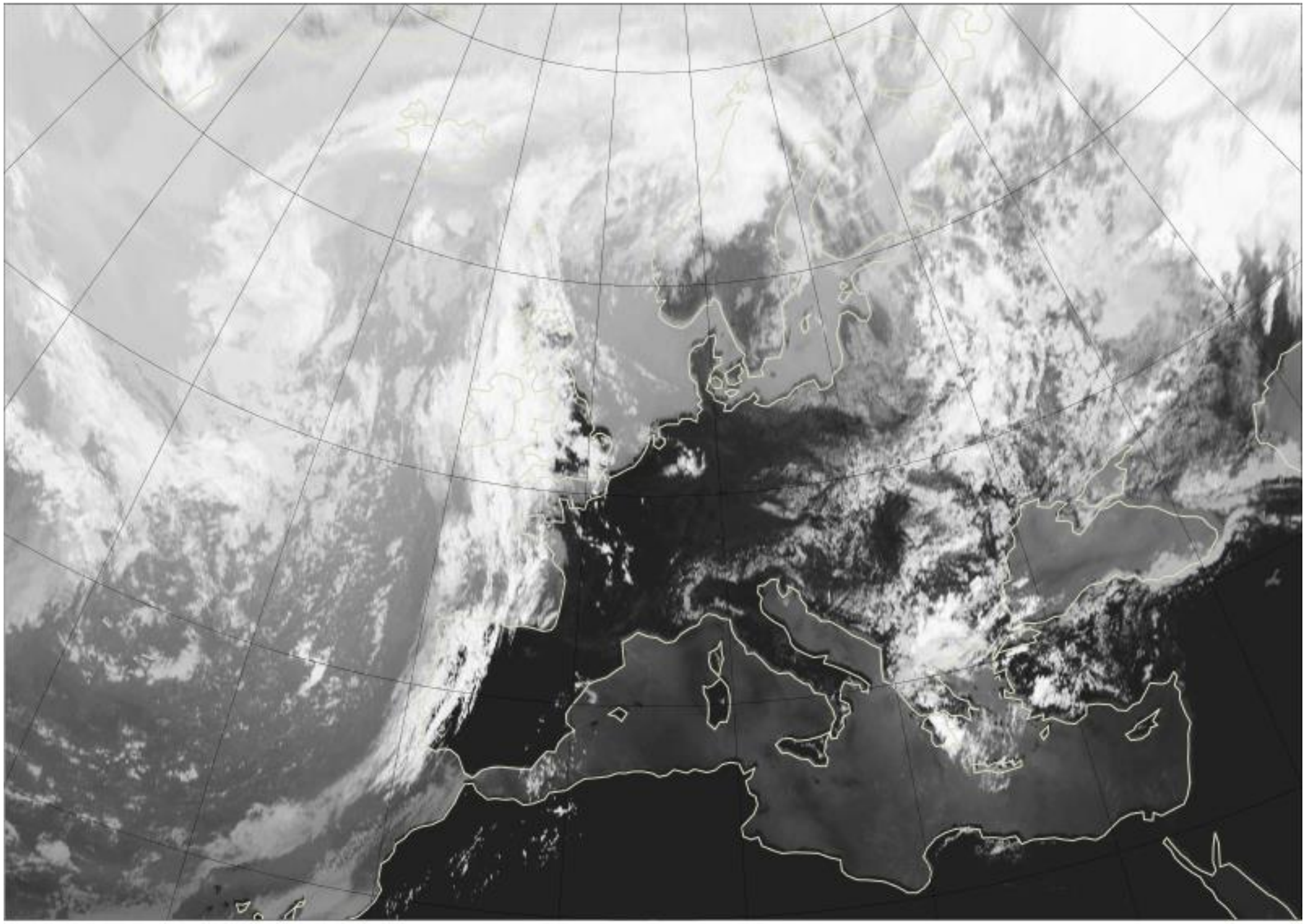
Diagnostics used in the university research context

Christian M. Grams, M. Sprenger, and H. Wernli

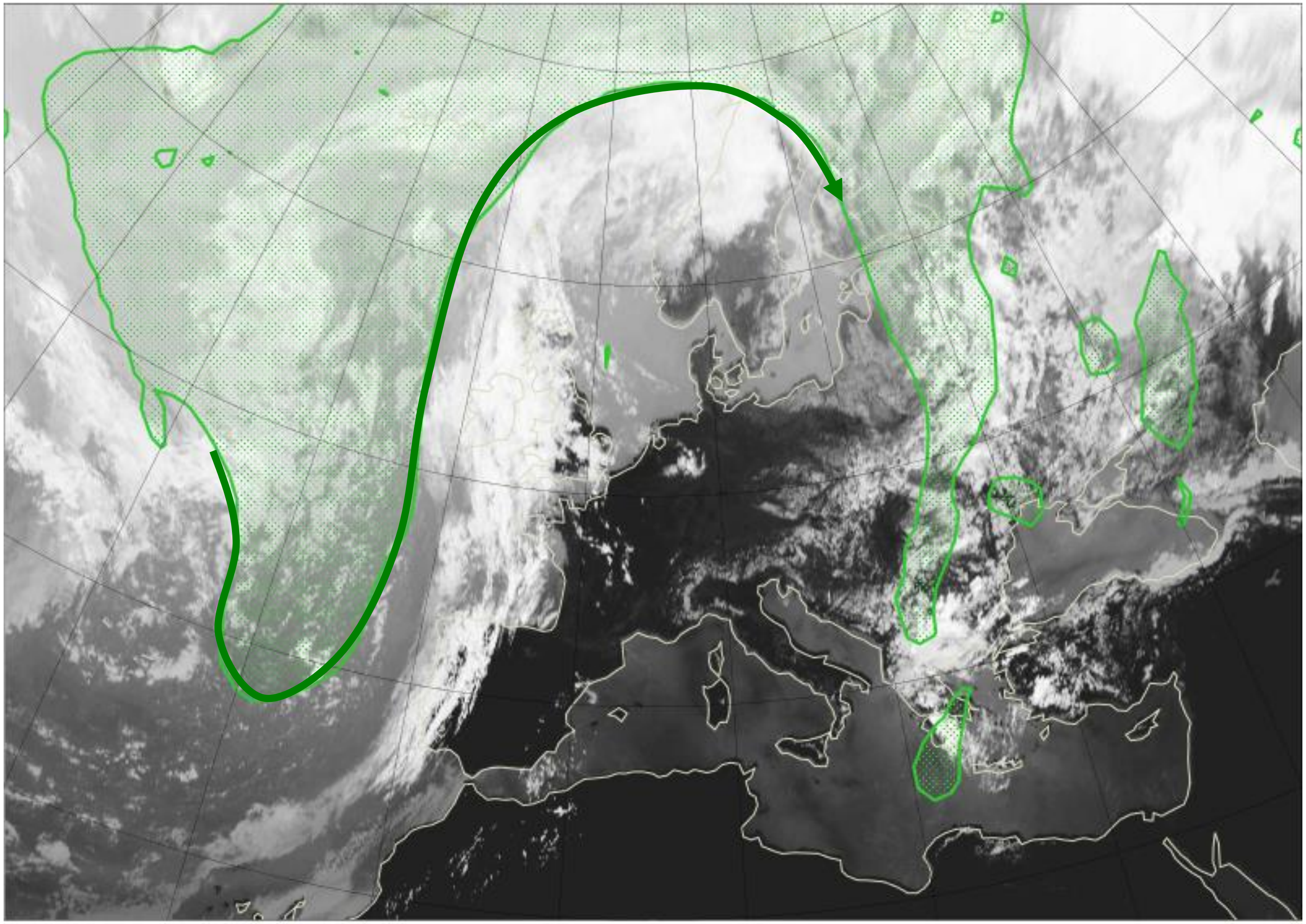
with contributions from the entire Atmospheric Dynamics Group, ETH Zurich

Heatwave Europe July 2015



MSG IR satellite 12 UTC 1 July 2015

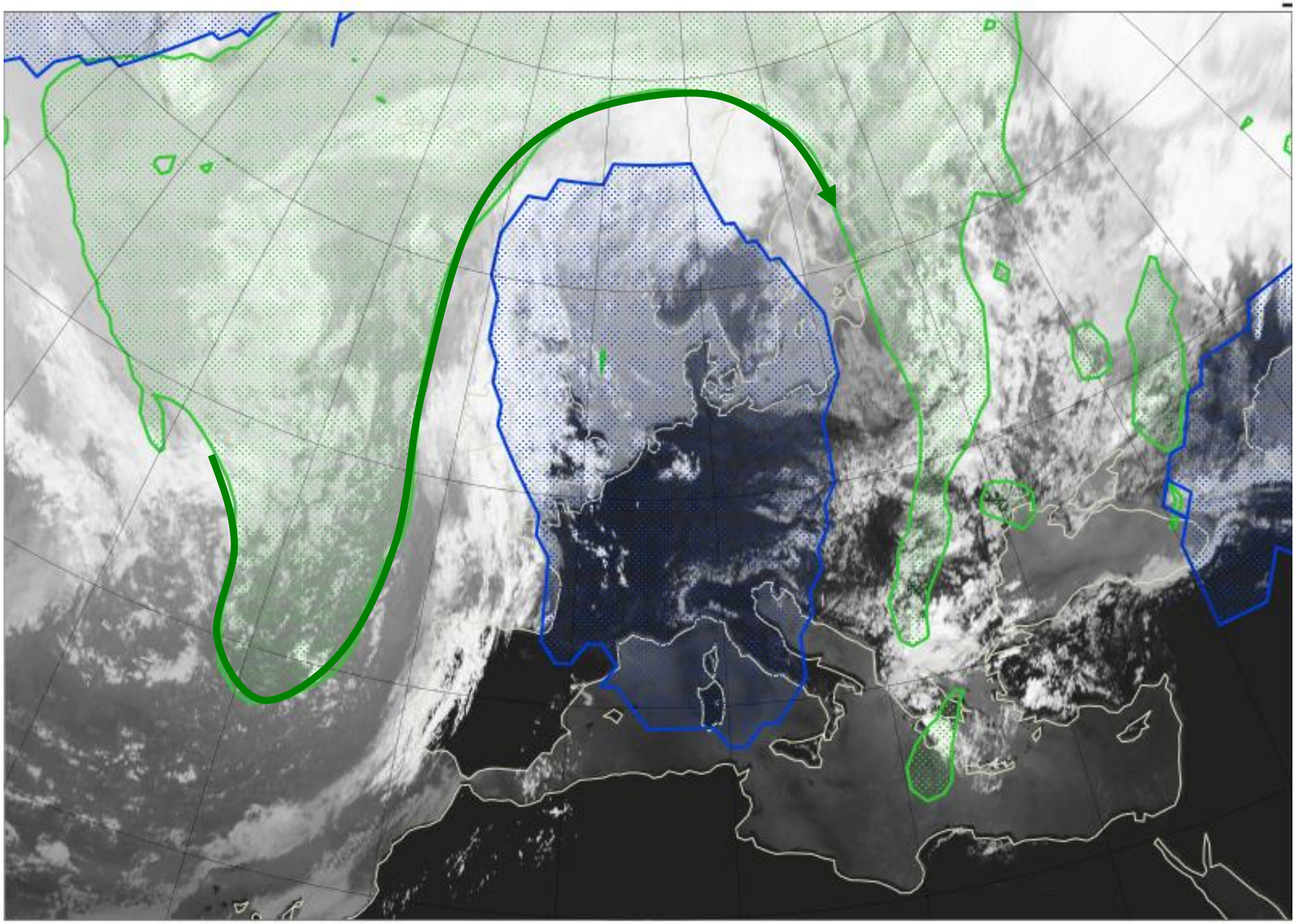
Heatwave Europe July 2015



MSG IR satellite 12 UTC 1 July 2015

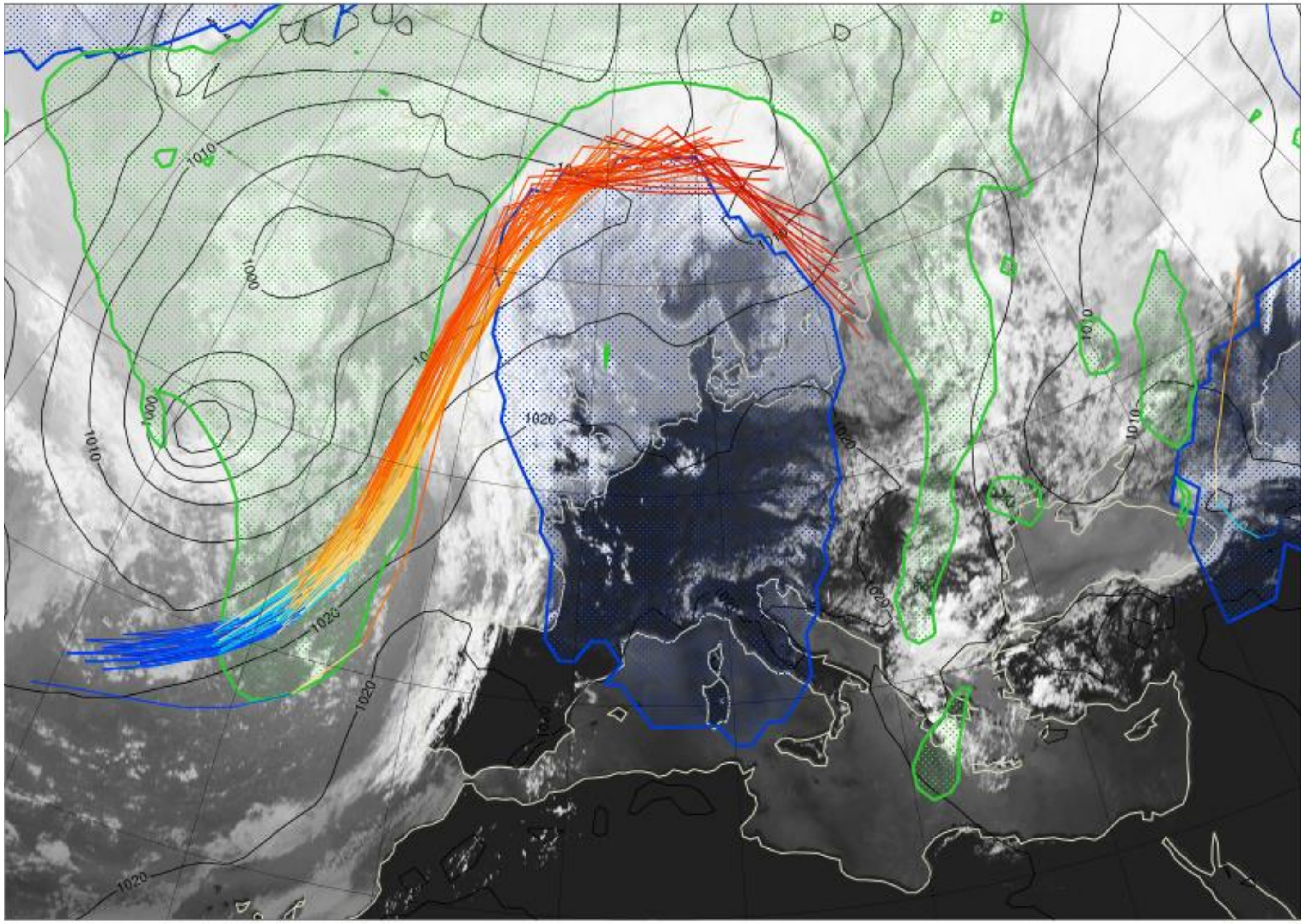
Jetstream deflected towards Scandinavia (2PVU@325K)

Heatwave Europe July 2015



MSG IR satellite 12 UTC 1 July 2015, jetstream (2PVU@325K)
Atmospheric blocking extends over heat wave region

Heatwave Europe July 2015



MSG IR satellite 12 UTC 1 July 2015, jetstream (2PVU@325K), blocking
Strongly ascending and precipitating airstream – associated with North Atlantic cyclone - reaches into blocking region (MSLP 12 UTC 29 June 2015)

Outline

1. Feature-based diagnostics
2. Diabatic influences on blocking
3. Operational applications
4. A recent forecast bust
5. Demonstration NAWDEX
6. Summary

1. Feature-based diagnostics: Overview

Sprenger, M., G. Fragkoulidis, et al.: Global climatologies of Eulerian and Lagrangian flow features based on ERA-Interim reanalyses. *Bull. Amer. Meteor. Soc.* doi:10.1175/BAMS-D-15-00299.1, in press.

Feature-based diagnostics: Overview

Eulerian	Lagrangian
Cyclones	*Warm conveyor belts*
Blocking	Strat.-Trop. Exchange
PV streamer	Tropical moisture exports
PV cutoff	*Dry intrusions* (S. Raveh-Rubin)
Fronts	Cold air outbreaks (L. Papritz, UBergen)
Jetstreams	
Tropopause folds	
Atmospheric rivers (H.Wernli)	
Baroclinicity (L. Papritz, UBergen)	

explained in this talk monthly clim. freely available work in progress

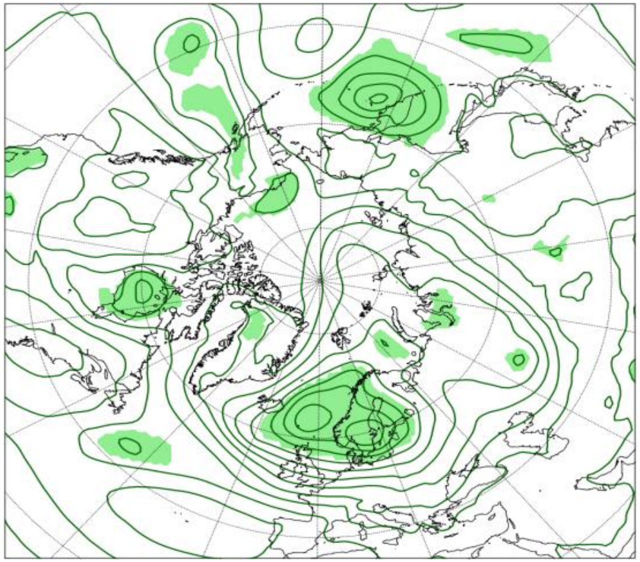
Sprenger, M., G. Fragkoulidis, et al.: Global climatologies of Eulerian and Lagrangian flow features based on ERA-Interim reanalyses. *Bull. Amer. Meteor. Soc.* doi:10.1175/BAMS-D-15-00299.1, in press.

1. Feature-based diagnostics: cyclones

Sprenger, M., G. Fragkoulidis, et al.: Global climatologies of Eulerian and Lagrangian flow features based on ERA-Interim reanalyses. *Bull. Amer. Meteor. Soc.* doi:10.1175/BAMS-D-15-00299.1, in press.

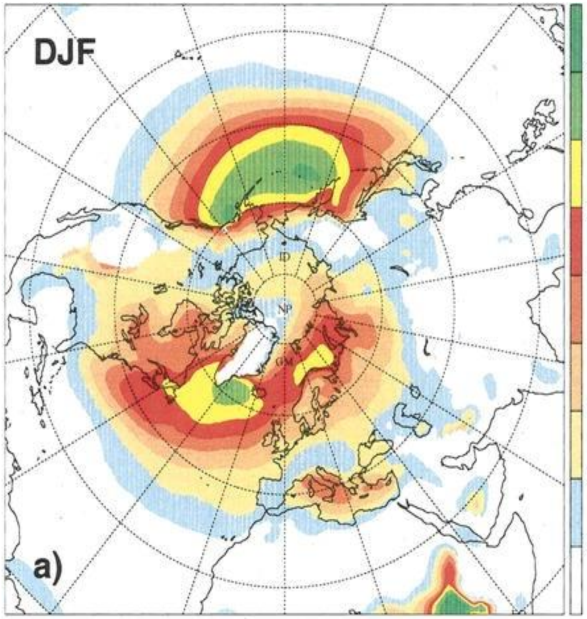
Wernli, H. and C. Schwierz, 2006: Surface cyclones in the ERA-40 Dataset (1958-2001). Part I: Novel identification method and global climatology. *J. Atmos. Sci.*, **63**, 2486-2507. doi:10.1175/JAS3766.1

Cyclones



SLP, 00 UTC 27 Feb 1990

Cyclone frequency DJF



- closed SLP contours around minima
- Set 0/1 mask
- unique label for each cyclone
- ranking into 1st, 2nd,… minimum
- Split multi-centre cyclones
- Tracking every 6h

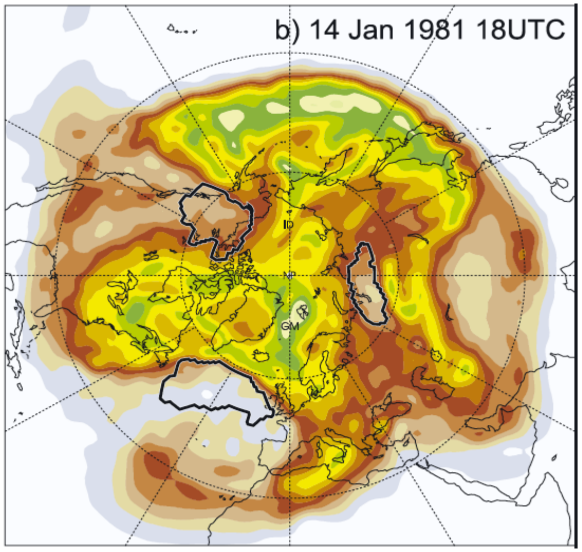
Sprenger, M., G. Fragkoulidis, et al. (2017), *BAMS*,. doi:10.1175/BAMS-D-15-00299.1
Wernli, H. and C. Schwierz, (2006), *JAS*, doi:10.1175/JAS3766.1 .

1. Feature-based diagnostics: Blocking

Sprenger, M., G. Fragkoulidis, et al.: Global climatologies of Eulerian and Lagrangian flow features based on ERA-Interim reanalyses. *Bull. Amer. Meteor. Soc.* doi:10.1175/BAMS-D-15-00299.1, in press.

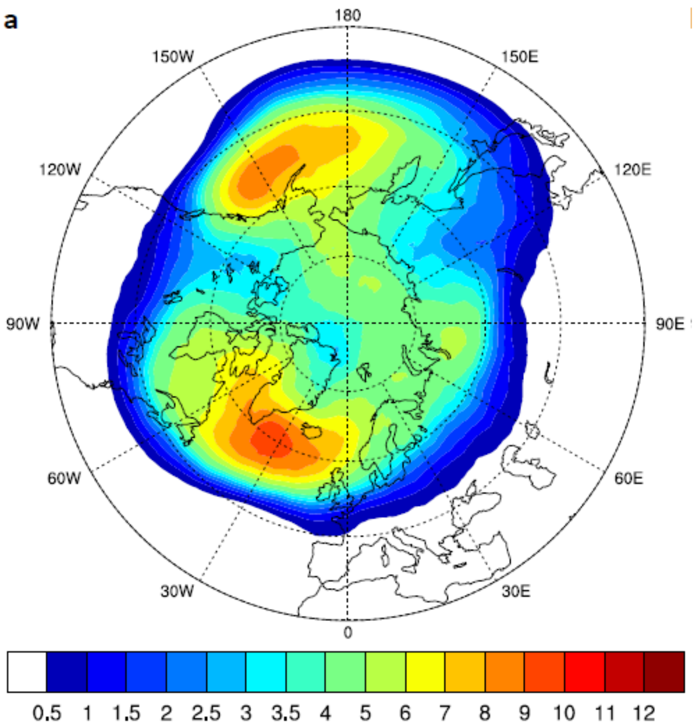
Schwierz, C., M. Croci-Maspoli, and H. C. Davies (2004), Perspicacious indicators of atmospheric blocking, *Geophys. Res. Lett.*, **31**, L06125, doi:10.1029/2003GL019341.

Blocking



- calculate vertically averaged PV (VAPV) between 500 and 150 hPa
- negative VAPV anomalies wrt. monthly climatology < 1.3 PVU
- track anomalies in time
- anomalies living longer than 5 days (with at least 70% overlap at each 6-hourly time step) are identified as blocks

Blocking frequency full year



(MA Roman Attinger; ETHZ, 2016)

Sprenger, M., G. Fragkoulidis, et al. (2017), *BAMS*,. doi:10.1175/BAMS-D-15-00299.1
Schwierz et al., (2004), *GRL*, doi:10.1029/2003GL019341.

1. Feature-based diagnostics: LAGRANTO

Sprenger, M. and Wernli, H. (2015): The LAGRANTO Lagrangian analysis tool - version 2.0, Geosci. Model Dev., 8, 2569–2586, doi:10.5194/gmd-8-2569-2015.

ETHzürich Home Examples Tutorial Download Publications

http://lagranto.ethz.ch/

LAGRANTO

The Lagrangian Analysis Tool

Contact

LAGRANTO:

Heini Wernli

Michael Sprenger

LAGRANTO.OCEAN:

Sebastian Schemm

About

Lagrangian parcel trajectories are widely used in the atmospheric and oceanic sciences, for instance, to identify flow structures in extratropical cyclones (e.g., warm conveyor belts) or ocean eddies, long-range transport pathways of moisture, or to study the physical processes underlying the formation of sea surface temperature, salinity or potential vorticity anomalies.

1. LAGRANTO.ECMWF

It is used to compute air-parcel trajectories typically based on 6-hourly ERA-Interim data on a regular lat/lon grid. In addition it was applied also to 20CR data.

Citation:

Sprenger, M. and Wernli, H. (2015): The LAGRANTO Lagrangian analysis tool - version 2.0, *Geosci. Model Dev.*, **8**, 2569–2586, doi:10.5194/gmd-8-2569-2015.

2. LAGRANTO.COSMO

Is the version used to compute air-parcel trajectories based on the output of the COSMO mode. An online and offline version of the tools is available. For the online computation the actual model time step is used, which increase the accuracy of the trajectories.

Citation:

Miltenberger, A.K., Pfahl S., and Wernli H. (2013): An online trajectory module (version 1.0) for the nonhydrostatic

3. LAGRANTO.OCEAN

The ocean version is the latest member of the LAGRANTO family. It can be used to compute ocean-parcel trajectories based on ECMWF's Ocean Reanalysis data (ORAS5). The triangular grid of the input data is transformed and rotated into a regular lat/lon grid. At the boundaries no-normal and no-slip boundary conditions are applied. This version is under development.

Citation:

- Computation of Lagrangian parcel forward/backward trajectories
- Multiple options for selection of subsets (spatial & temporal criteria, physical properties)
- Freely available (versions for IFS, COSMO, WRF, UM)

Sprenger, M. and Wernli, H. (2015): The LAGRANTO Lagrangian analysis tool - version 2.0, Geosci. Model Dev., 8, 2569–2586, doi:10.5194/gmd-8-2569-2015.

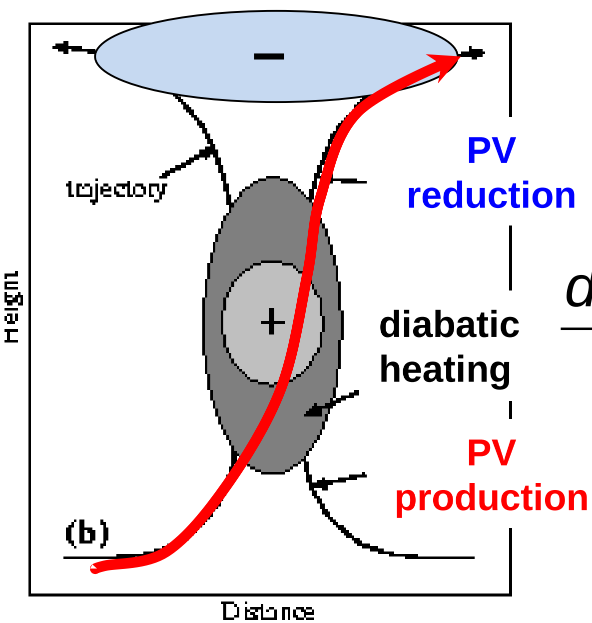
1. Feature-based diagnostics: WCBs

Madonna, E., et al., 2014: Warm Conveyor Belts in the ERA-Interim Dataset (1979–2010). Part I: Climatology and Potential Vorticity Evolution. *J. Climate*, **27**, 3–26, doi:10.1175/JCLI-D-12-00720.1.

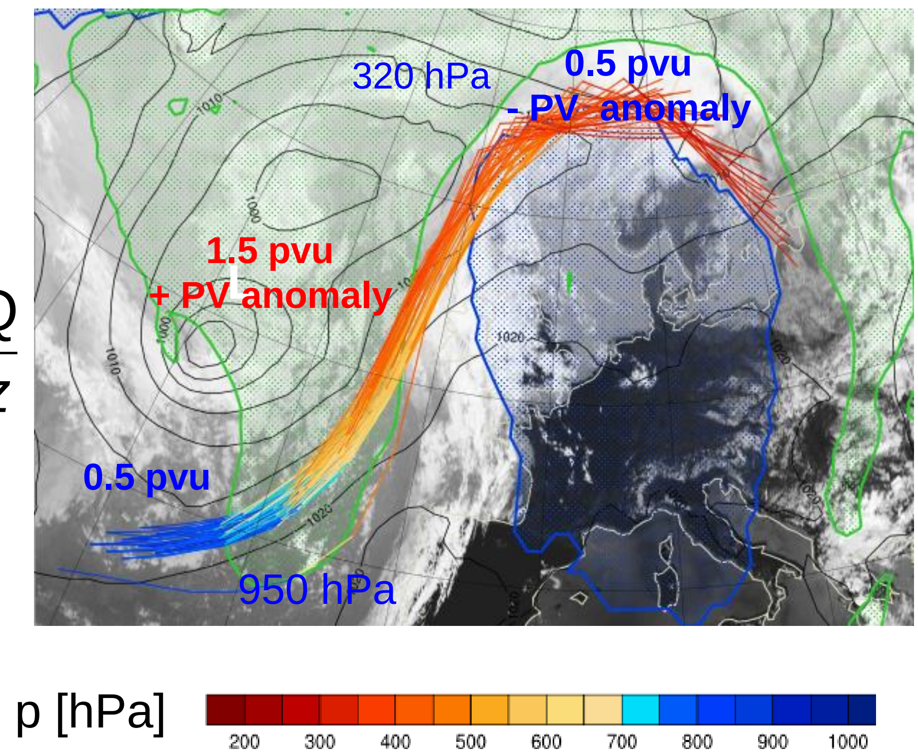
Warm conveyor belts

- rapidly ascending cross isentropic air flows (>600hPa/48h)
- diabatic heating of about 20K / 48h
- diabatic PV production below level of maximum heating
- diabatic PV reduction and low PV values at upper levels

see WCB clim. by Madonna et al. (2014)



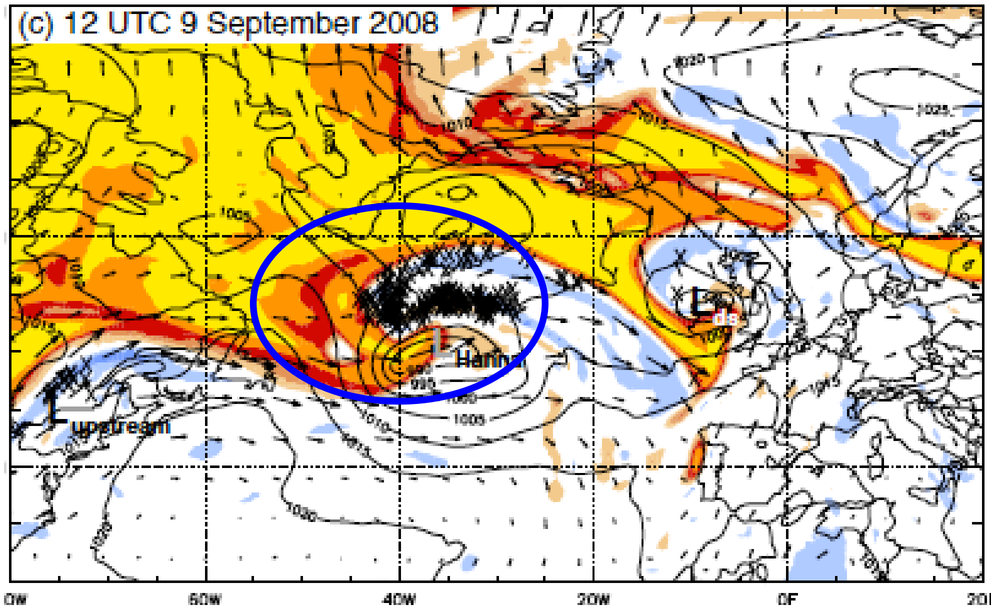
$$\frac{dPV}{dt}\ \mu\ \frac{d\dot{Q}}{dz}$$

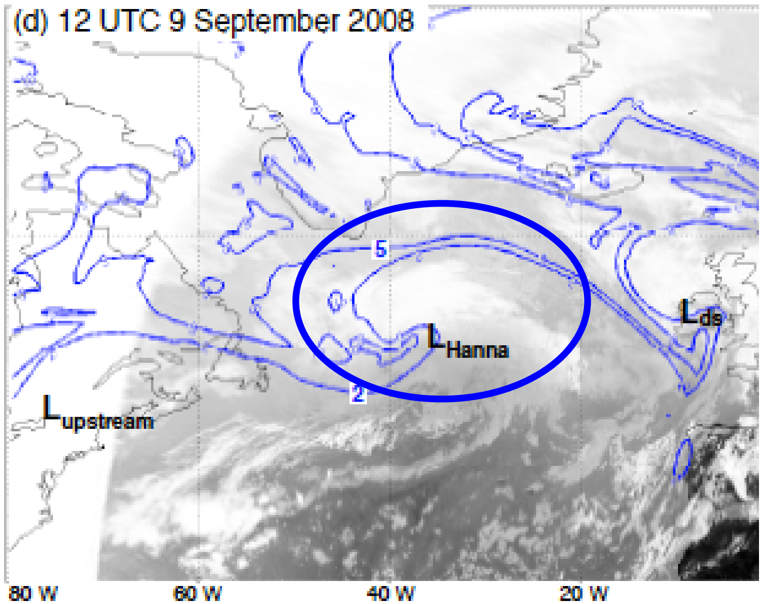


Wernli and Davies (1997), *QJRMS*

WCB outflow and upper-level flow

PV on 320 K





Grams et al. (2011), *QJRMS*

$$\frac{dPV}{dt} = \boxed{\frac{1}{\rho}\vec{\eta} \cdot \nabla\dot{\Theta}} + \frac{1}{\rho}(\nabla \times \vec{F}) \cdot \nabla\Theta$$

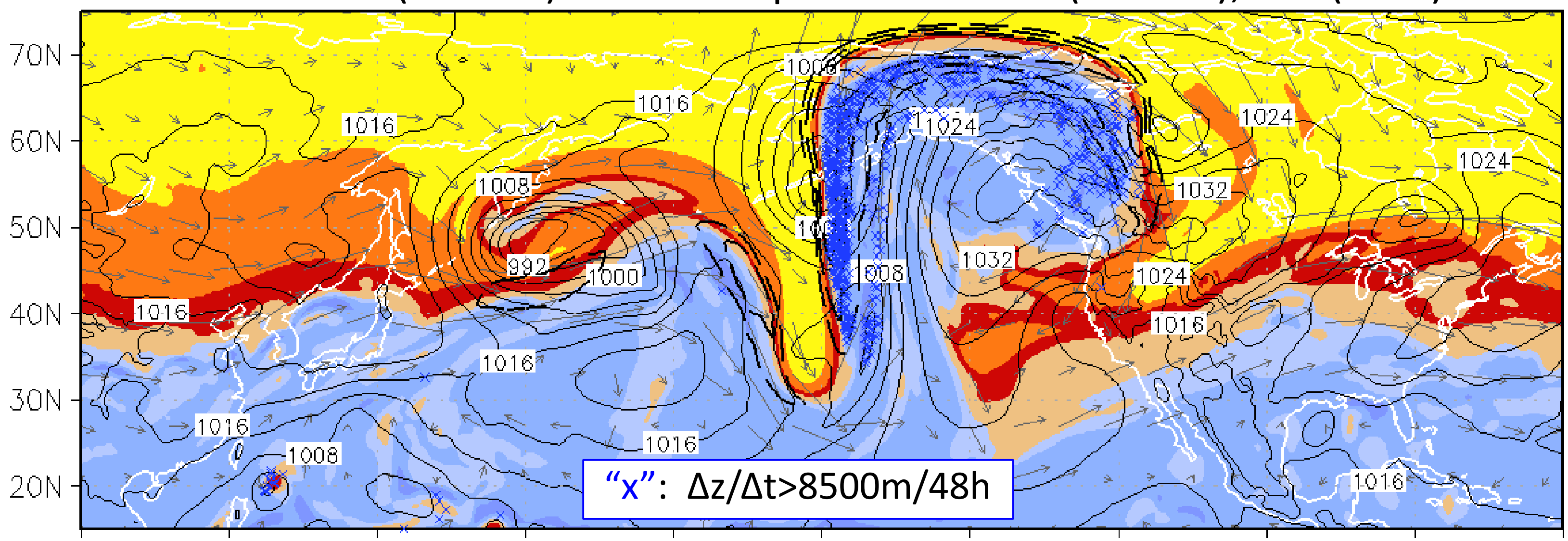
Total change in PV

diabatic PV modification

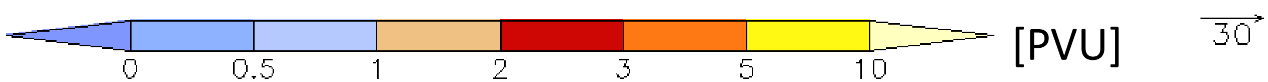
frictional processes

WCB outflow and upper-level flow

335-K PV (shaded) and wind speed >50 m s^{-1} (dashed); SLP (solid)



Grams and Archambault (2016), *MWR*, doi: 10.1175/MWR-D-15-0419.1



$$\frac{dPV}{dt} = \boxed{\frac{1}{\rho}\vec{\eta}\cdot\nabla\dot{\Theta}} + \frac{1}{\rho}(\nabla\times\vec{F})\cdot\nabla\Theta$$

Total change in PV

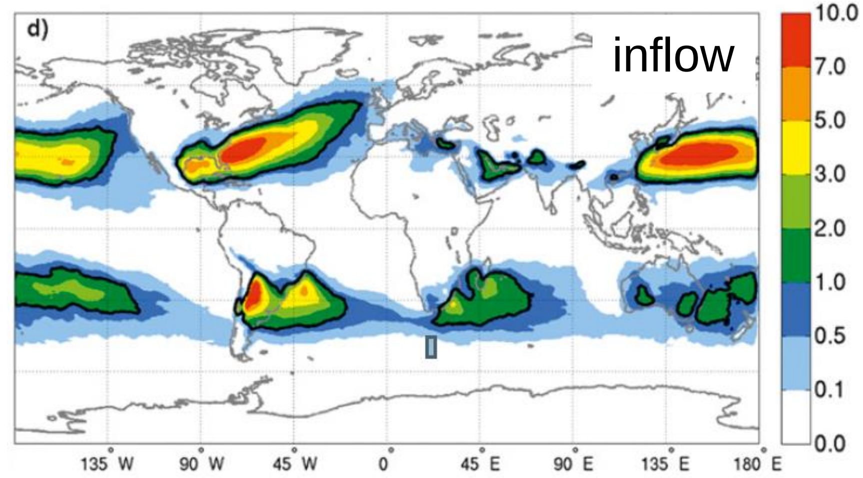
diabatic PV modification

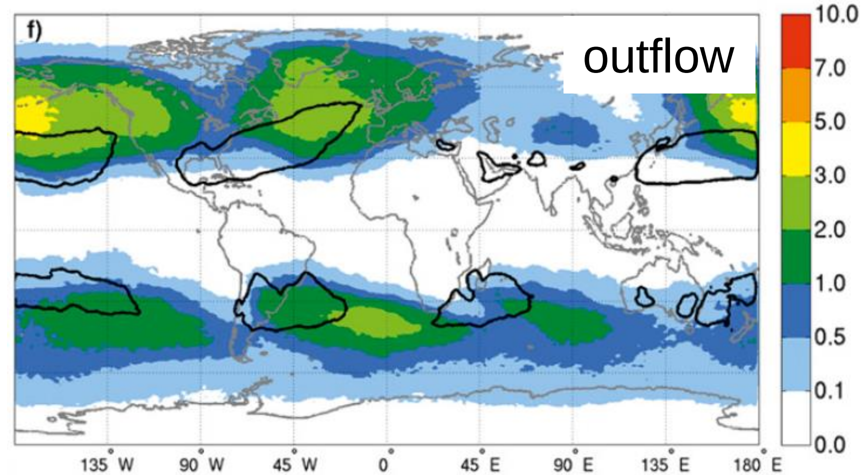
frictional processes

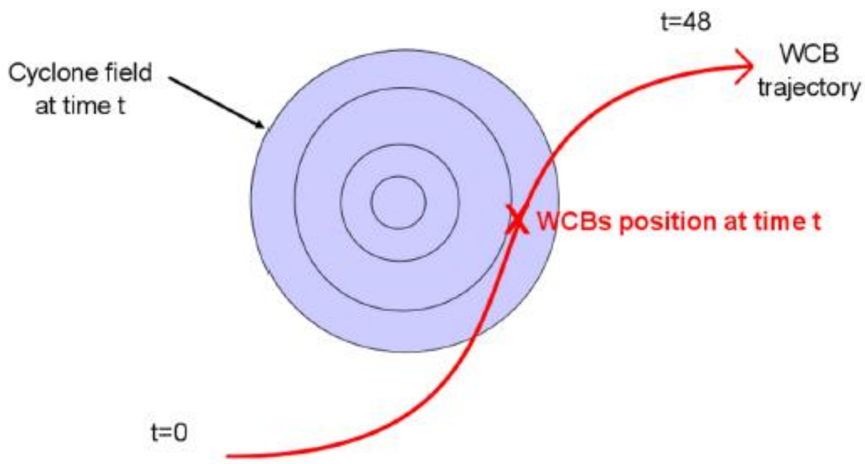
WCB climatology

- Ascending more than 600 hPa in 48 h
- vicinitiy of extratropical cyclone (to exclude rapid ascent in convective systems)
- tracing forward and backward along WCB trajectory: Q, LWC, IWC, RH, TH, PV

WCB frequency DJF



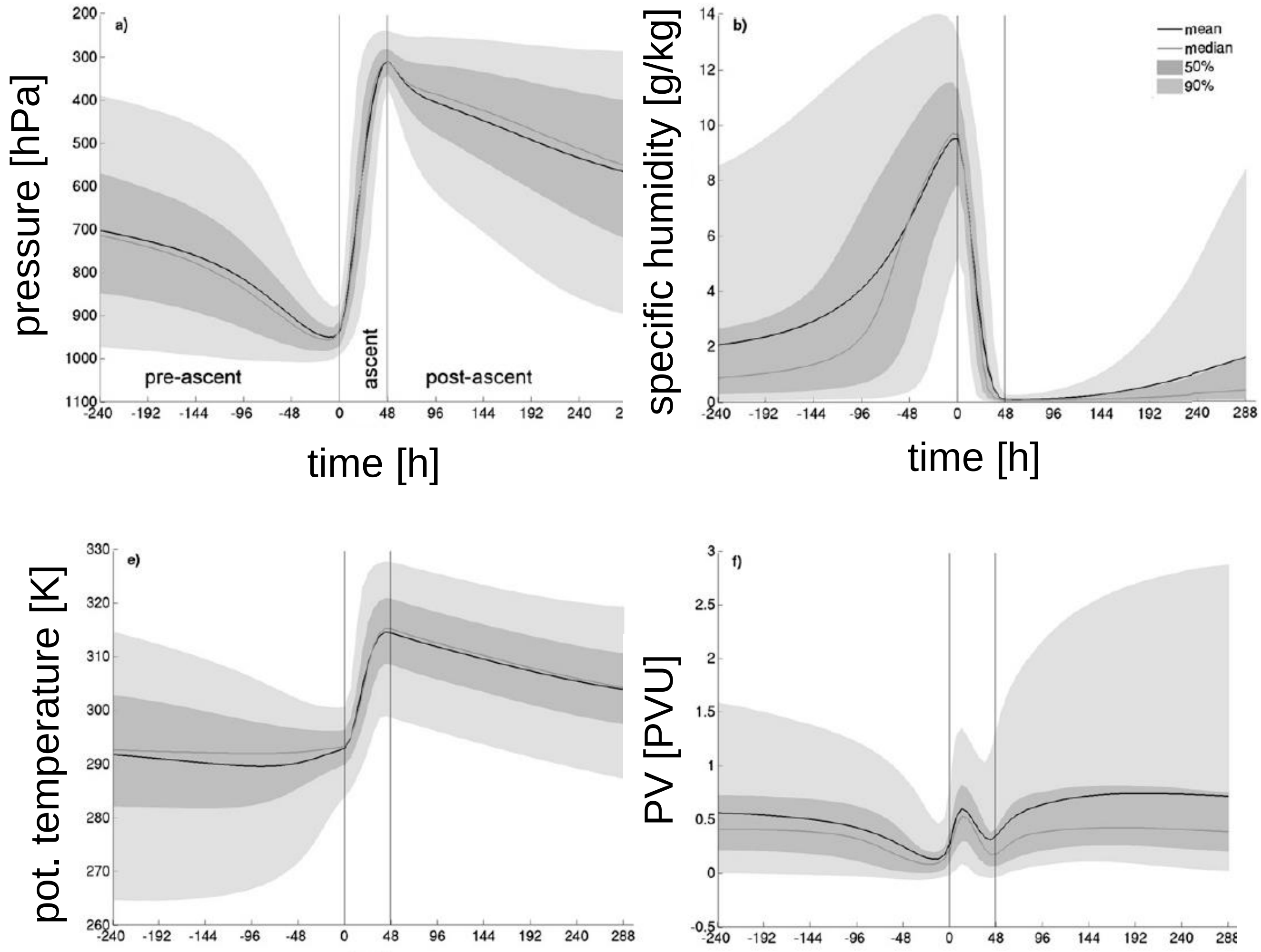




Madonna, E., et al., 2014: Warm Conveyor Belts in the ERA-Interim Dataset (1979–2010). Part I: Climatology and Potential Vorticity Evolution. *J. Climate*, **27**, 3–26, doi:10.1175/JCLI-D-12-00720.1.

 christian.grams@env.ethz.ch

WCB climatology



- Loss of specific humidity (precipitation)
- Cross-isentropic ascent (latent heat release due to condensation)
- Net transport of low-PV air to upper troposphere

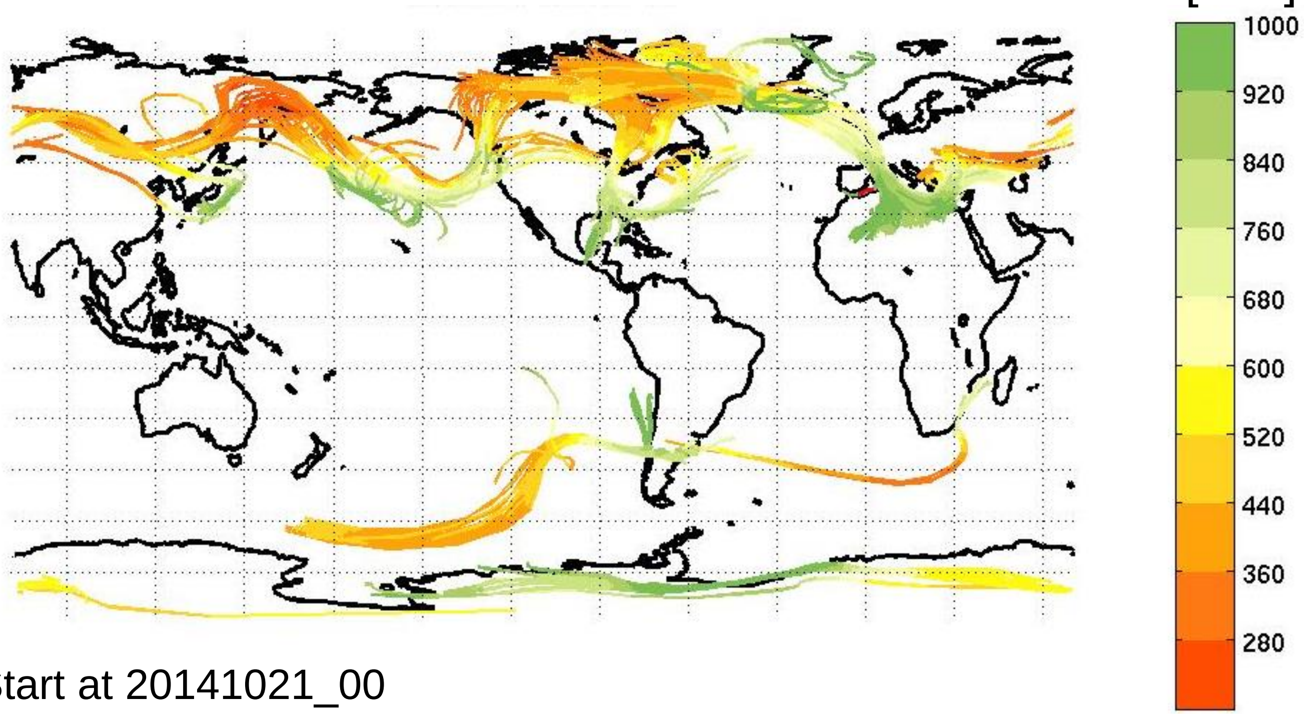
Madonna, E., et al., 2014: Warm Conveyor Belts in the ERA-Interim Dataset (1979–2010). Part I: Climatology and Potential Vorticity Evolution. *J. Climate*, **27**, 3–26, doi:10.1175/JCLI-D-12-00720.1.

1. Feature-based diagnostics: Dry intrusions

Raveh-Rubin, S., 2017: Dry intrusions: Lagrangian climatology and dynamical impact on the planetary boundary layer. *J. Climate*, [doi: 10.1175/JCLI-D-16-0782.1](https://doi.org/10.1175/JCLI-D-16-0782.1)

Dry intrusions

400-hPa descent in 48 h

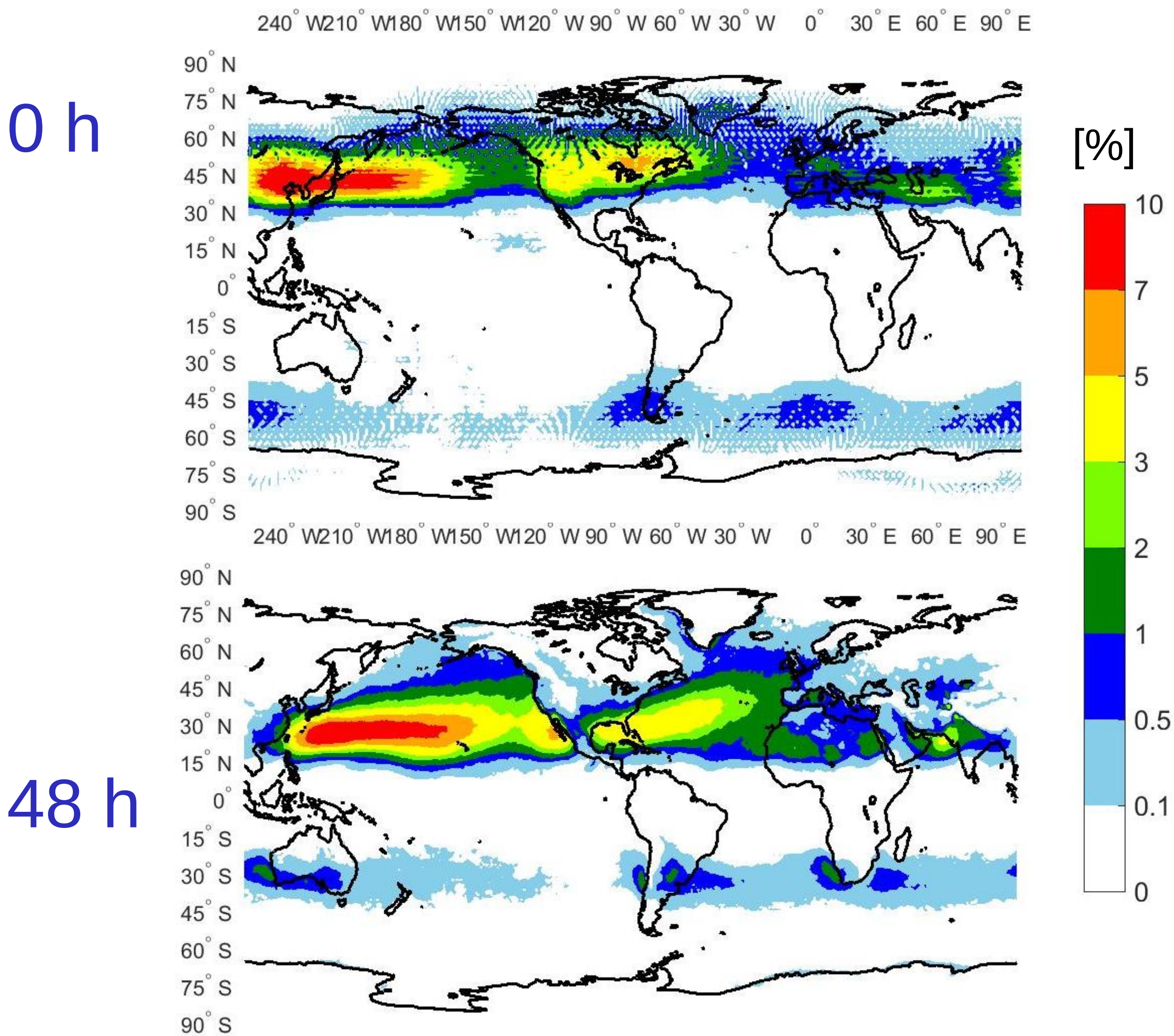


Start at 20141021_00

- Forward trajectories start from a 3-D global grid every 6 h

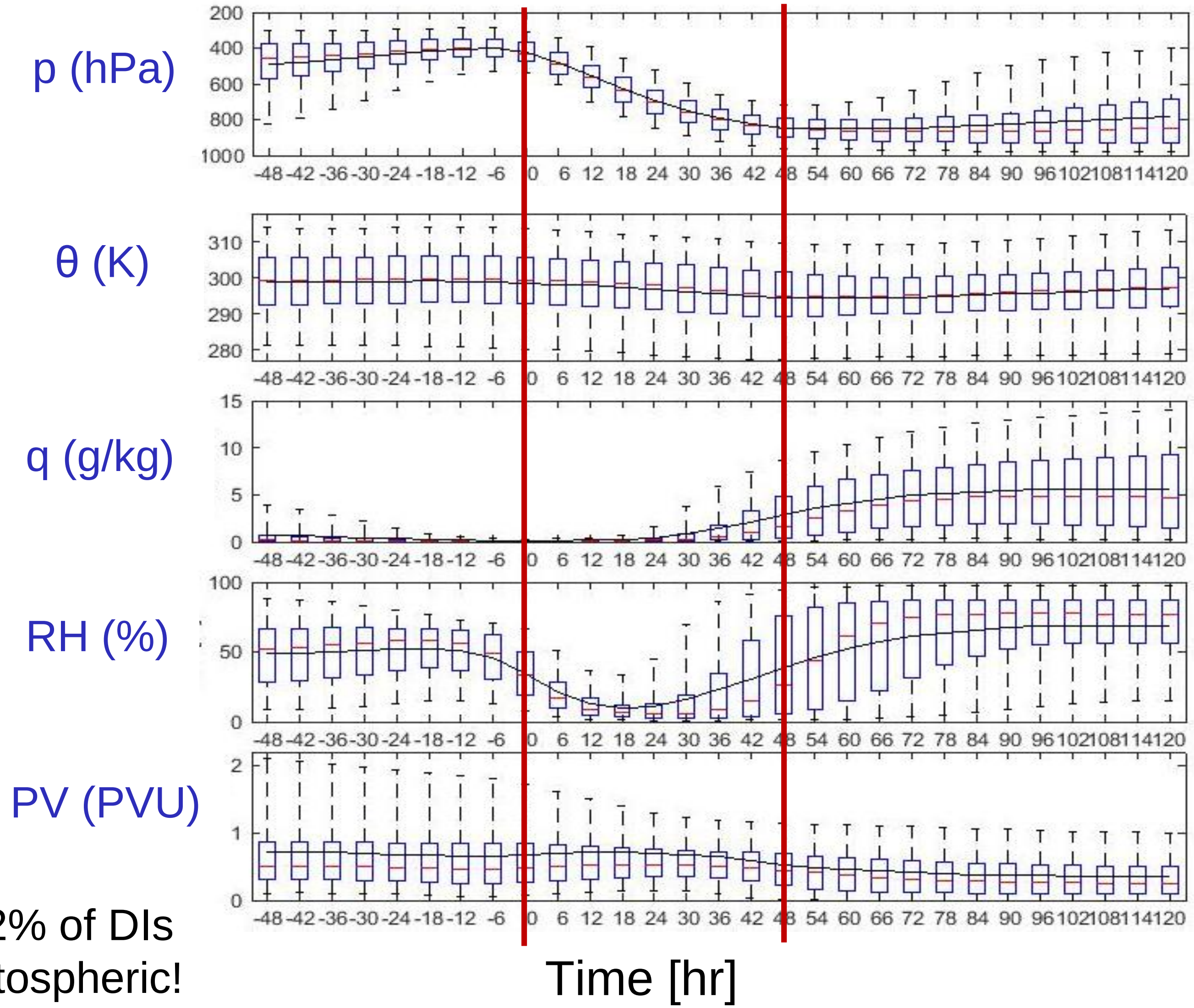
Raveh-Rubin, S., 2017: Dry intrusions: Lagrangian climatology and dynamical impact on the planetary boundary layer. *J. Climate*, [doi: 10.1175/JCLI-D-16-0782.1]

Dry intrusions: climatology DJF

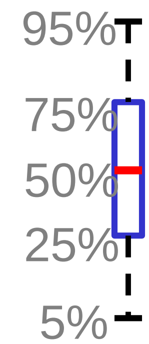


Raveh-Rubin, S., 2017: Dry intrusions: Lagrangian climatology and dynamical impact on the planetary boundary layer. *J. Climate*, [doi: 10.1175/JCLI-D-16-0782.1](https://doi.org/10.1175/JCLI-D-16-0782.1)

Dry intrusions: evolution



26.6·10^6 trajectories



Only 1.2% of DIs are stratospheric!

Raveh-Rubin, S., 2017: Dry intrusions: Lagrangian climatology and dynamical impact on the planetary boundary layer. *J. Climate*, doi: 10.1175/JCLI-D-16-0782.1

1. Feature-based diagnostics: website

http://eraiclim.ethz.ch/

Sprenger, M., G. Fragkoulidis, et al.: Global climatologies of Eulerian and Lagrangian flow features based on ERA-Interim reanalyses. *Bull. Amer. Meteor. Soc.* doi:10.1175/BAMS-D-15-00299.1, in press.

ETH Zürich | DUSYS Departement Umweltsystemwissenschaften | IAC

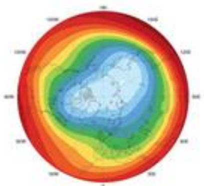
Register

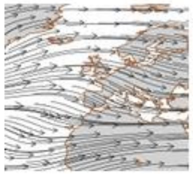
Feature-based ERA-Interim Climatologies

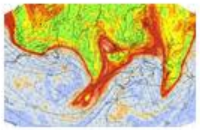
This collection of ERA-Interim based global climatologies of Eulerian and Lagrangian flow features is based on past and ongoing research of the **Atmospheric Dynamics group** at ETH Zürich. This webpage offers you access to monthly or longer-term averaged global fields from these climatologies. You can download netCDF, png or pdf files for the desired time period. The available fields span the period from January 1979 until (currently) February 2014.

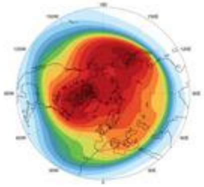
Reference for the ERA-Interim dataset:
Dee, D. P. and coauthors, 2011: The ERA-Interim reanalysis: Configuration and performance of the data assimilation system, Quarterly Journal of Royal Meteorological Society, 137, 553–597, DOI:10.1002/qj.828.

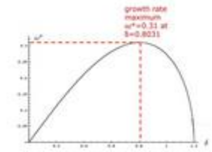
Reference for the feature climatologies:
Sprenger, M., G. Fragkoulidis, H. Binder, M. Croci-Maspoli, P. Graf, C. M. Grams, P. Knippertz, E. Madonna, S. Schemm, B. Škerlak, and H. Wernli: Global climatologies of Eulerian and Lagrangian flow features based on ERA-Interim reanalyses. Bull. Amer. Meteor. Soc. doi:10.1175/BAMS-D-15-00299.1, in press.

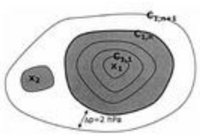

Pot. Temperature (TH)

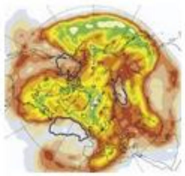

Wind Velocity


Pot. Vorticity (PV)


Tropopause Pressure

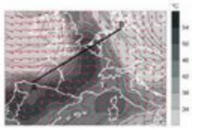

Eady Growth Rate


Cyclones / Anticyclones


Atmospheric Blocks

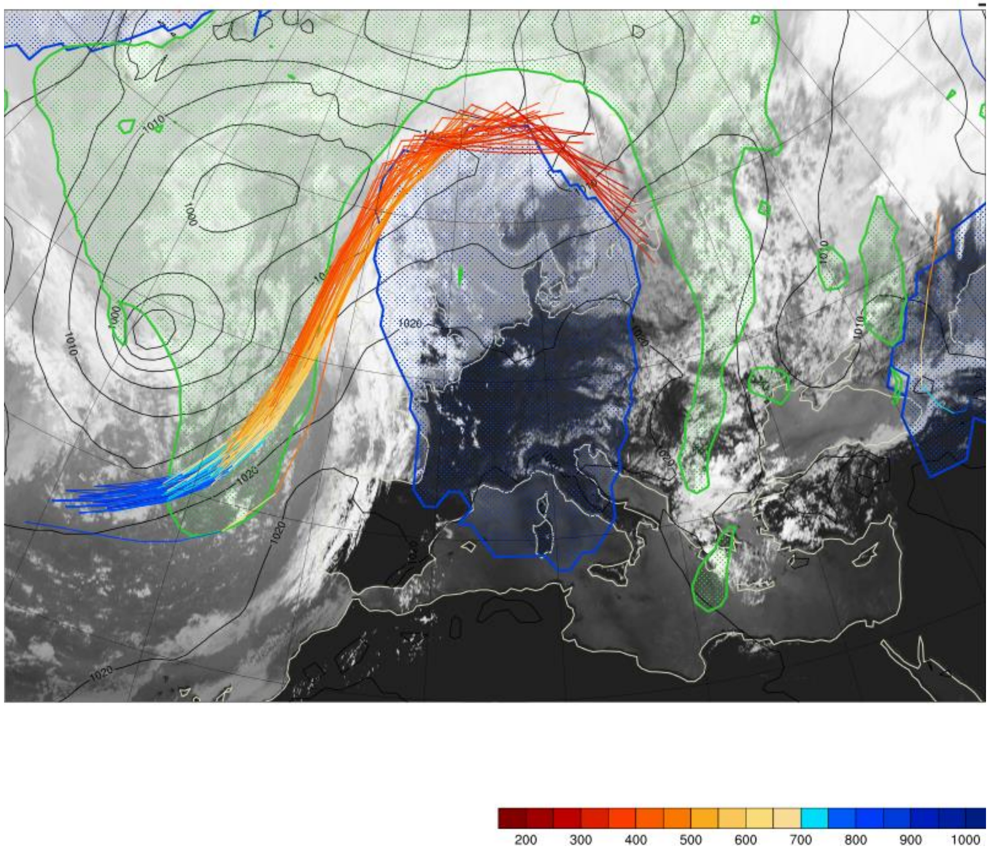

PV Streamers


PV Cutoffs


Fronts

http://eraiclim.ethz.ch/

2. Diabatic influences on blocking

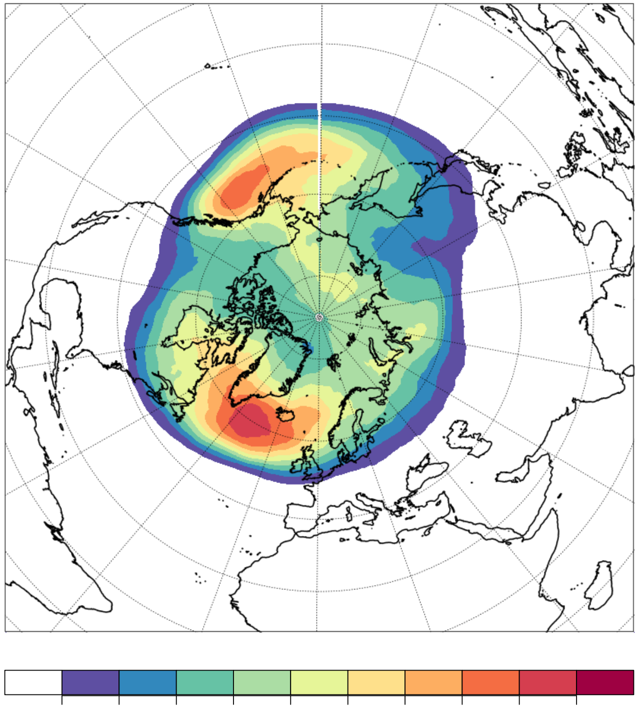


Pfahl, S., C. Schwierz, M. Croci-Maspoli, C. M. Grams, and H. Wernli, 2015: Importance of latent heat release in ascending air streams for atmospheric blocking. *Nature Geosci*, **8**, 610–614, doi:10.1038/ngeo2487.

Diabatic influence on blocking

Pfahl, S., et al. (2015), *NatGeo*, doi:10.1038/ngeo2487.

- Analyze ERA-Interim reanalysis data for the period 1989-2009.
- Identify atmospheric blocking as temporally persistent negative potential vorticity anomalies in the middle/upper troposphere (Schwierz et al., 2004).
- Calculate 7-day backward trajectories from grid points within blocking anticyclones.



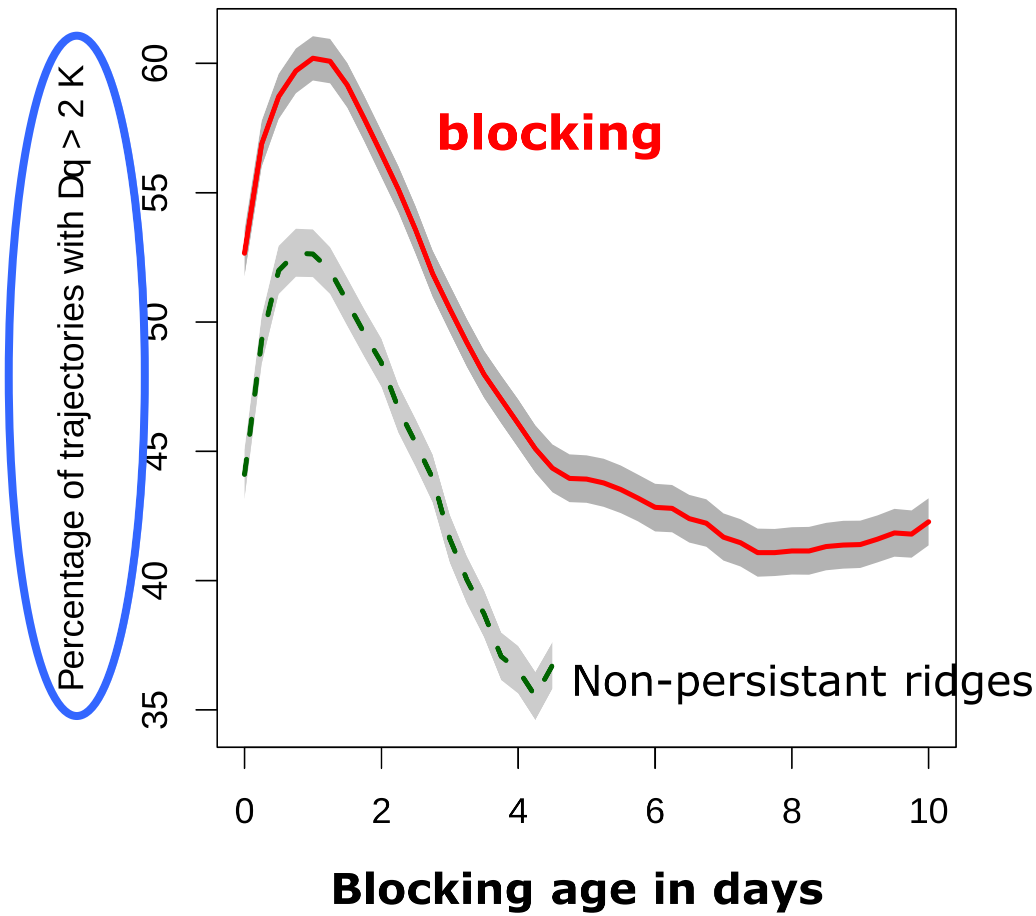
Annual mean blocking frequency (%).

slides by Stephan Pfahl

Diabatic heating and PV anomalies

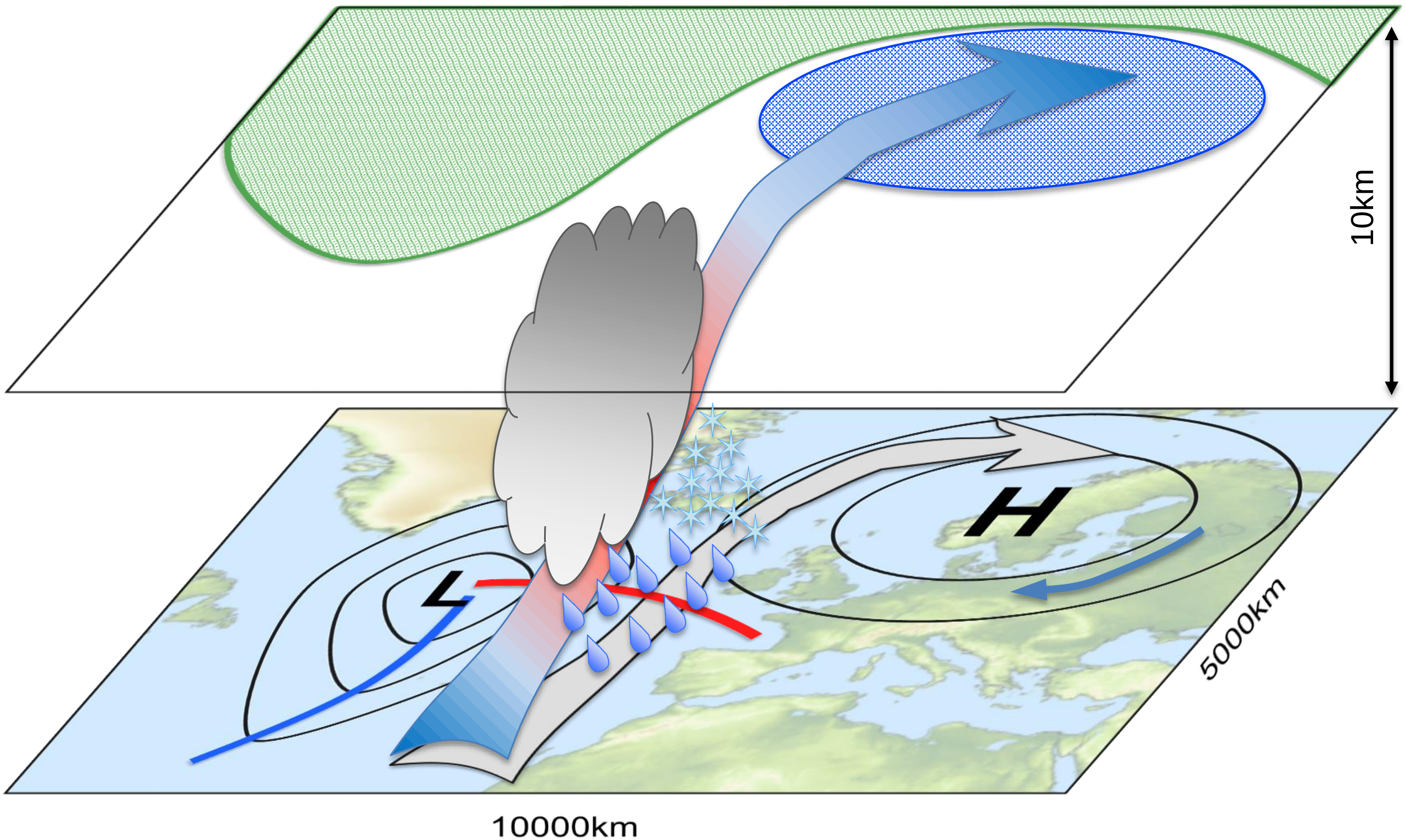
Pfahl, S., et al. (2015), *NatGeo*, doi:10.1038/ngeo2487.

Diabatic heating during 3 days before arriving in the blocking region



slides by Stephan Pfahl

Summary diabatic outflow and blocking



3. Operational forecast products

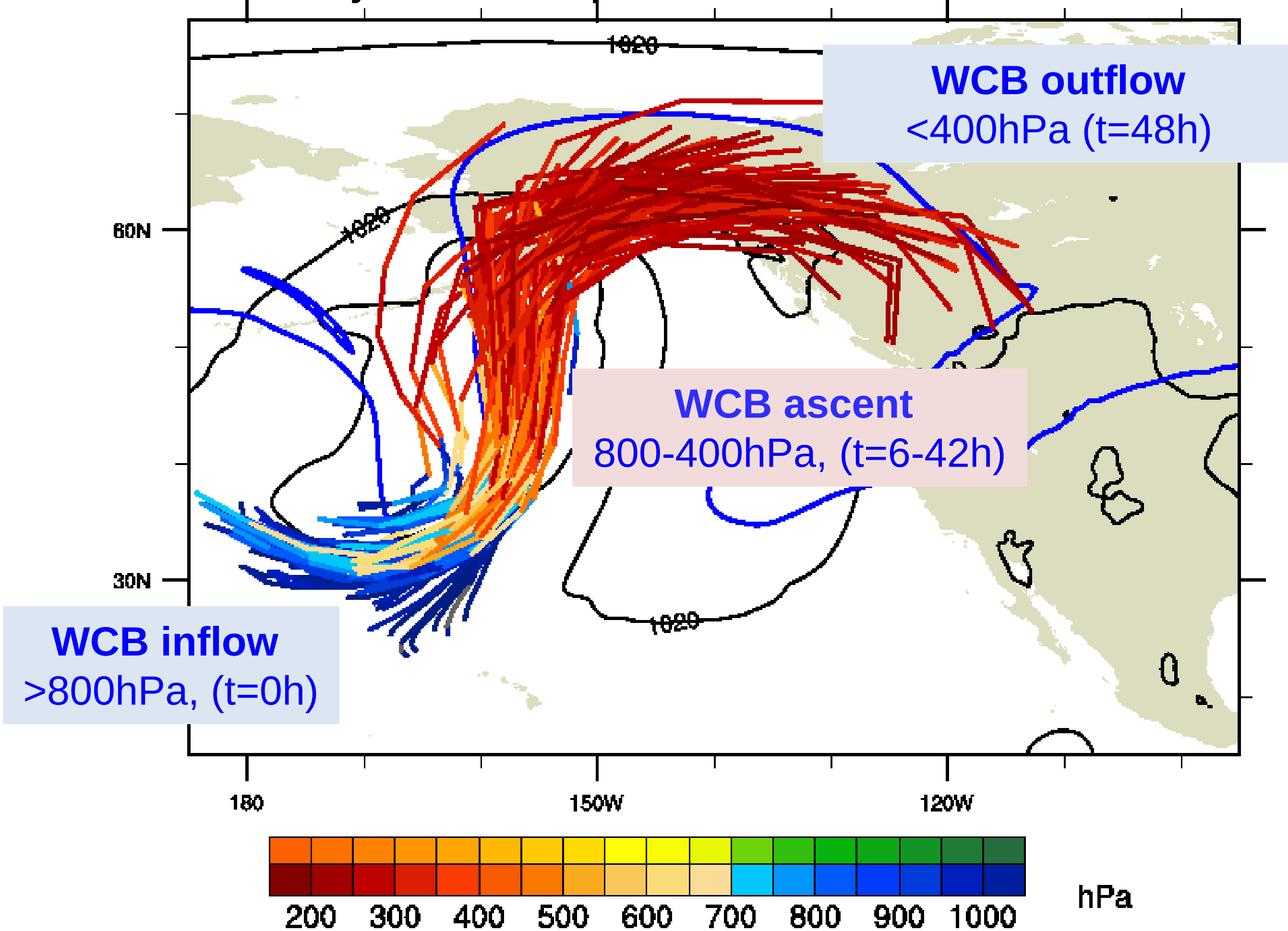
https://data.iac.ethz.ch/ml_cirrus/ec.ensemble/
(restricted access)

Schäfler, A., M. Boettcher, C. M. Grams, M. Rautenhaus, H. Sodemann, and H. Wernli, 2014: Planning aircraft measurements within a warm conveyor belt. *Weather*, **69**, 161–166, doi:10.1002/wea.2245.

Rautenhaus, M., C. M. Grams, A. Schäfler, and R. Westermann, 2015: Three-dimensional visualization of ensemble weather forecasts – Part 2: Forecasting warm conveyor belt situations for aircraft-based field campaigns. *Geosci. Model Dev.*, **8**, 2355–2377, doi:10.5194/gmd-8-2355-2015.

Warm conveyor belts

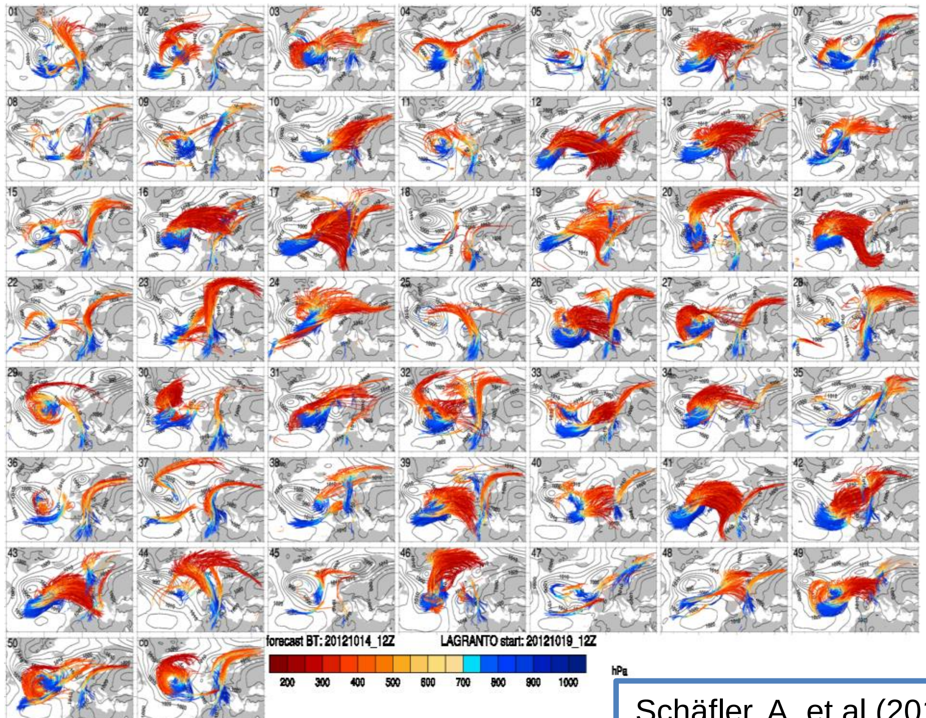
- operational ECMWF **high resolution** forecast
- **model level data** +0h to +96h every 3h; +96h to +192h every 6h
- 48h forward trajectories Δp/Δt >= 600hPa/48h



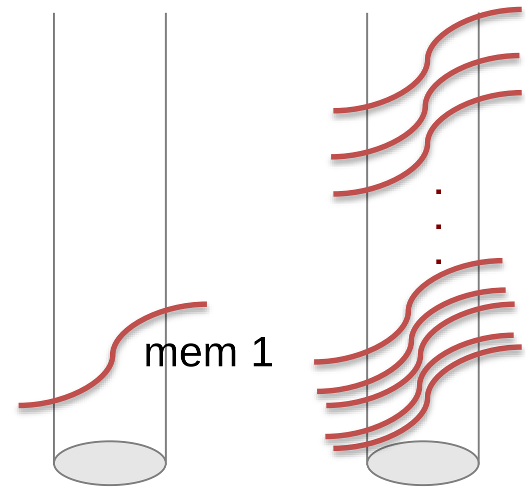
WCB ensemble forecast

- operational ECMWF **ensemble** forecast
- **model level data** +0h to +168h every 6h
- 48h forward trajectories Δp/Δt >= 550hPa/48h

WCB calculations for each ECMWF ensemble member on ecgate



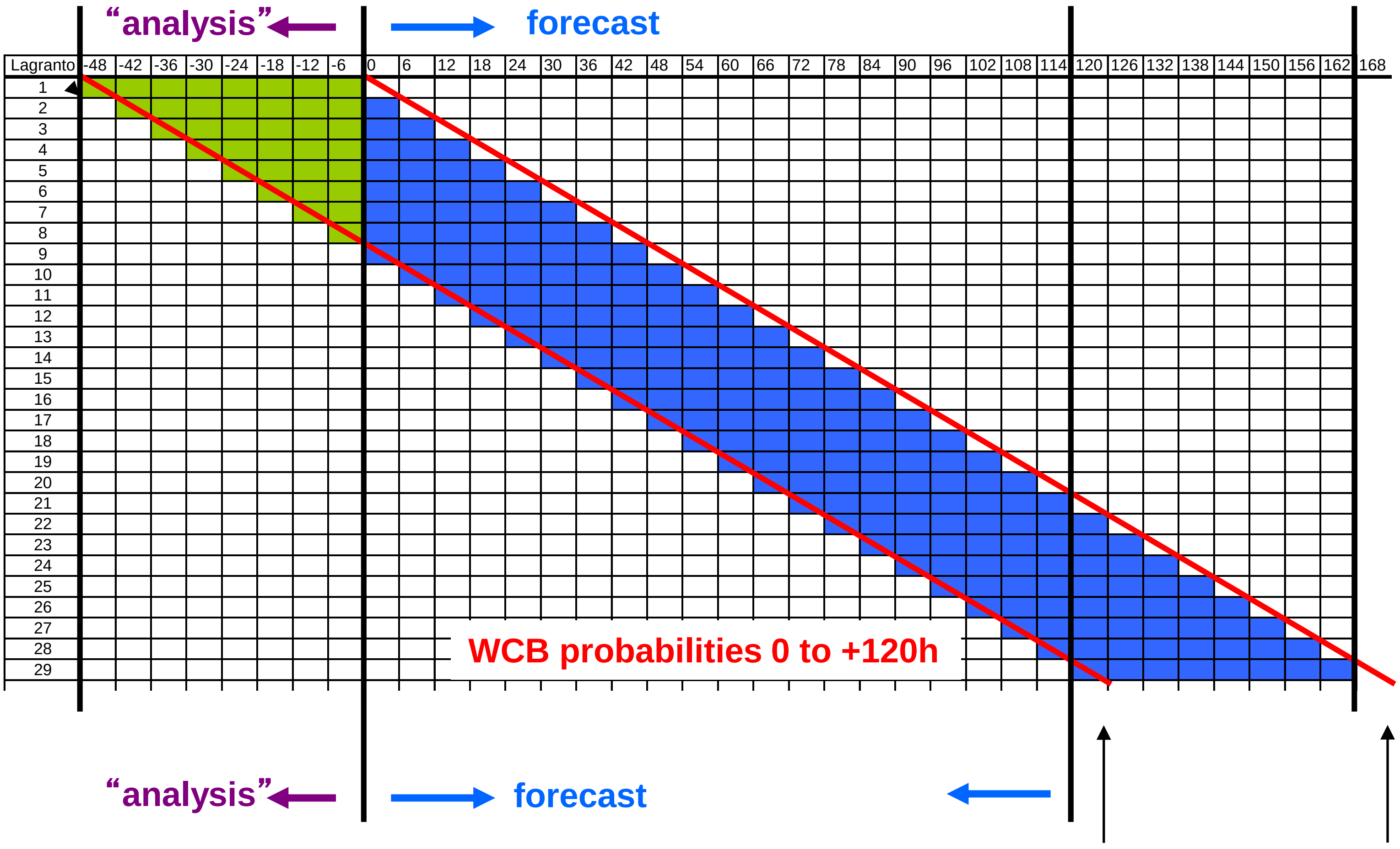
∑=51 → 100%



Schäfler, A. et al (2014), *Weather*, doi:10.1002/wea.2245.
Rautenhaus, M., C. Grams, et al. (2015), *GMD*, doi:10.5194/gmd-8-2355-2015.

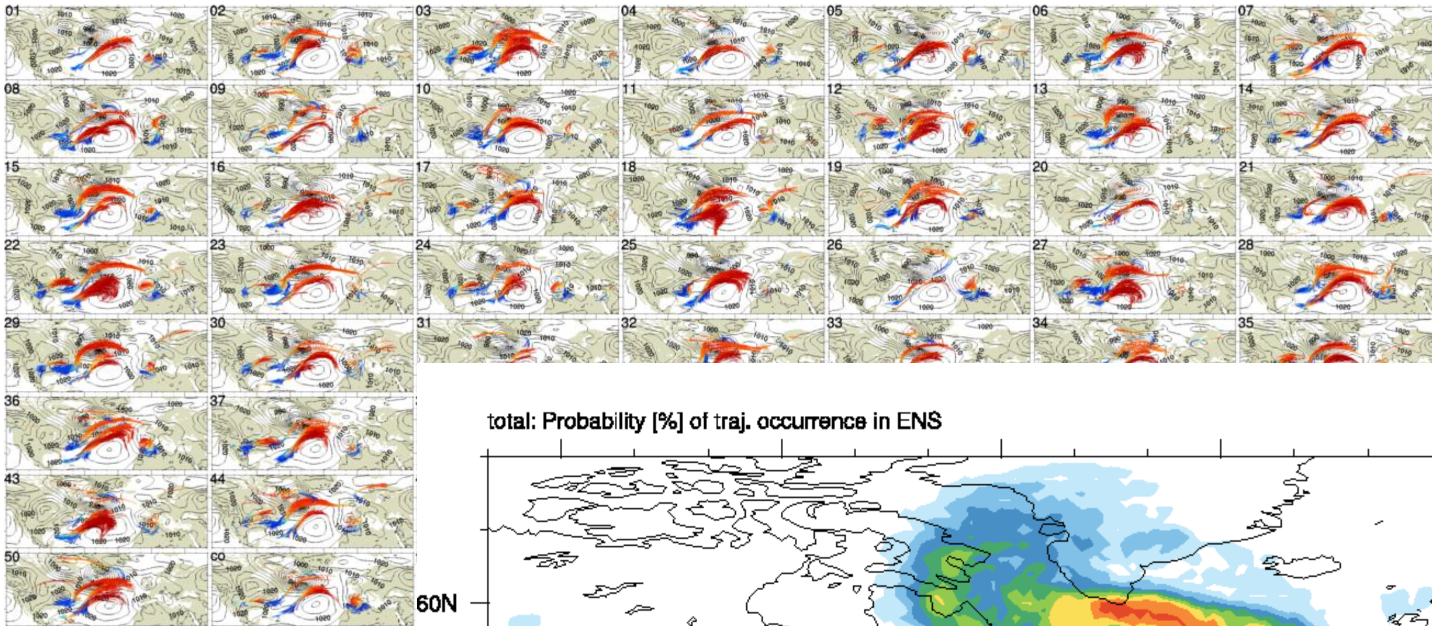
WCB ensemble forecast

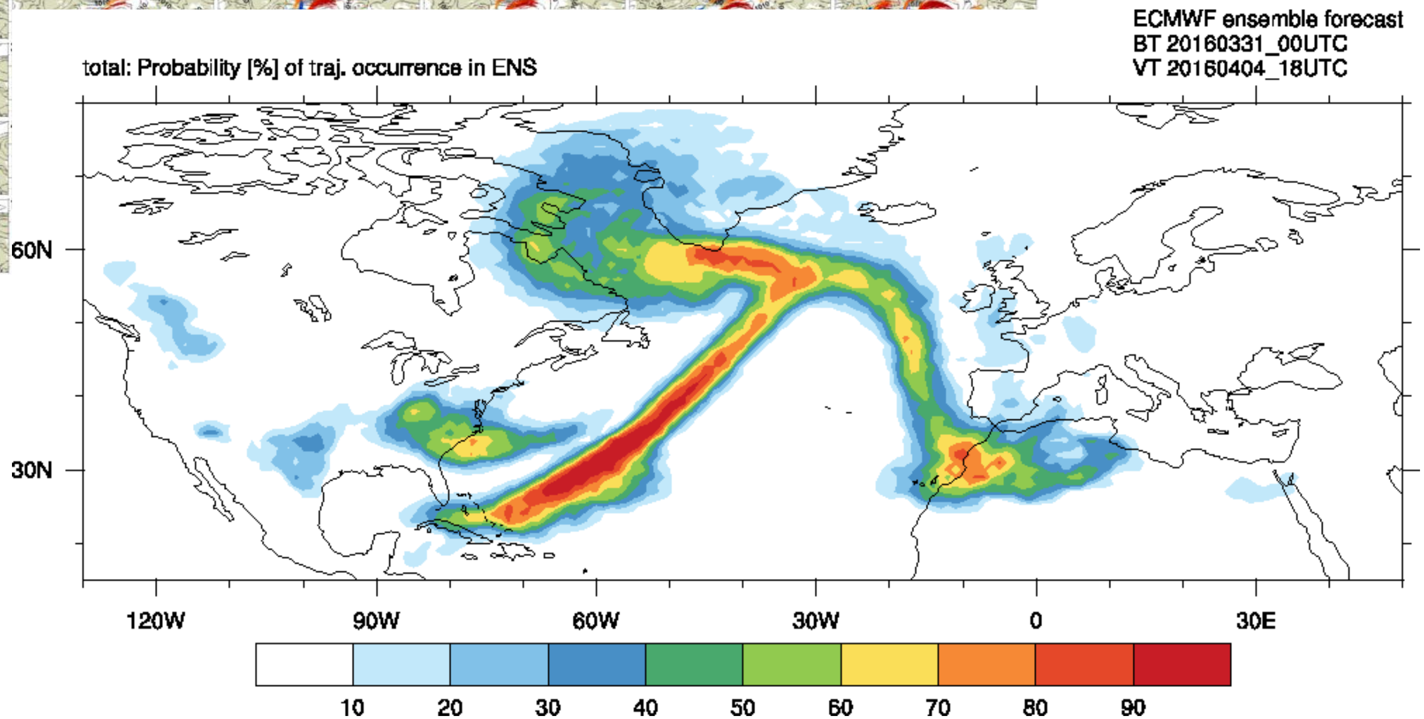
- Illustration of time-lagged Lagranto for **one** forecast



- **at each fc time (0 to 120 hours) trajectories from 9 LAGRANTO calculations for one fc**

WCB ensemble forecast





Probabilities for different layers:

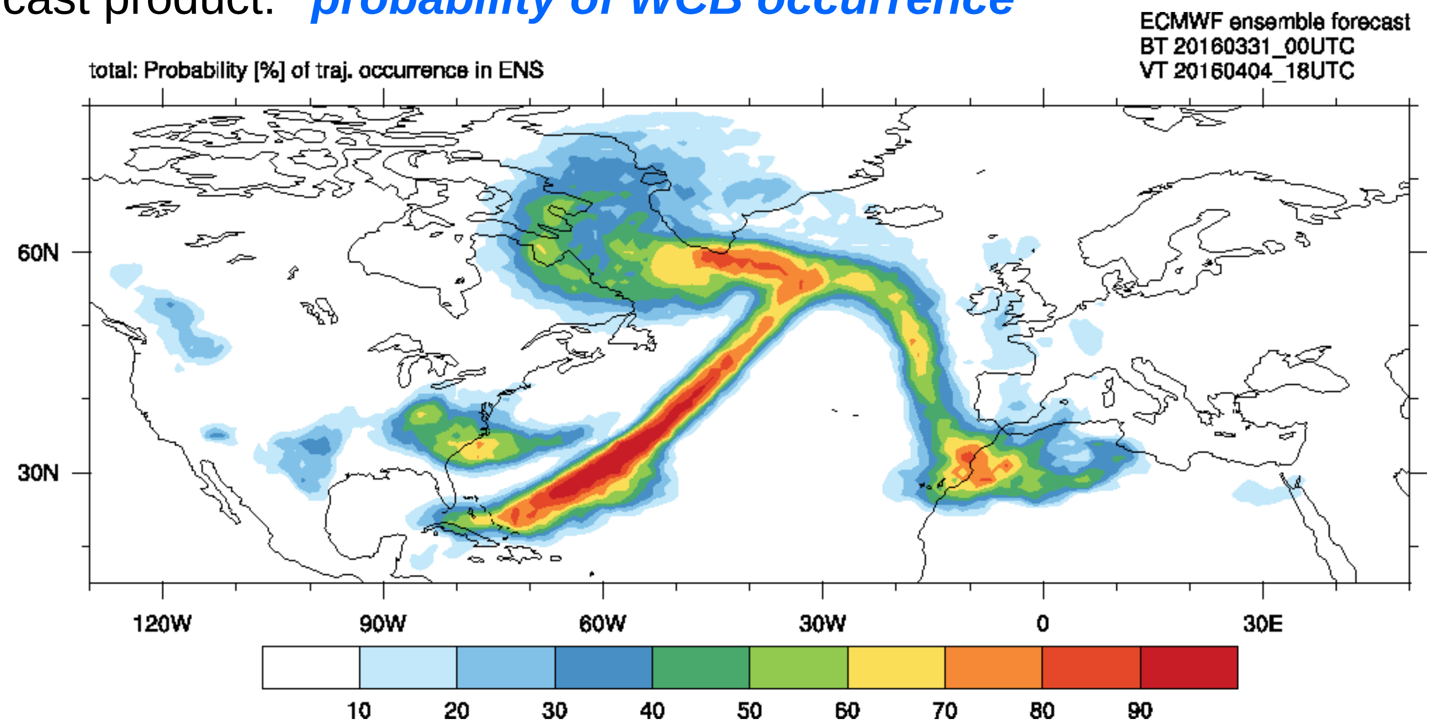
- Total
- Outflow
- Ascent
- Inflow

Schäfler, A. et al (2014), *Weather*, doi:10.1002/wea.2245.
Rautenhaus, M., C. Grams, et al. (2015), *GMD*, doi:10.5194/gmd-8-2355-2015.

WCB ensemble forecast

WCB probability BT 20160331_00 VT +114h 20160404_18
Total column

- Forecast product: ***probability of WCB occurrence***



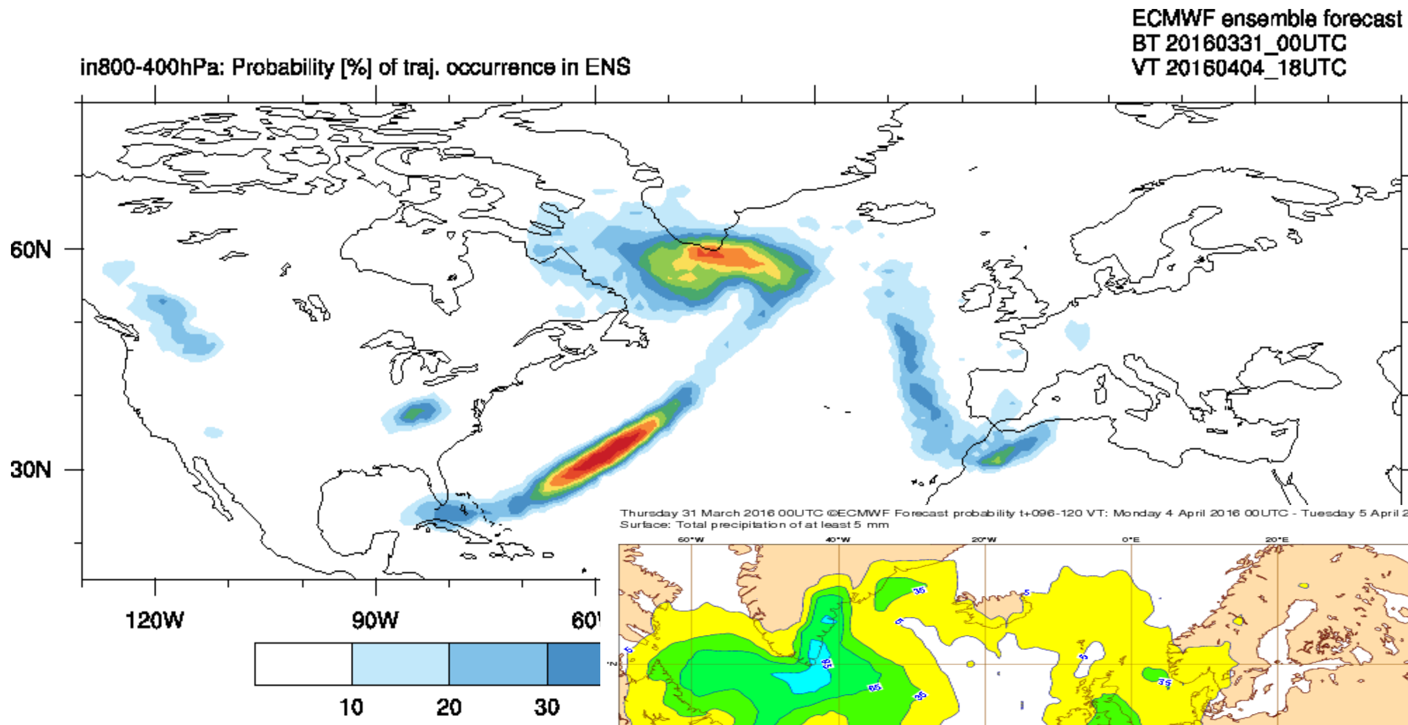
$$\boxed{\frac{1}{\mathbf{E}}\sum_{e}\mathbf{M}_{i,j}^{e}}$$

M: mask indicating if (M=1) or if not (M=0) ens mem. **e** has a traj at **(i,j)**
E: number of ens. members (=51)
i,j: index of gridpoint **(i,j)**
e: index of ensemble member **e**

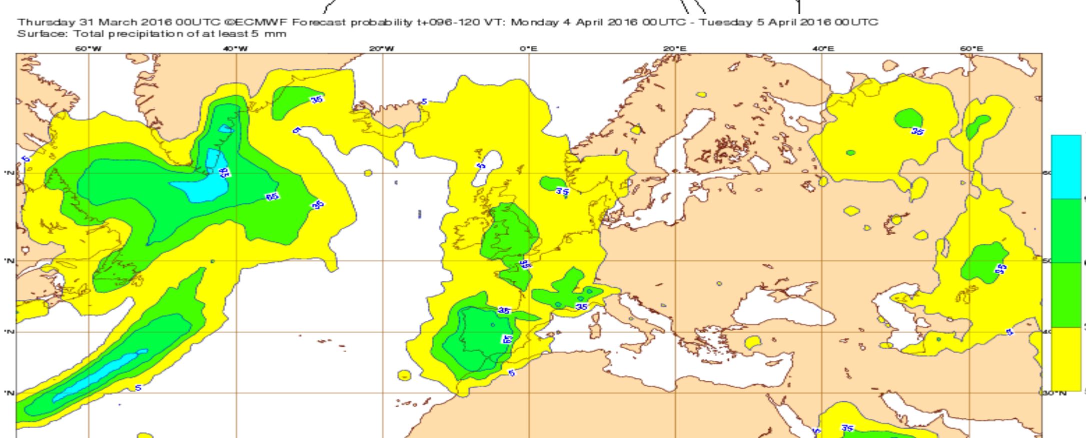
Schäfler, A. et al (2014), *Weather*, doi:10.1002/wea.2245.
Rautenhaus, M., C. Grams, et al. (2015), *GMD*, doi:10.5194/gmd-8-2355-2015.

WCB ensemble forecast

WCB probability BT 20160331_00 VT +114h 20160404_18
Ascent (800-400hPa)



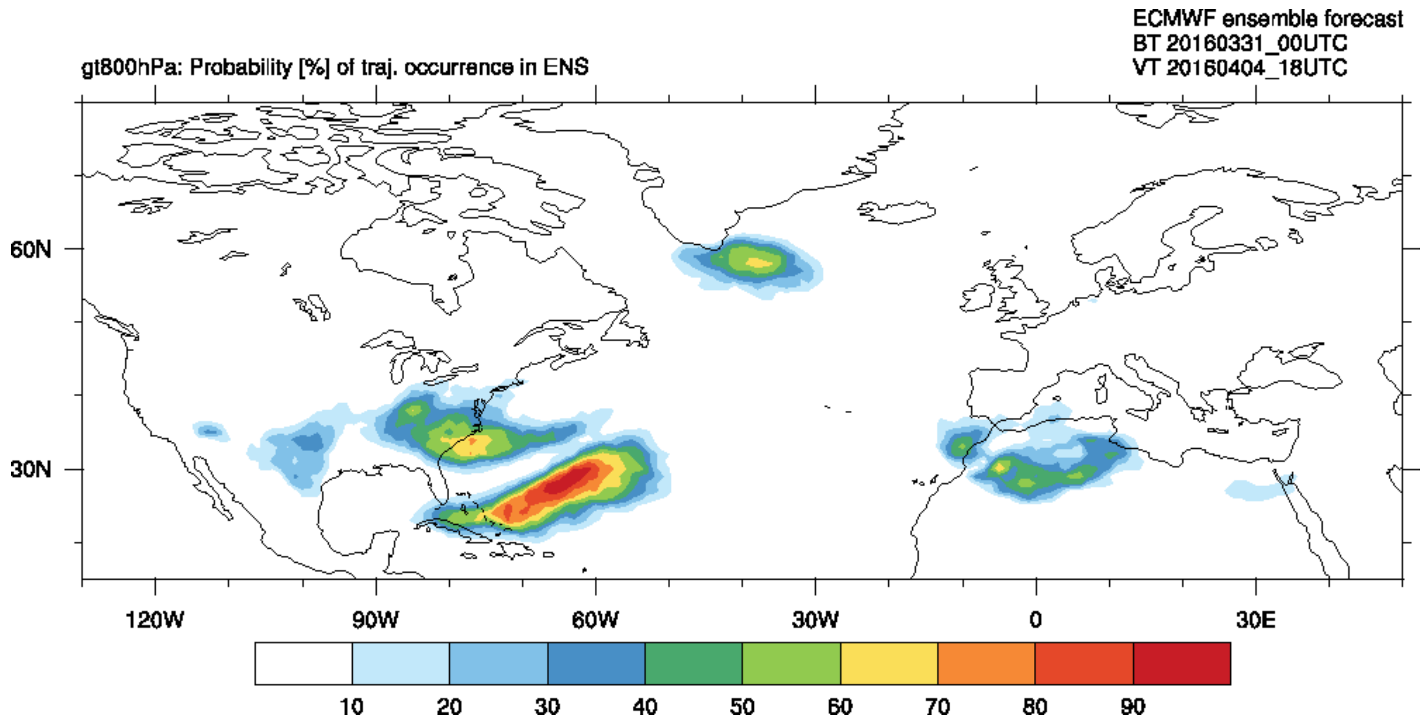
Probability precip>5mm
BT 20160331_00 VT +96 to 120h



Schäfler, A. et al (2014), *Weather*, doi:10.1002/wea.2245.
Rautenhaus, M., C. Grams, et al. (2015), *GMD*, doi:10.5194/gmd-8-2355-2015.

WCB ensemble forecast

WCB probability BT 20160331_00 VT +114h 20160404_18
Inflow (>800hPa)



Schäfler, A. et al (2014), *Weather*, doi:10.1002/wea.2245.
Rautenhaus, M., C. Grams, et al. (2015), *GMD*, doi:10.5194/gmd-8-2355-2015.

WCB ensemble forecast

Demonstration of current forecast products:

- High resolution forcast
- Ensemble forecast
- (crosstool)

https://data.iac.ethz.ch/ml_cirrus/ec.ensemble/

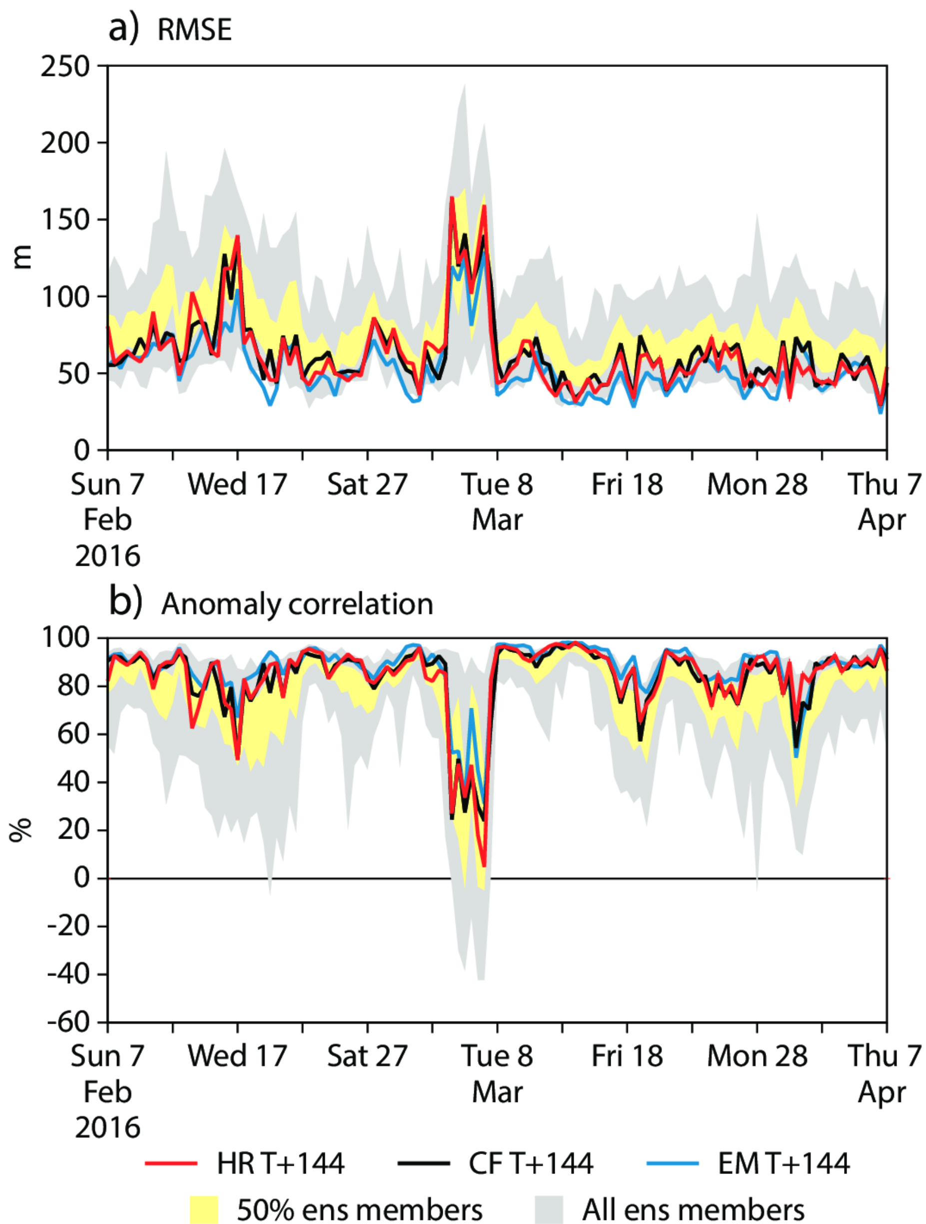
(restricted access)

4. A recent forecast bust

Madonna, E., M. Boettcher, C. M. Grams, H. Joos, O. Martius, and H. Wernli, 2015: Verification of North Atlantic warm conveyor belt outflowsin ECMWF forecasts. *Q.J.R. Meteorol. Soc.*, **141**, 1333–1344, doi:10.1002/qj.2442.

Grams, C.M., L. Magnusson, and E. Madonna, 2017: An atmospheric dynamics' perspective on the amplification and propagation of forecast error in numerical weather prediction models: a case study. *In preparation for QJRMS*

00UTC 7 March 2016 forecast bust



Z500 RMSE and ACC for HRES and ENS - Europe

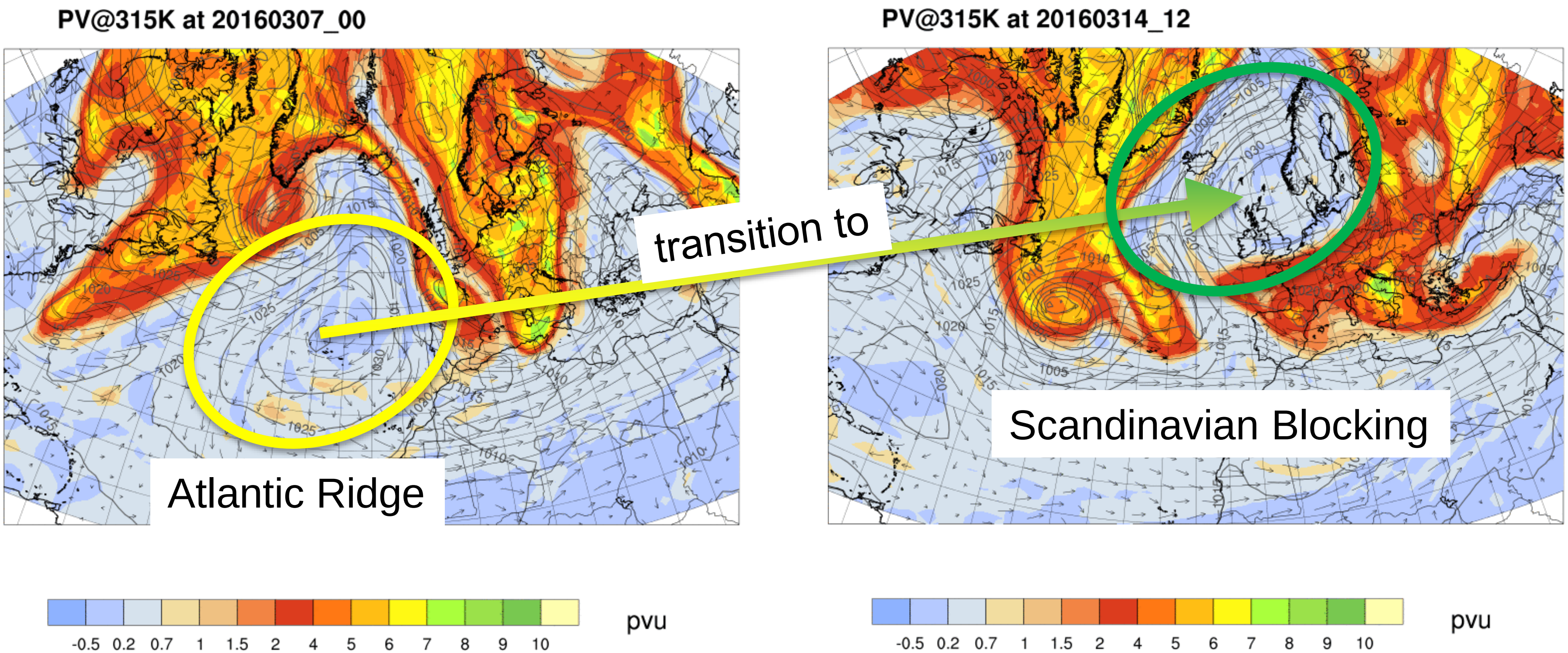
Plots by Linus Magnusson (ECMWF)

Synoptic evolution

AR to **BL** transition from **20160307_00** to **20160308_18**

ECMWF analysis
PV@315K, 00 UTC 7 March

PV@315K, 12UTC 14 March



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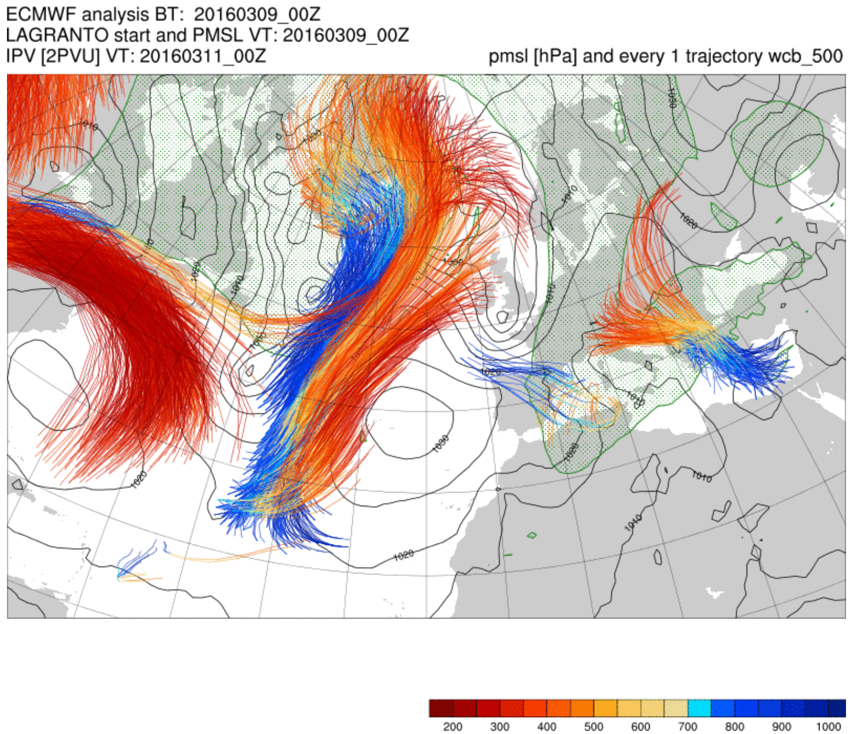
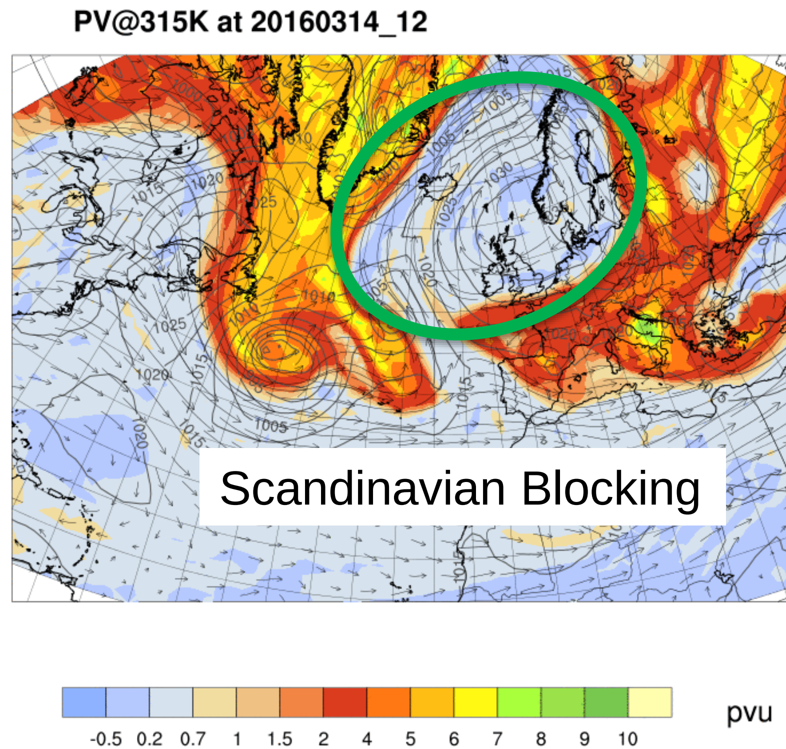
Synoptic evolution

AR to **BL** transition from **20160307_00** to **20160308_18**

ECMWF analysis

PV@315K, 12UTC 14 March

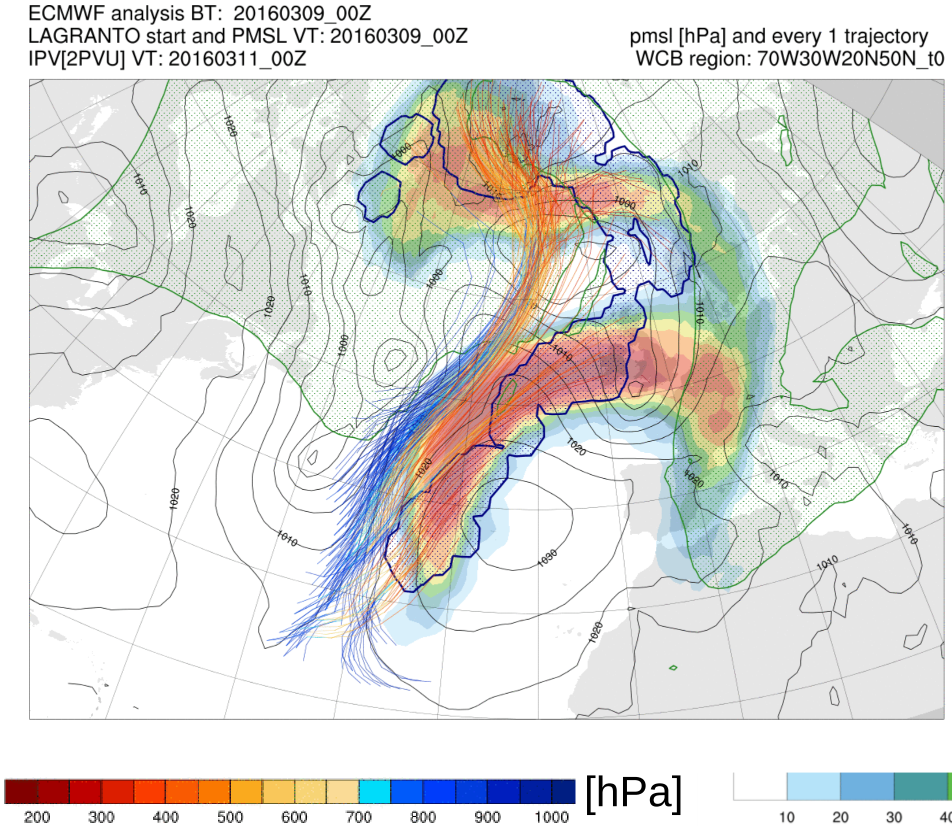




WCB
start 00 UTC 9 March → end 00 UTC 11 March
& PMSL &PV@315K

The PAL forecast metric

- Metric for quantifying the **P**V, **A**mplitude, and **L**ocation error of WCB outflow objects
- **P** term: <0, too weak / >0, too strong negative PV anomaly in outflow
- **A** term: <0, too few / >0 too many trajectories
- **L** term: 0 good; close to 2 → objects in opposite corners



Madonna et al. (2014), *QJRMS,* [doi:10.1002/qj.2442](https://doi.org/10.1002/qj.2442)

tra starting & pmsl 20160309_00

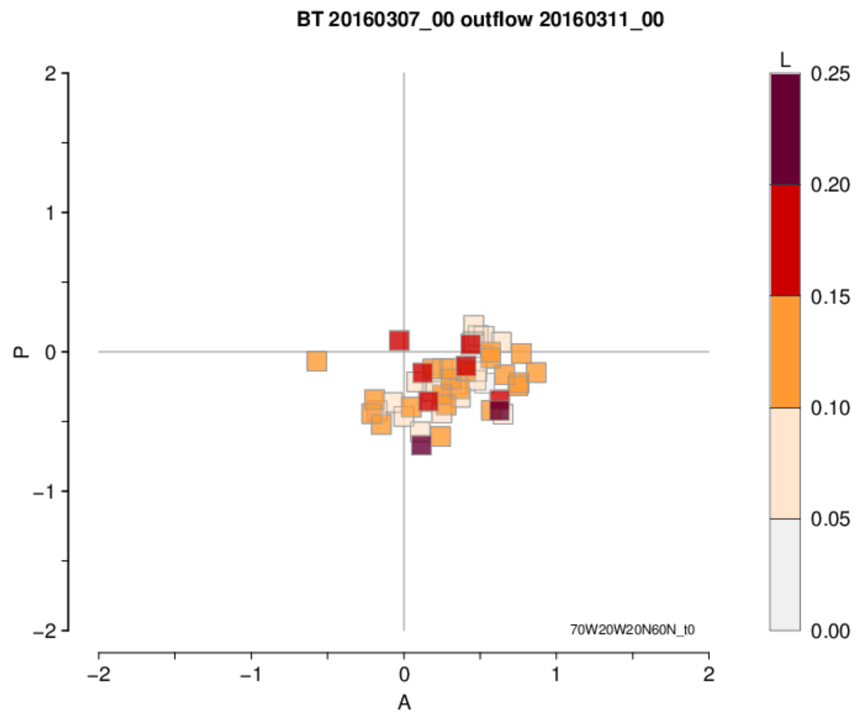
tra ending & 2PVU@315K &

WCB outflow probabilities [%] 20160311_00

The PAL forecast metric

- Metric for quantifying the **P**V, **A**mplitude, and **L**ocation error of WCB outflow objects
- **P** term: <0, too weak / >0, too strong negative PV anomaly in outflow
- **A** term: <0, too few / >0 too many trajectories
- **L** term: 0 good; close to 2 → objects in opposite corners

PAL diagram illustrates the three components, for different forecast members



Madonna et al. (2014), *QJRMS*, [doi:10.1002/qj.2442](https://doi.org/10.1002/qj.2442)

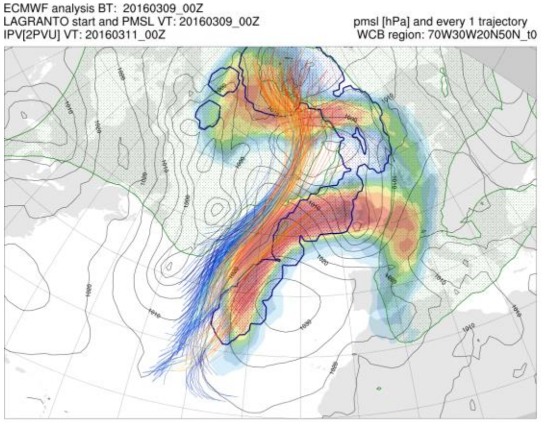
Plot by Erica Madonna (Uni Bergen)

Role of WCB in forecast bust

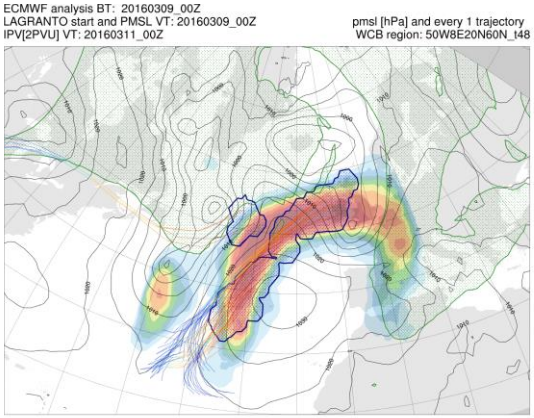
ECMWF ensemble initial time **20160307_00**

focus on WCB **starting 00 UTC 9 March (+48h) → ending 00 UTC 11 March (+96h)**

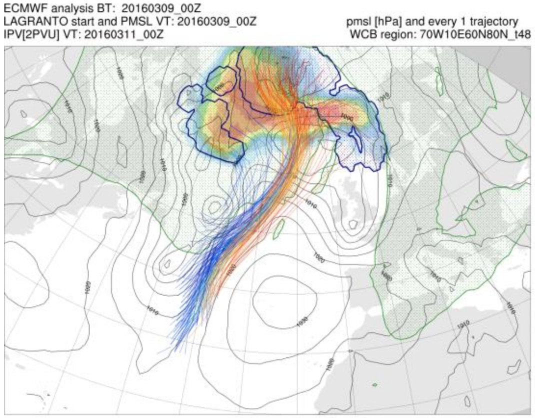
ALL

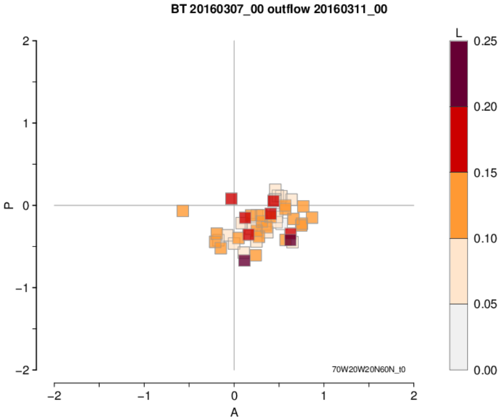


SOUTH



NORTH



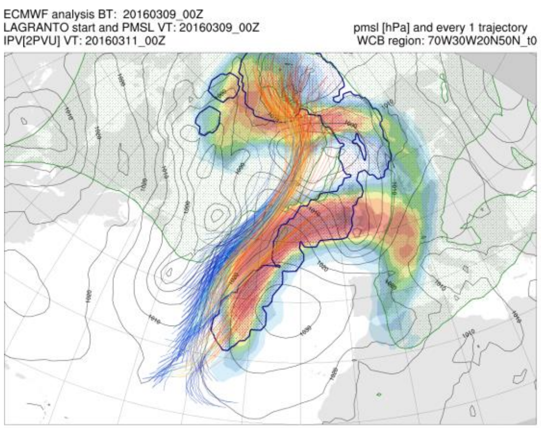


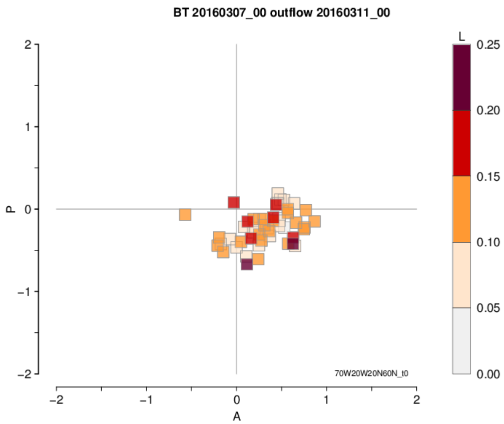
Role of WCB in forecast bust

ECMWF ensemble initial time **20160307_00**

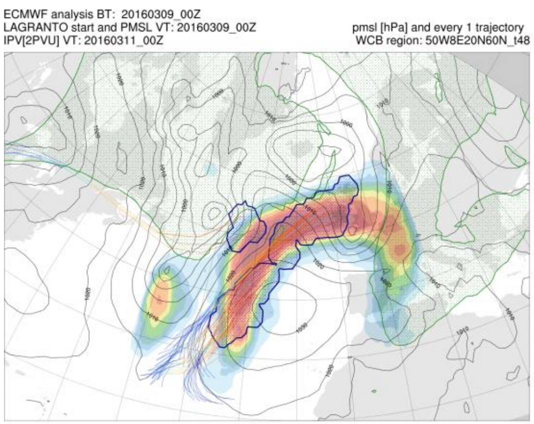
focus on WCB **starting at 09_00Z (+48h) → ending at 11_00Z (+96h)**

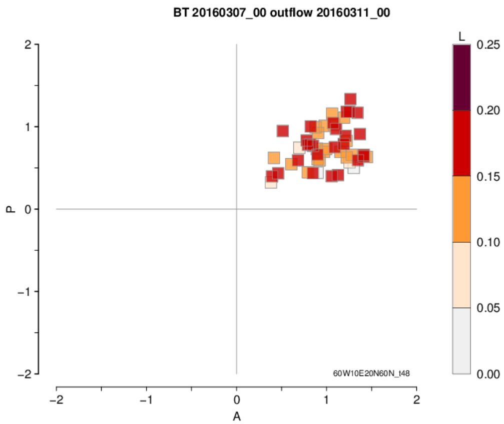
ALL



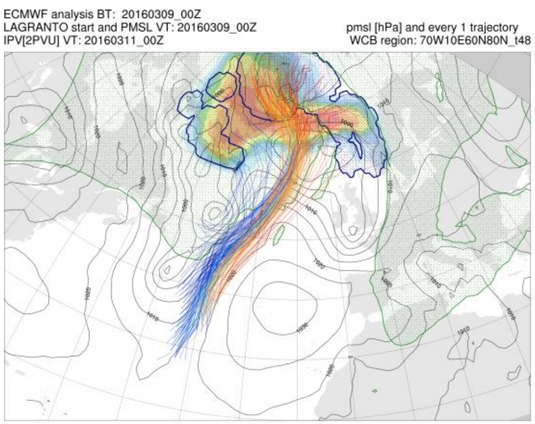


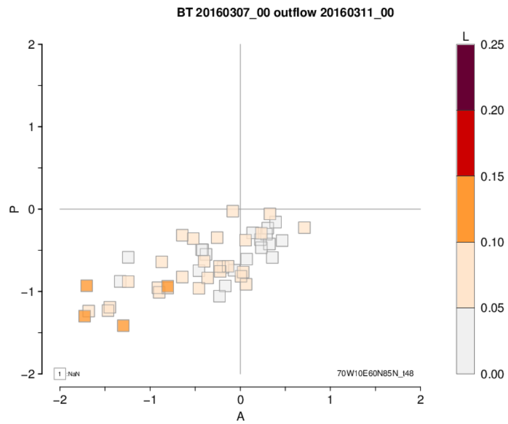
SOUTH





NORTH

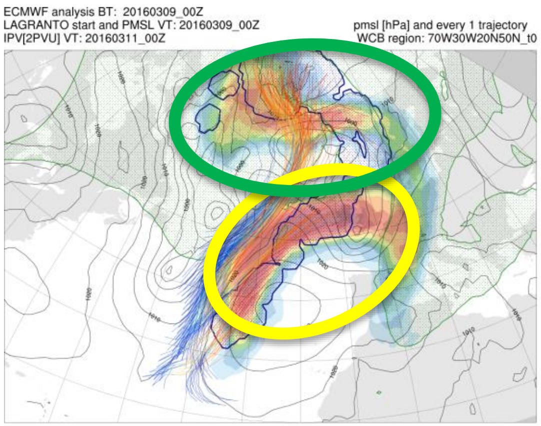




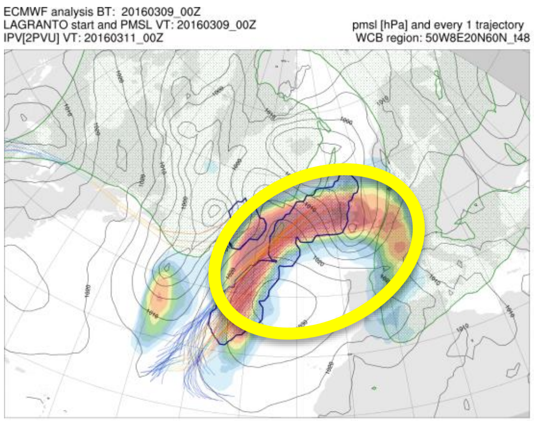
 christian.grams@env.ethz.ch

Role of WCB in forecast bust

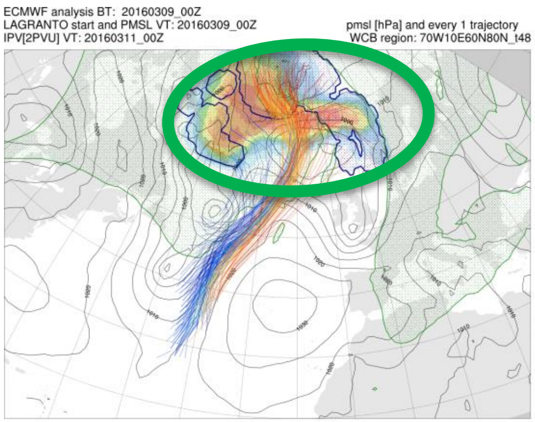
ALL



SOUTH



NORTH



- Southern WCB branch is too strong, rather maintains AR
- Northern branch is too weak, BL does not establish over Scandinavia

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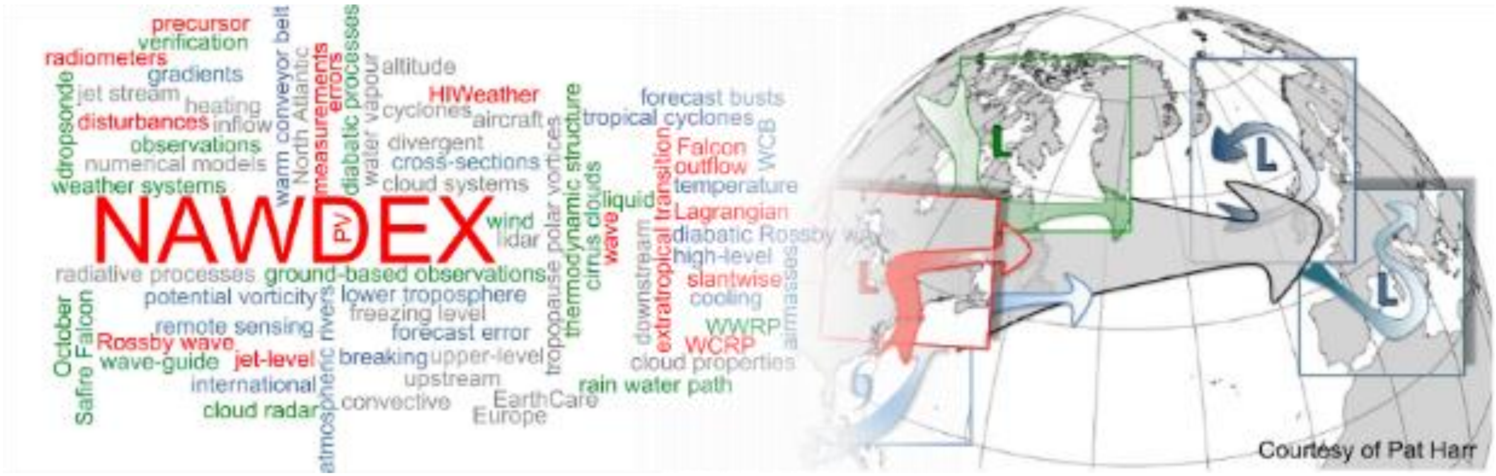
5. Demonstration NAWDEX

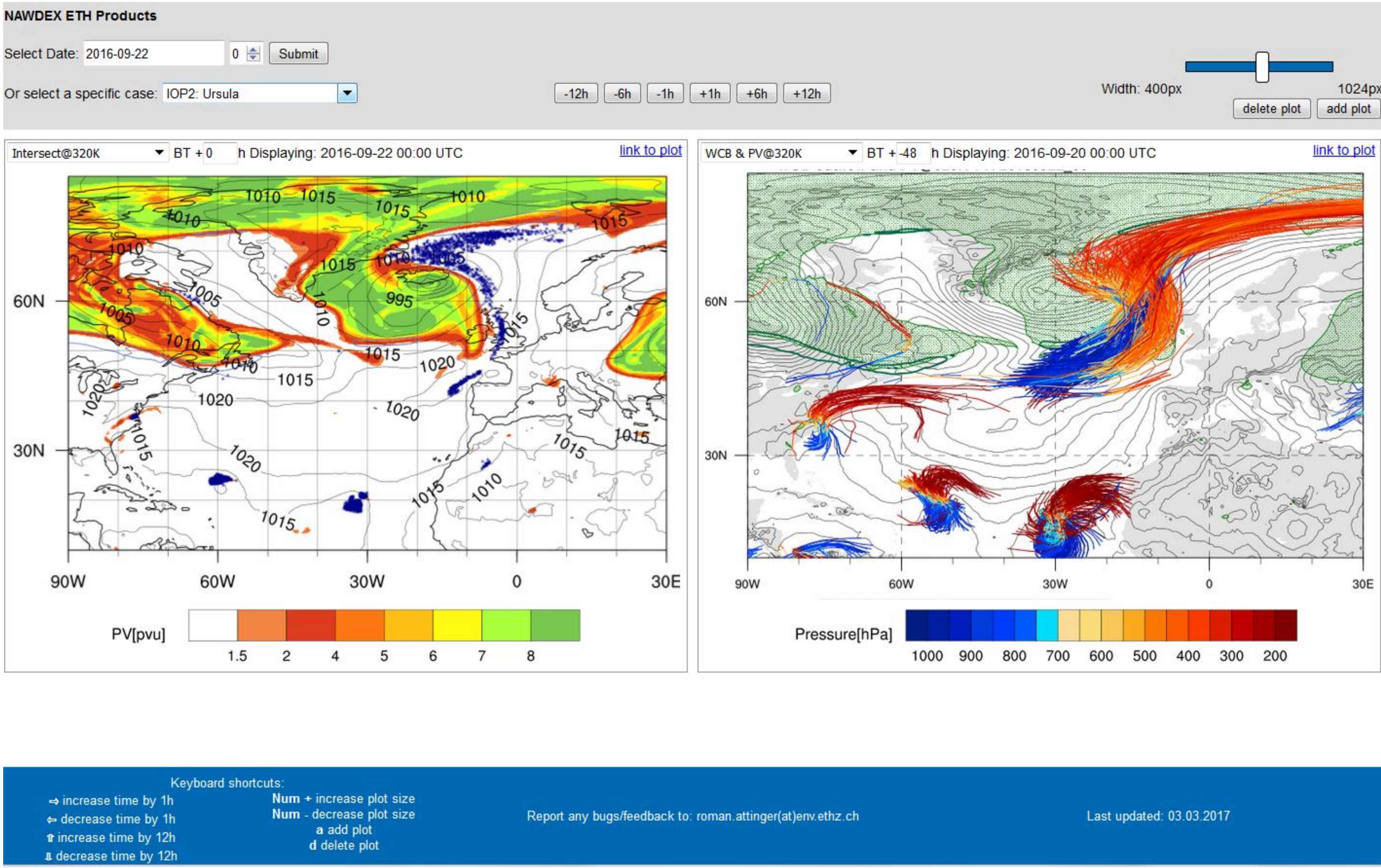


Demonstration of flight planning for IOP2 21 Sep 2016

http://nawdex.ethz.ch/

https://data.iac.ethz.ch/nawdex/index.php
(restricted access)

NAWDEX IOP2



https://data.iac.ethz.ch/nawdex/index.php

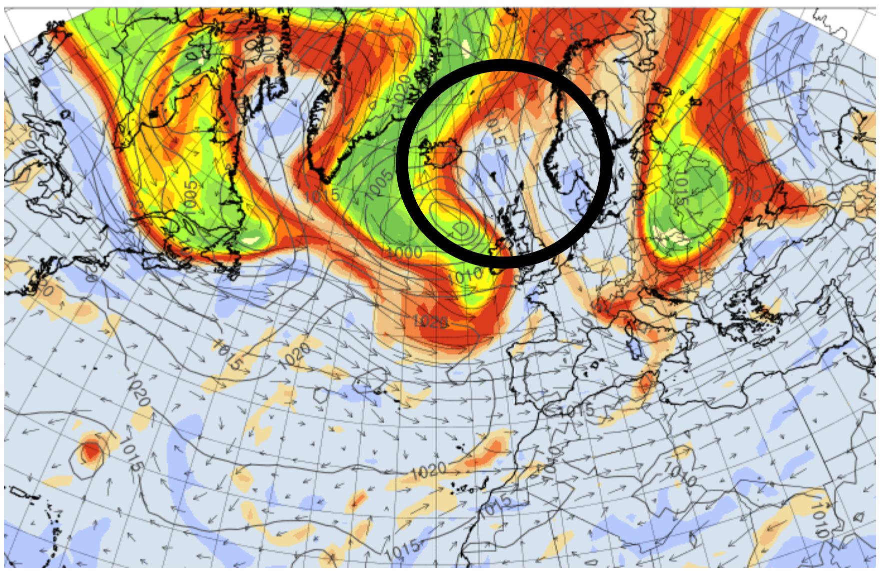
(restricted access)

Roman Attinger, Maxi Böttcher, Julian Quinting

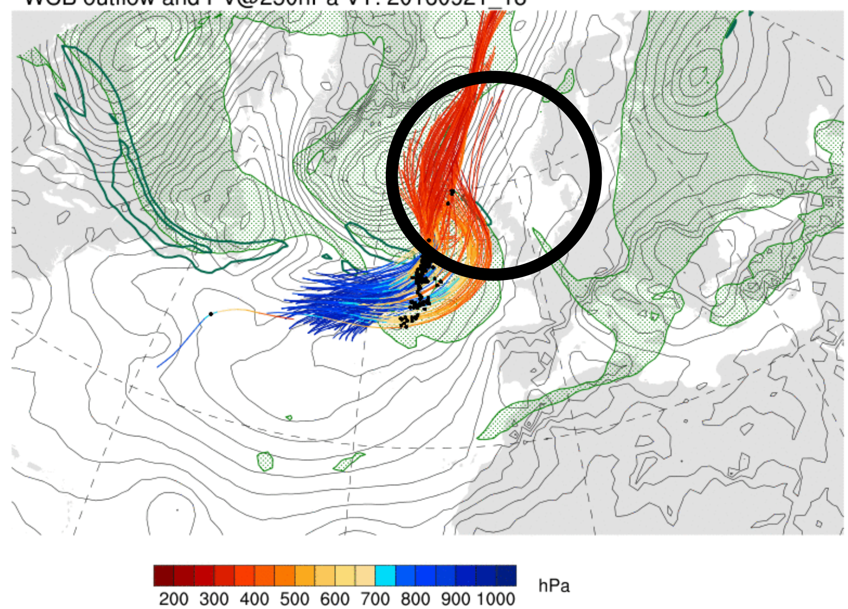
Forecast for Wed, 21 Sep 2016 18 UTC

BT18/00Z

PV@325K at 20160921_18



Trajectory start and SLP VT: 20160919_18
WCB outflow and PV@250hPa VT: 20160921_18



3 days before mission:

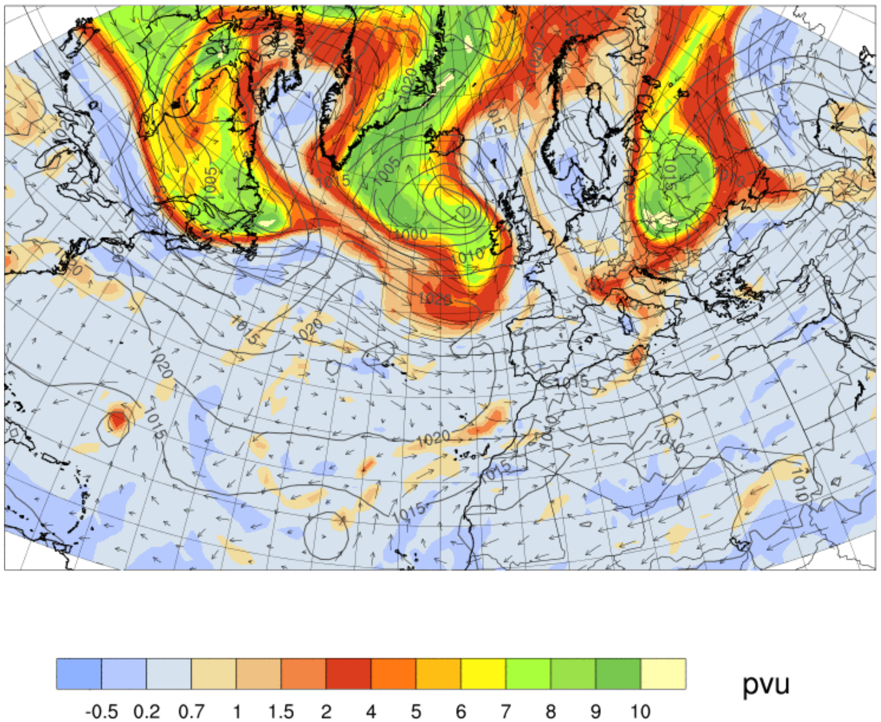
- Monitoring of evolution in **hres** and confirmation with **ensemble**

Maxi Böttcher and Julian Quinting

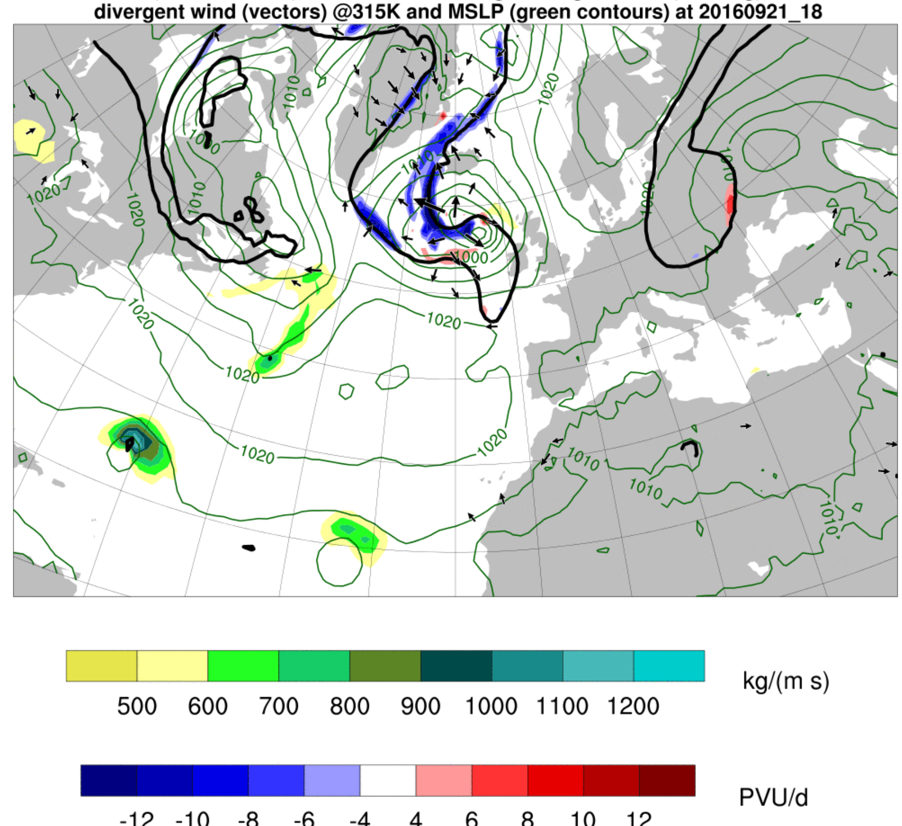
Forecast for Wed, 21 Sep 2016 18 UTC

BT18/00Z

PV@325K at 20160921_18



2 PVU (black contour), PV advection through divergent wind (shading), divergent wind (vectors) @315K and MSLP (green contours) at 20160921_18



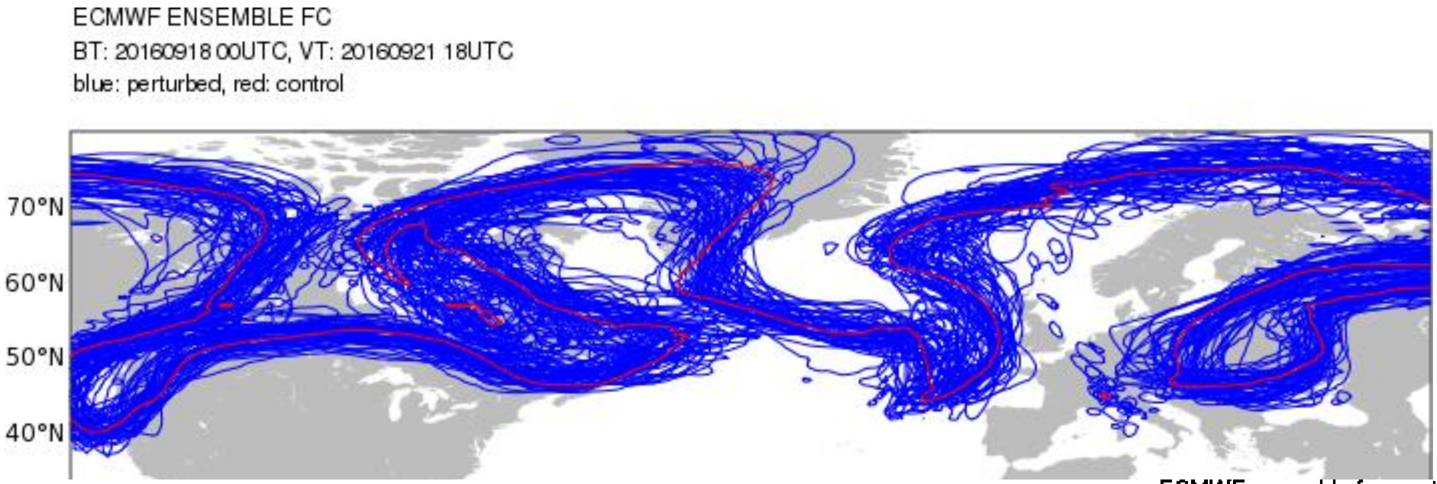
3 days before mission:

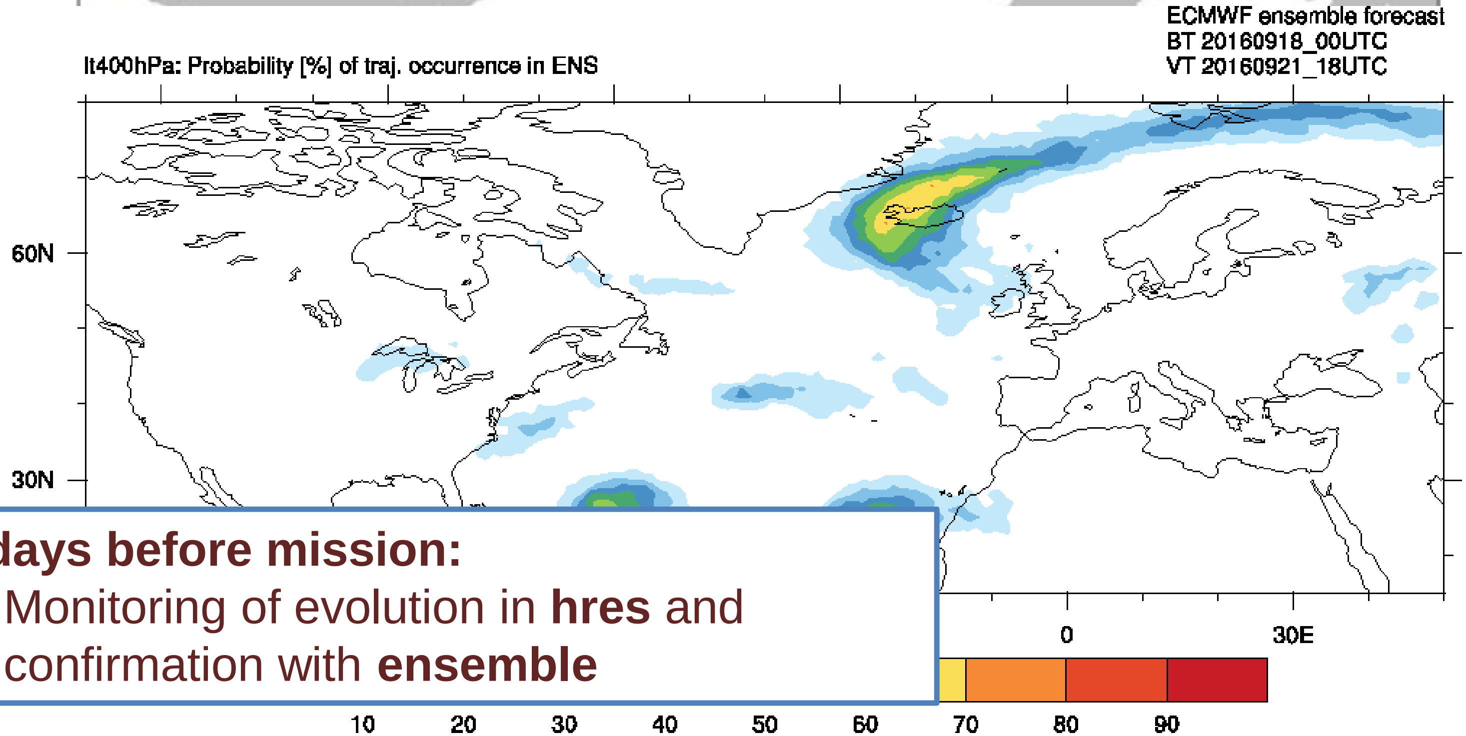
- Monitoring of evolution in **hres** and confirmation with **ensemble**

Maxi Böttcher and Julian Quinting

Forecast for Wed, 21 Sep 2016 18 UTC

BT18/00Z



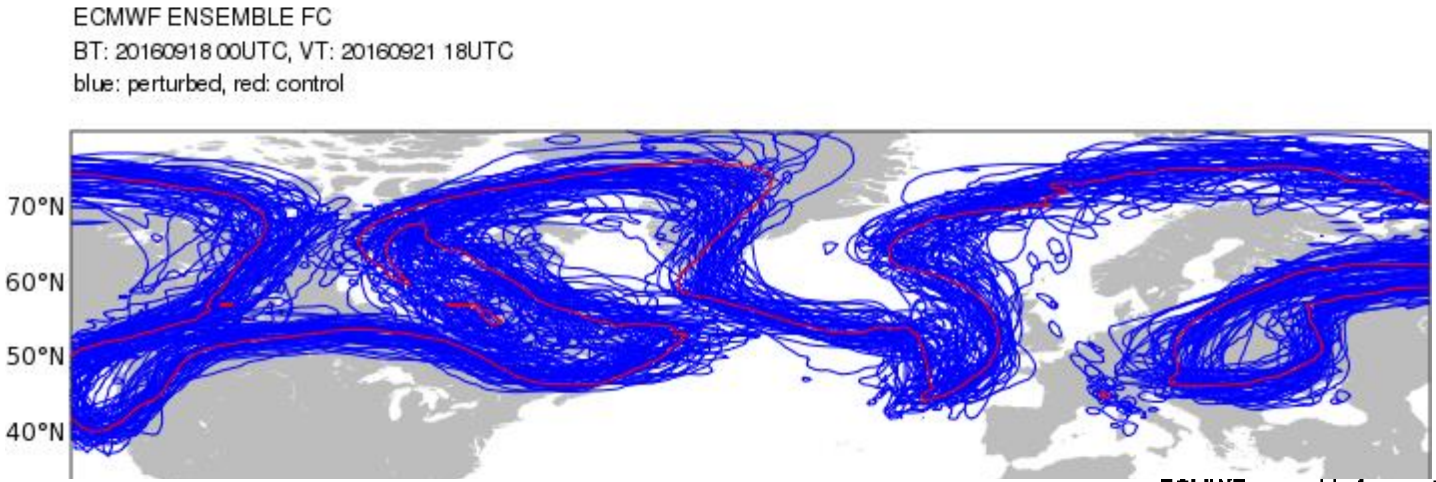


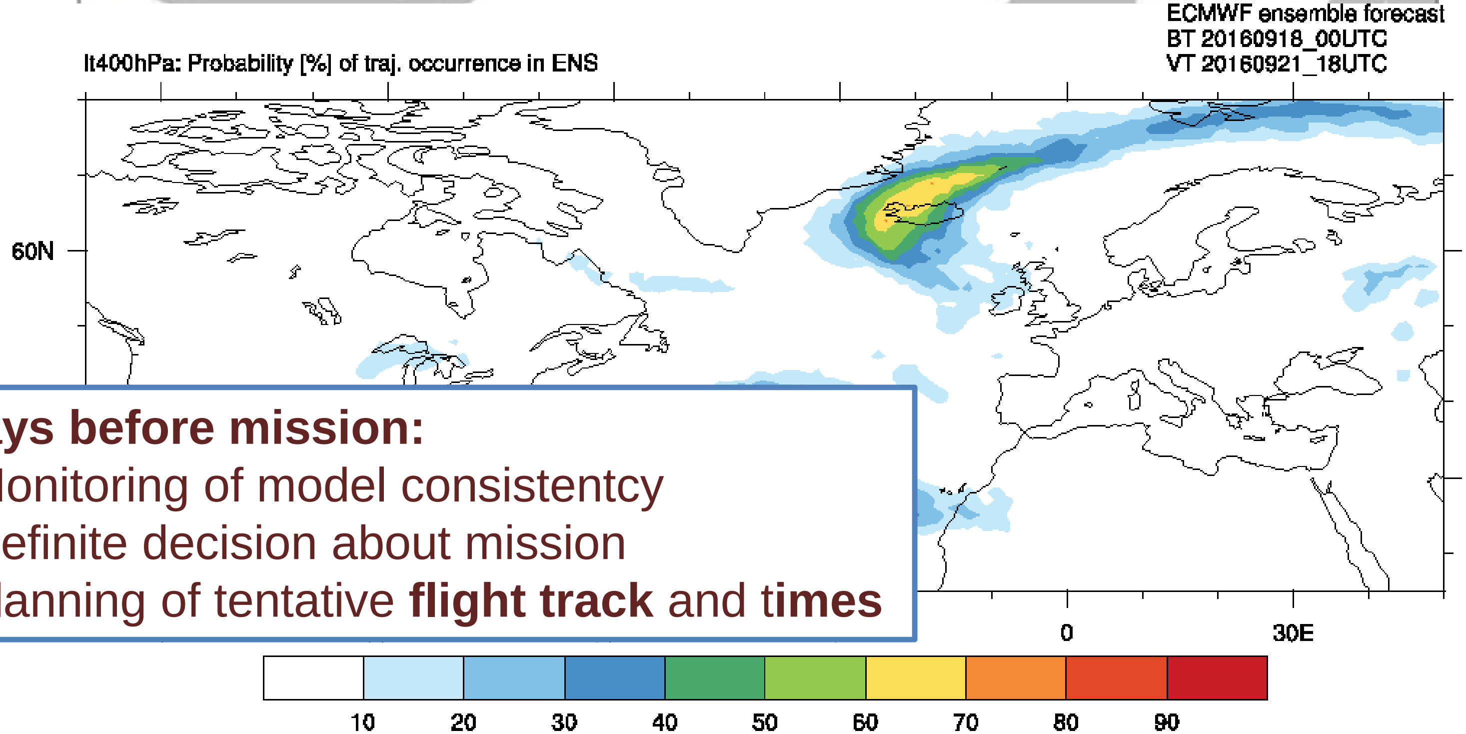
3 days before mission:

- Monitoring of evolution in **hres** and confirmation with **ensemble**

Forecast for Wed, 21 Sep 2016 18 UTC – Model consistency

BT18/00Z



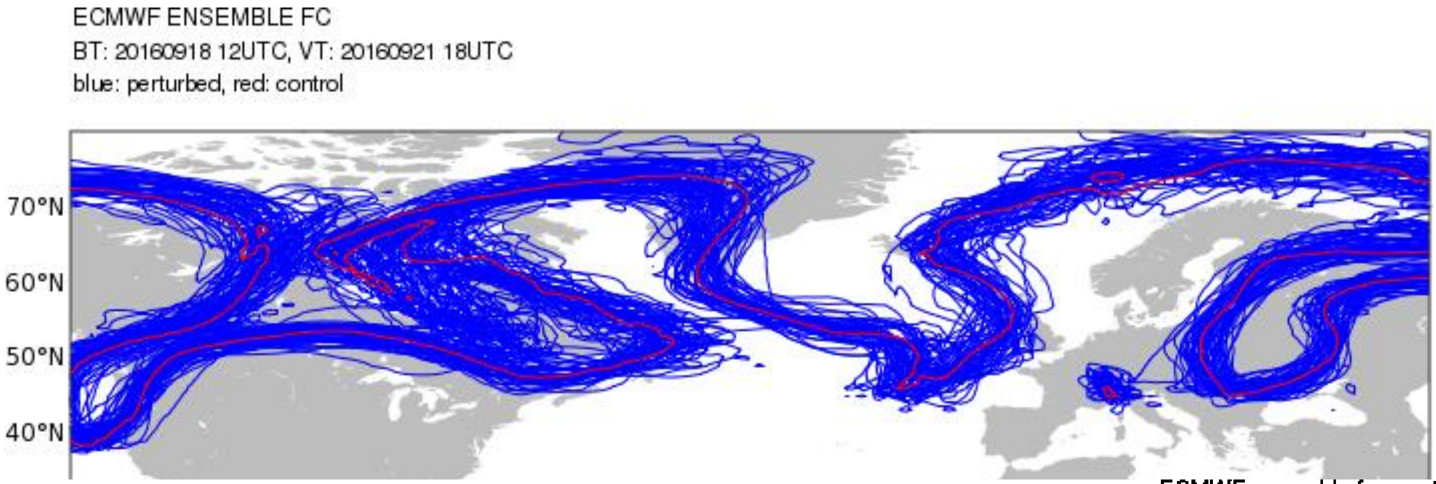


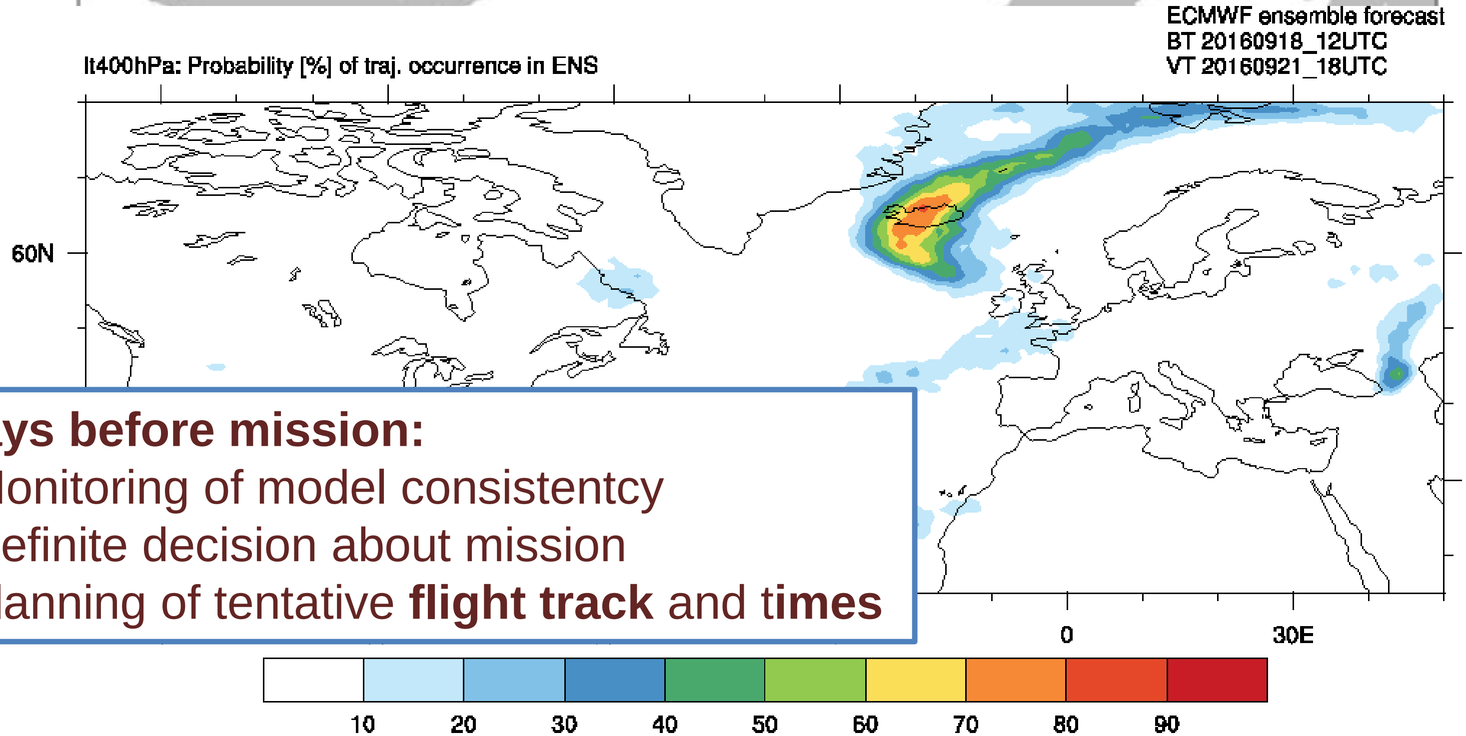
2 days before mission:

- Monitoring of model consistentcy
- Definite decision about mission
- planning of tentative **flight track** and t**imes**

Forecast for Wed, 21 Sep 2016 18 UTC – Model consistency

BT18/12Z



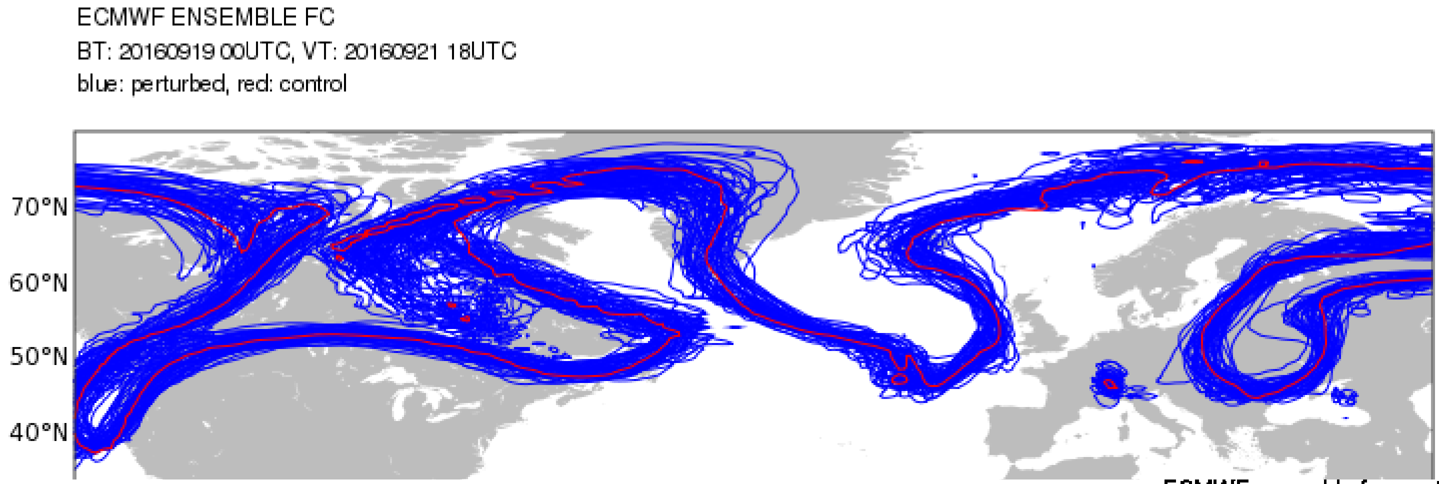


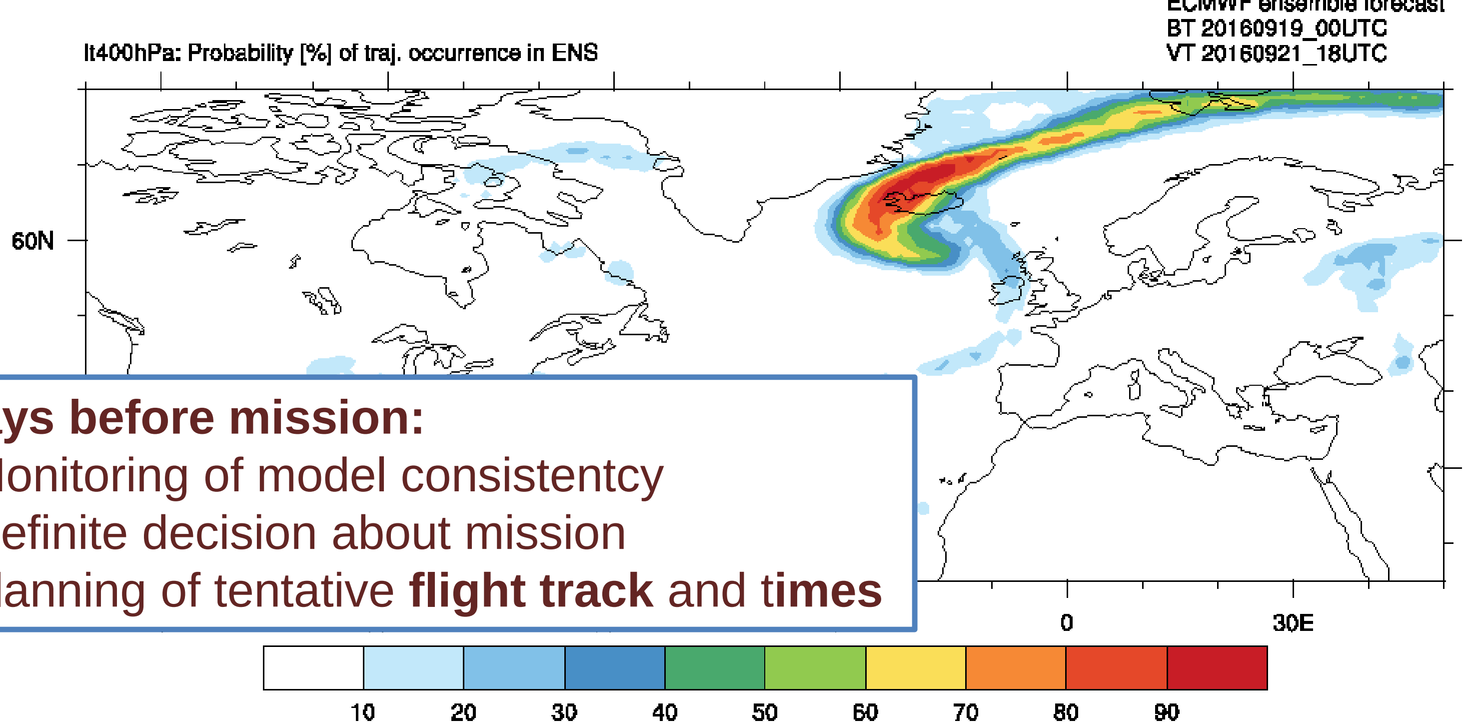
2 days before mission:

- Monitoring of model consistentcy
- Definite decision about mission
- planning of tentative **flight track** and **times**

Forecast for Wed, 21 Sep 2016 18 UTC – Model consistency

BT19/00Z





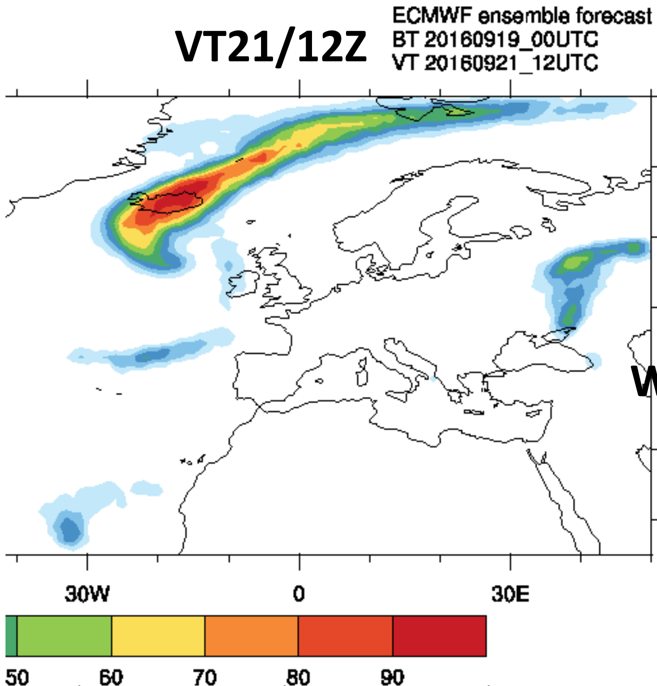
2 days before mission:

- Monitoring of model consistentcy
- Definite decision about mission
- planning of tentative **flight track** and **times**

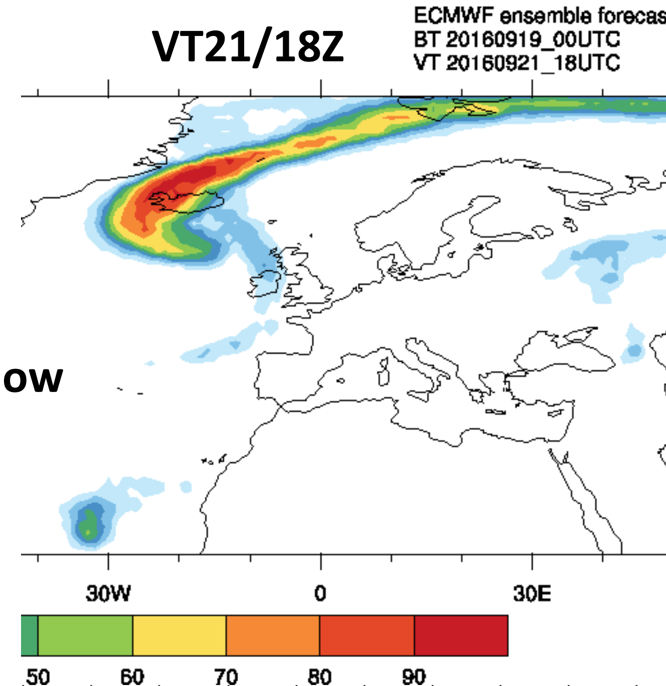
Forecast for Wed, 21 Sep 2016 18 UTC – Model consistency

BT19/00Z

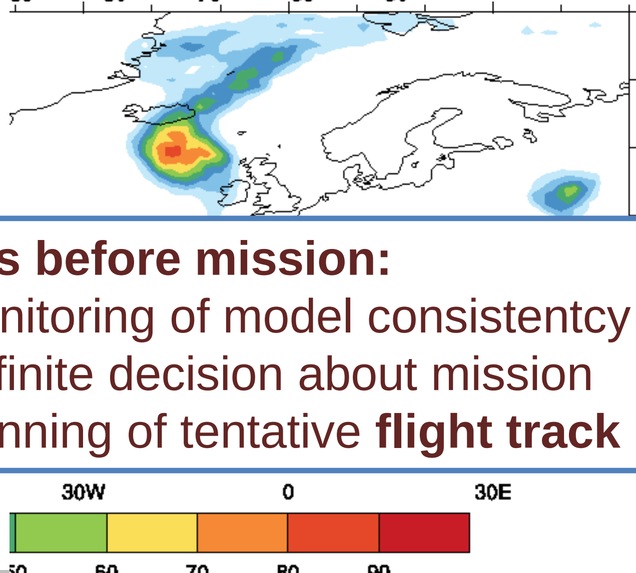
VT21/12Z



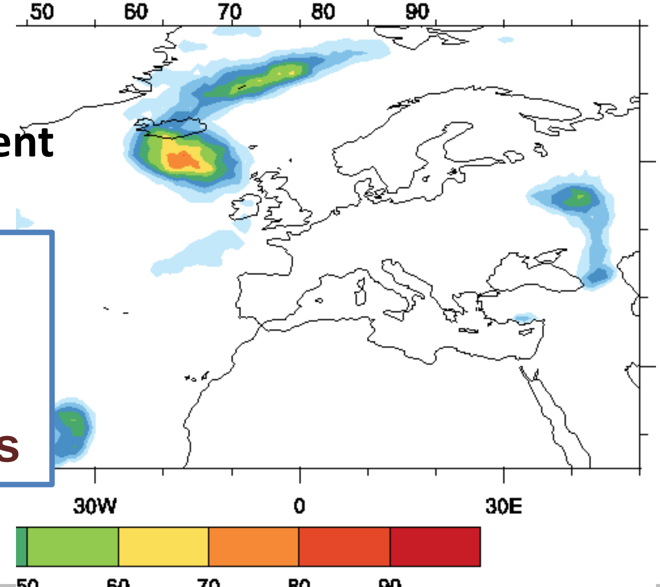
VT21/18Z



WCB outflow



WCB ascent



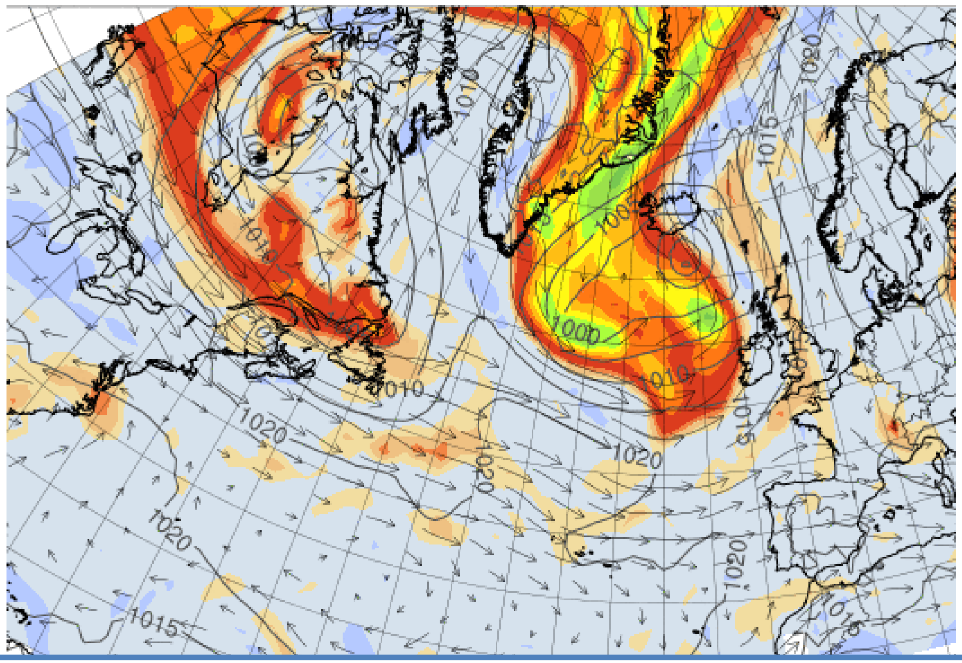
2 days before mission:

- Monitoring of model consistentcy
- Definite decision about mission
- planning of tentative **flight track** and **times**

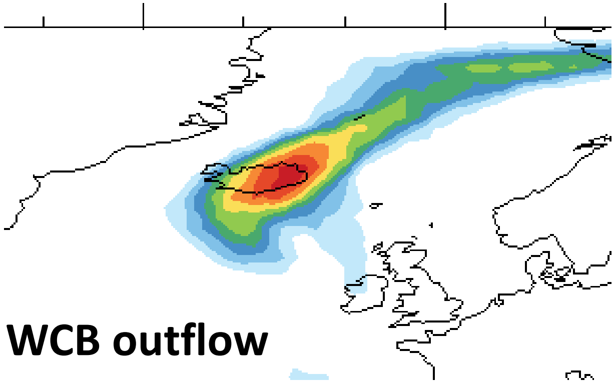
Mission on Wednesday
21 Sep 2016 15 UTC

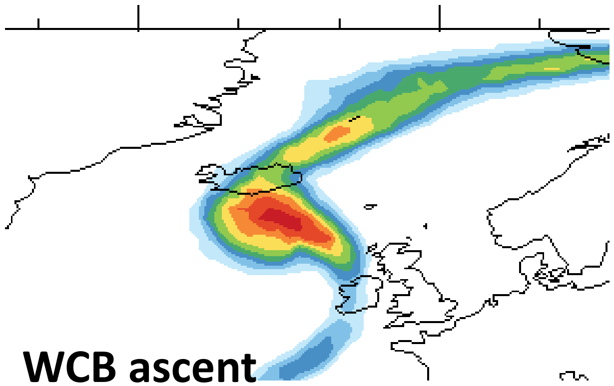
BT19/12Z

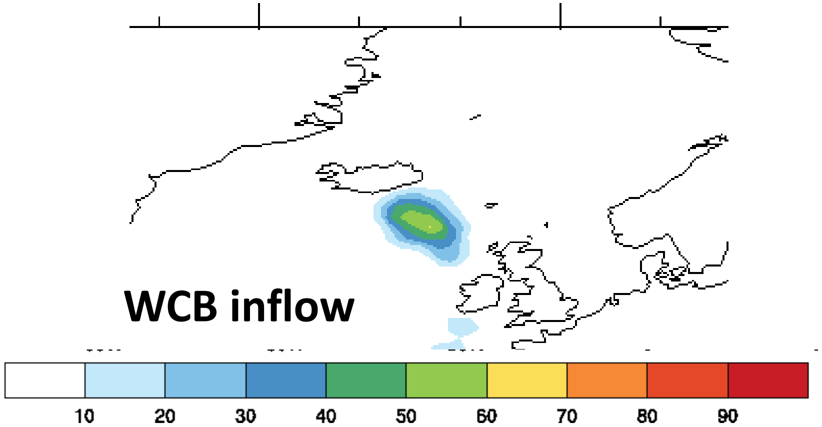
PV@315K at 20160921_15



WCB probabilites 21/12UTC





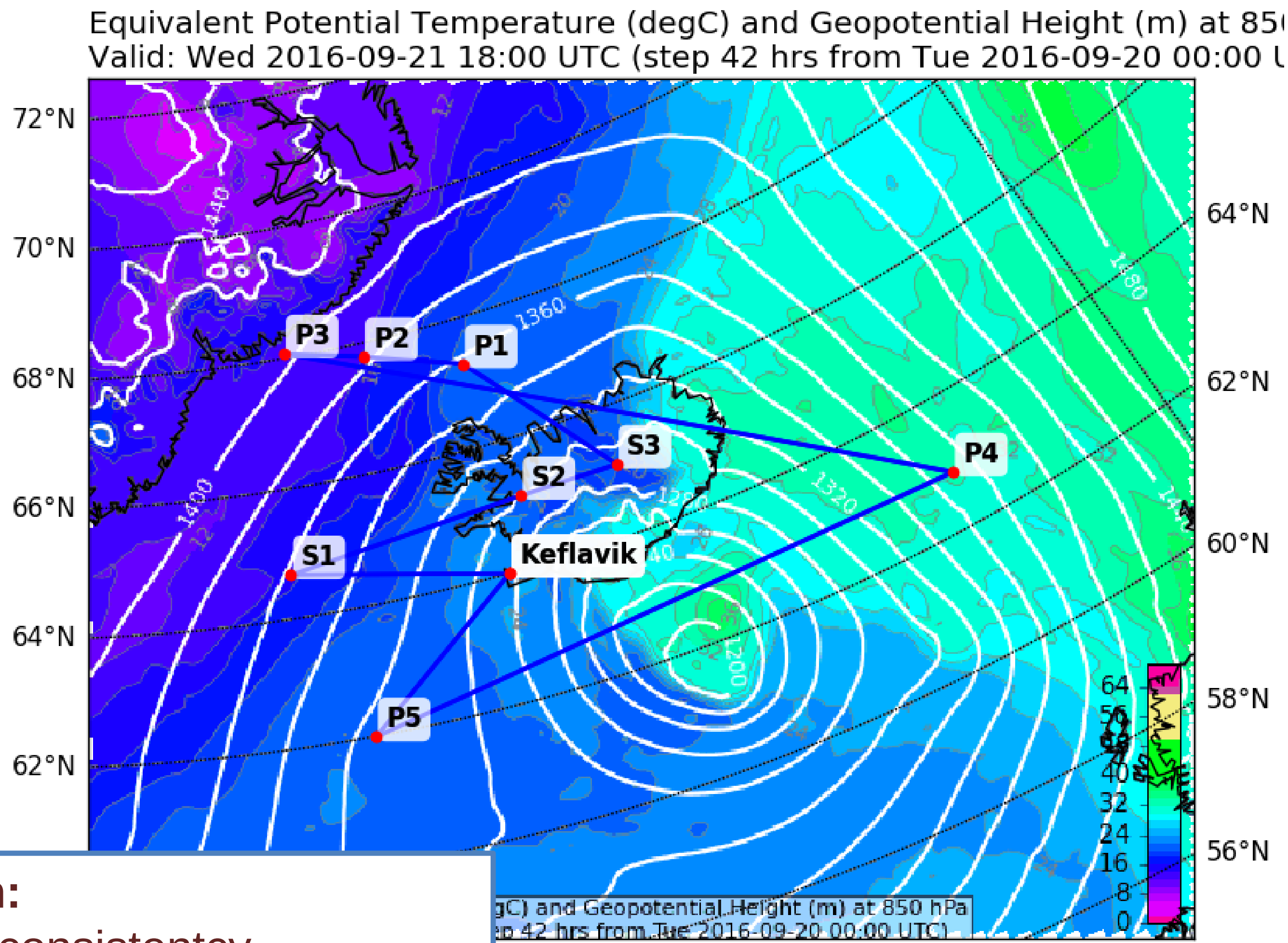


1 days before mission:

- Monitoring of model consistentcy
- Finalisation of flight track:
    - **Location & times**
    - **levels**

Flight pattern for Wednesday 21 September, 18UTC

HALO



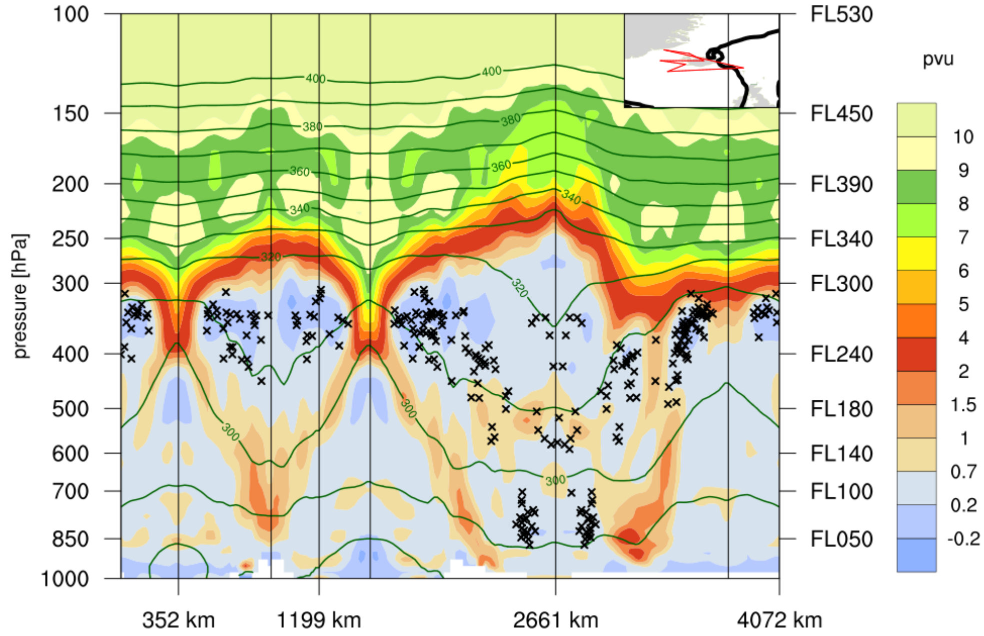
pling TP structure
region / warm sector 8 sondes

1 days before mission:

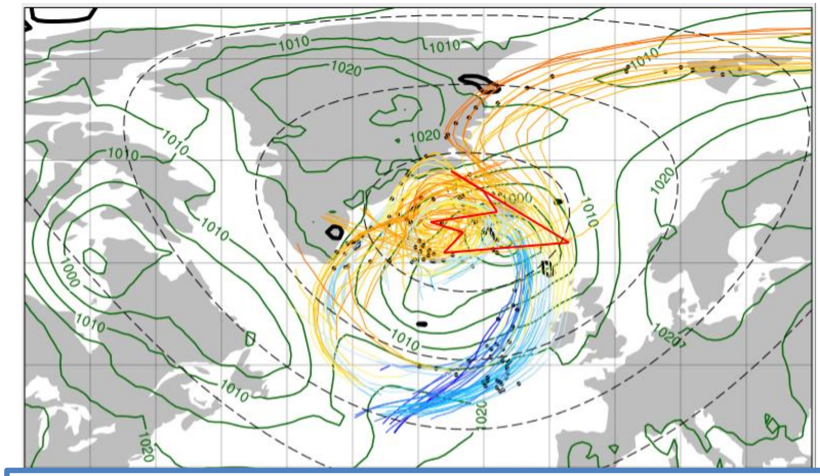
- Monitoring of model consistentcy
- Finalisation of flight track:
    - **Location & times**
    - **levels**

Trajectories from HALO flight track VT 21/18Z

HALO



BT20/00Z

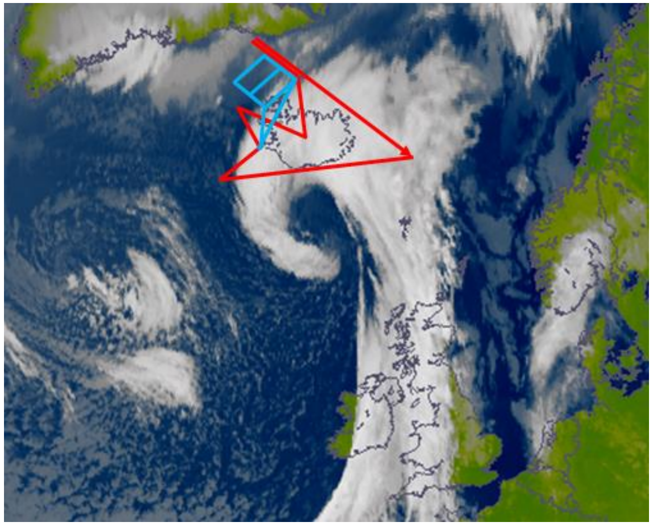


1 days before mission:

- Monitoring of model consistentcy
- Finalisation of flight track:
  - **Location & times**
  - **levels**

Maxi Böttcher and Julian Quinting

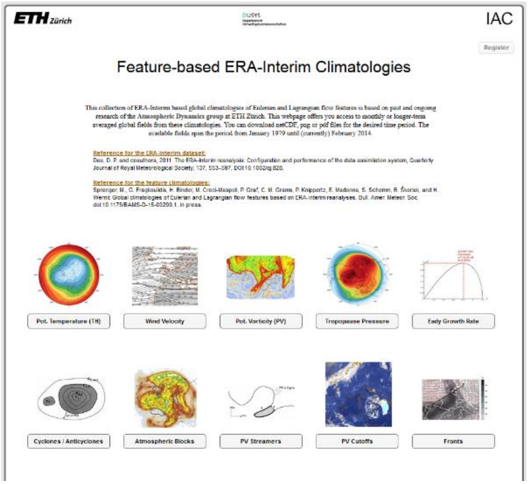
Successful Mission!

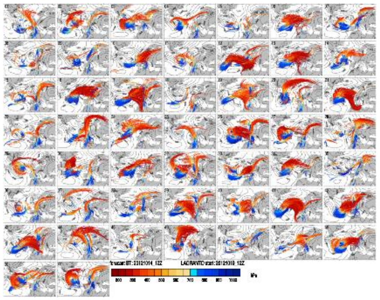


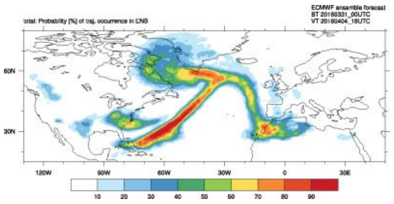
6. Summary and Outlook

- Comprehensive catalogue of feature-based ERA-I climatologies http://eraiclim.ethz.ch/
- LAGRANTO trajectory model http://lagranto.ethz.ch/

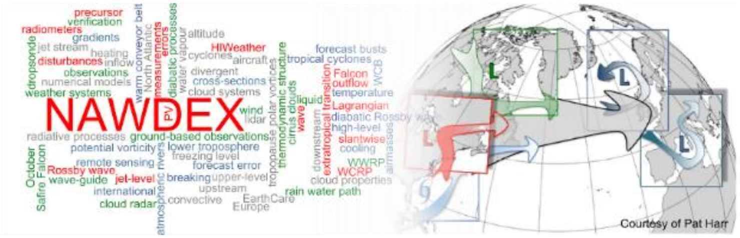
→ facilitate research of atmospheric dynamics from a weather system perspective







- Specific forecast products enable flight planning for atmospheric measurement campaigns http://nawdex.ethz.ch/



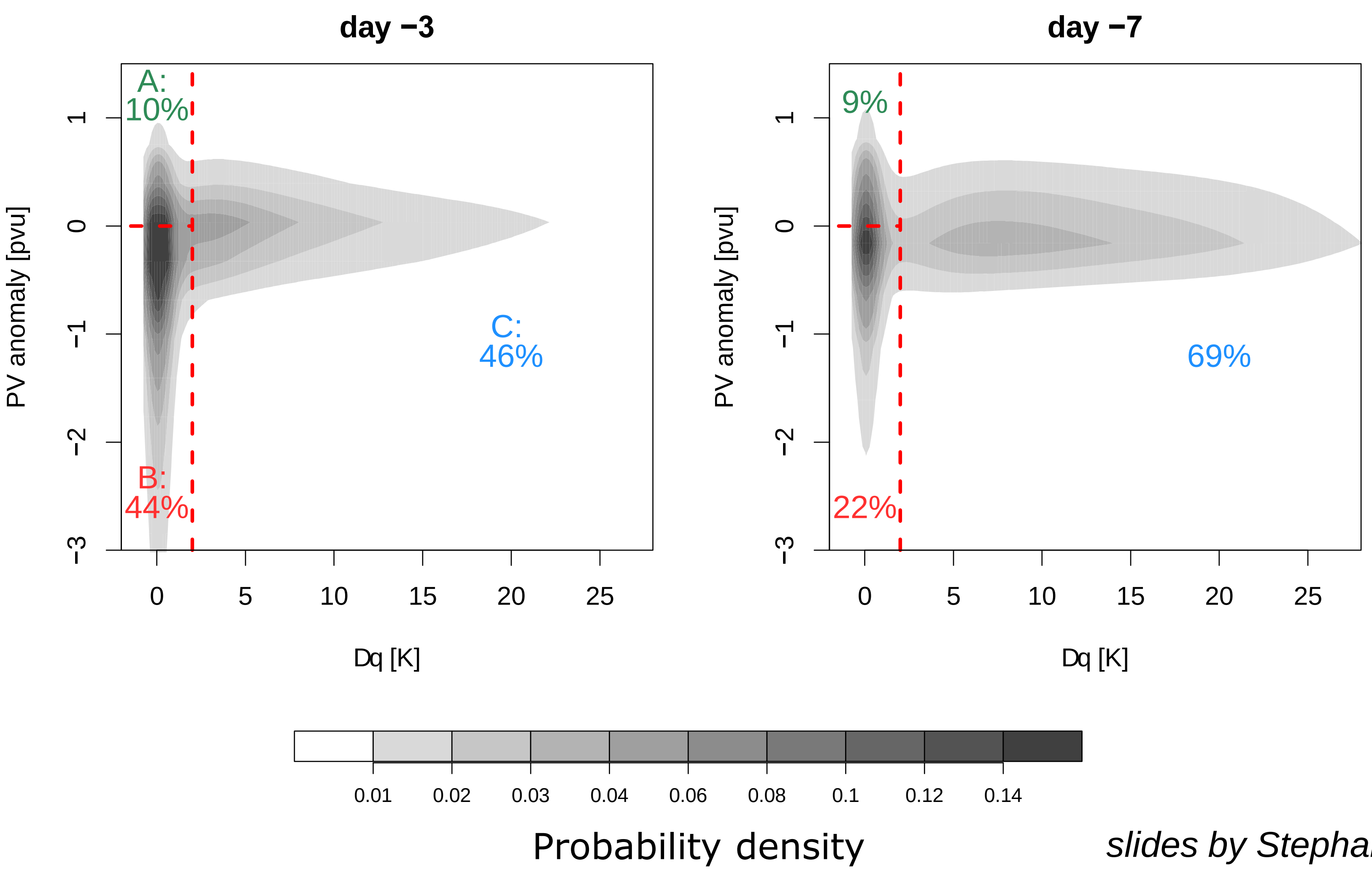
ERA-5 !?

A. Diabatic influences on blocking

Pfahl, S., C. Schwierz, M. Croci-Maspoli, C. M. Grams, and H. Wernli, 2015: Importance of latent heat release in ascending air streams for atmospheric blocking. *Nature Geosci*, **8**, 610–614, doi:10.1038/ngeo2487.

Diabatic heating and PV anomalies

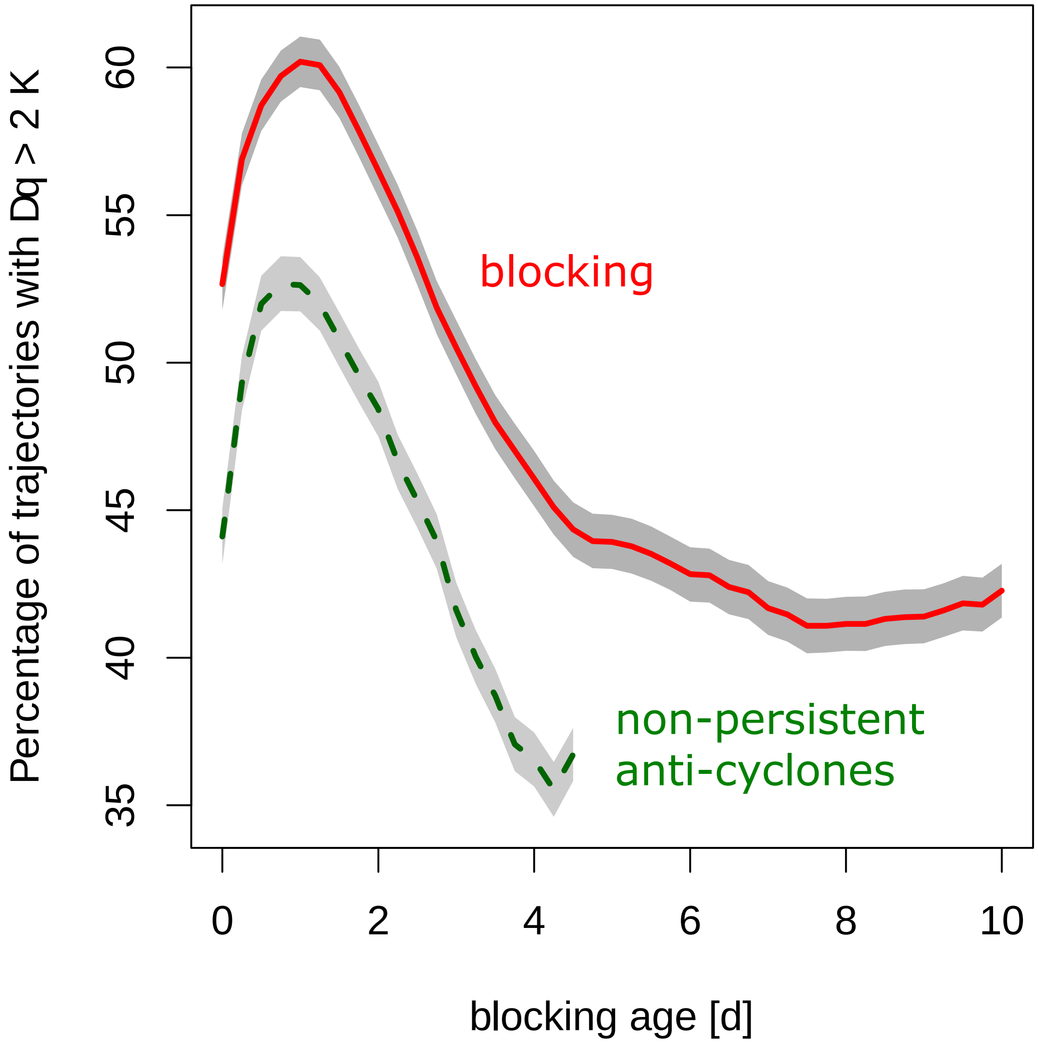
Pfahl, S., et al. (2015), *NatGeo*, doi:10.1038/ngeo2487.



slides by Stephan Pfahl

Diabatic heating during blocking life cycle

Pfahl, S., et al. (2015), *NatGeo,* doi:10.1038/ngeo2487.



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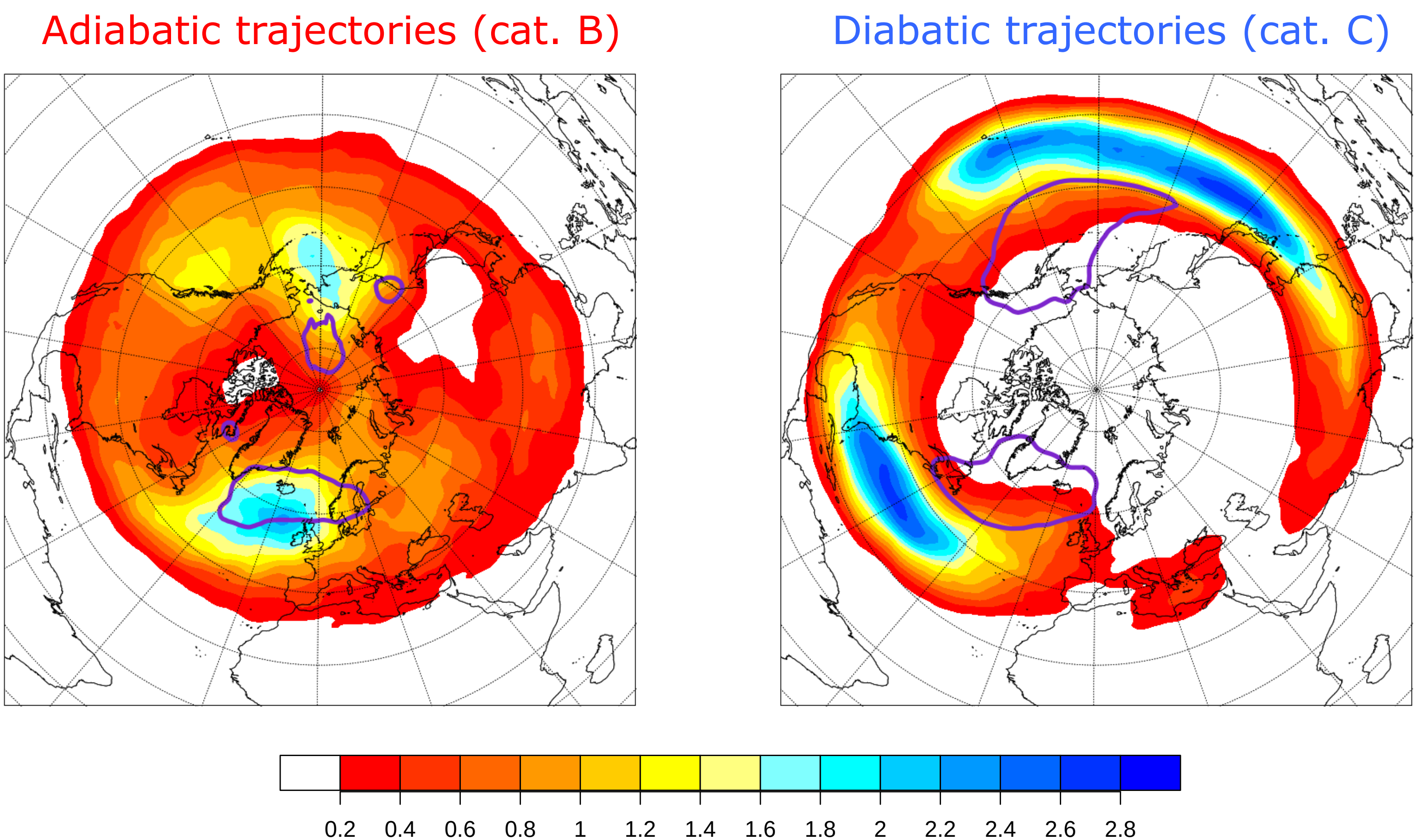
Spatial distributions of trajectories

Pfahl, S., et al. (2015), *NatGeo*, doi:10.1038/ngeo2487.



Normalized trajectory density 3 days before arrival in the blocking region for winter. Purple contour indicates main trajectory starting regions.

slides by Stephan Pfahl

A. Potential Vorticity

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Potential vorticity

$$PV = \frac{1}{\rho}\vec{\eta}\cdot\nabla\Theta$$

$$\boxed{PV = \frac{1}{\rho}\eta\frac{\partial\Theta}{\partial z}}$$

unit: 1PVU = 10^{-6} K m^2 kg^{-1} s^{-1}

$$\eta = f + \vec{k}\cdot\nabla\times\vec{v}_h$$

Absolute vorticity / horizontal flow

Vertical stratification of the atmosphere/stability

$$\frac{dPV}{dt} = \frac{1}{\rho}\vec{\eta}\cdot\nabla\dot{\Theta} + \frac{1}{\rho}(\nabla\times\vec{F})\cdot\nabla\Theta$$

Total change in PV

diabatic PV modification

frictional processes

- PV is conserved under adiabatic frictionless flow (**conservation principle**)

→ use PV as air mass tracer on isentropic surfaces to identify PV signatures of weather systems

- PV can be inverted given a balance condition and boundary conditions (**inversion principle**)

→ derive wind, T, p field from a given PV distribution

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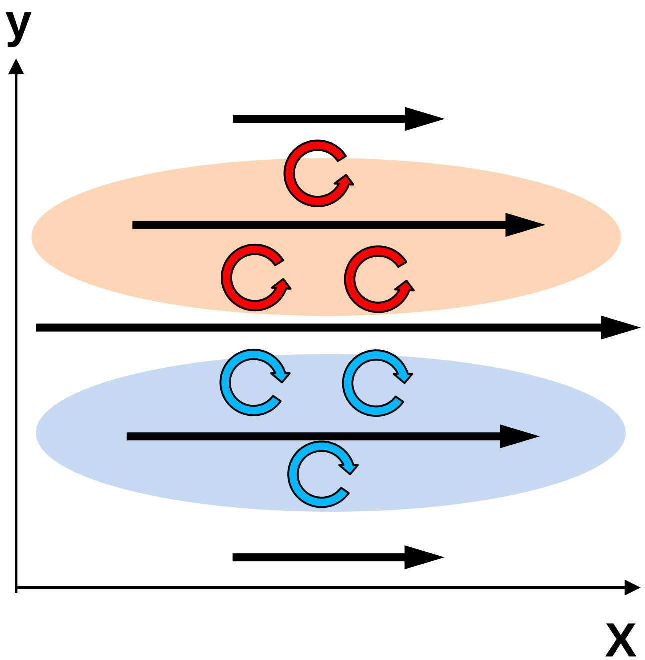
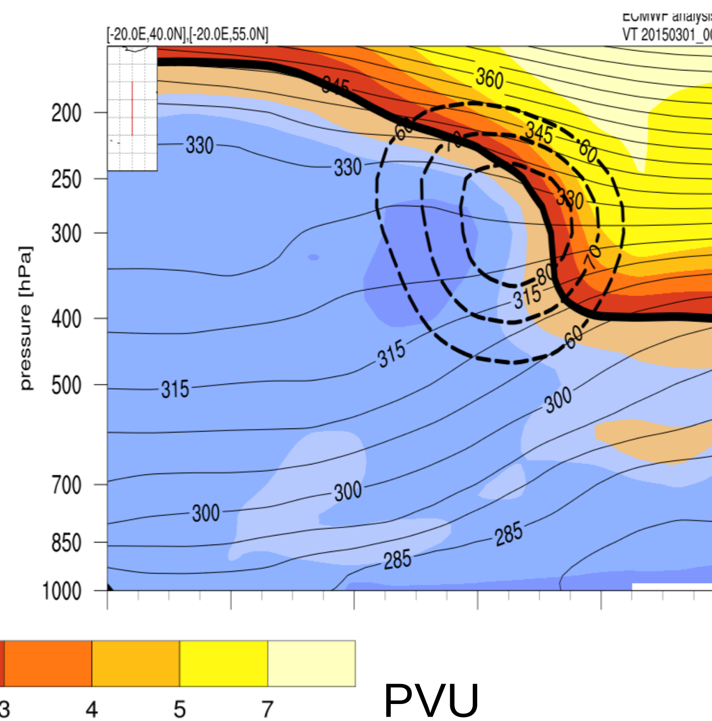


North of jet streak
Pos. shear vorticity,
high PV

South of jet streak
neg. shear vorticity,
low PV



Stratos phere:
High stability,
high PV

Tropos phere
Lower stability,
low PV

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