < -5×10^{-5} J/kg
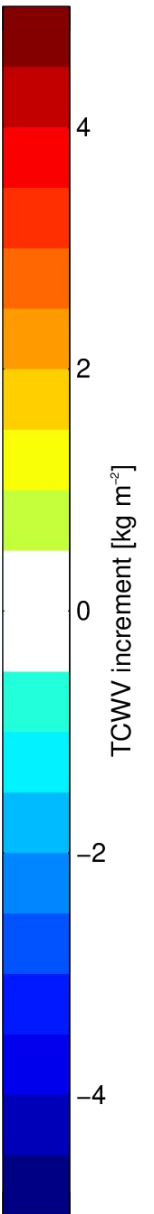
Summary

- All-sky microwave imagers provide unique information on water vapour, cloud and precipitation in high forecast sensitivity areas:

  - e.g: atmospheric rivers, frontal wave / cyclogenesis, tropical cyclones, warm conveyor belts

  - The most important information for the 24h forecast comes from a small number of observations in these areas, in a small area, on a small number of days

- Increments shown in these case studies rely on the full observing system – everything is important and beneficial:

  - 4D-Var turns surface pressure information into cloud increments

  - 4D-Var turns cloud information into surface pressure increments

- Limitations:

  - Not confirmed that WCB active in first two case studies

  - 24h FSOI seems to emphasise the impact of the cyclonic branch of the WCB (short range error growth) – would longer-range adjoint sensitivity emphasise downstream events, e.g. anticyclonic WCB branch, ridge building?