Prognostic criteria for Polar Lows

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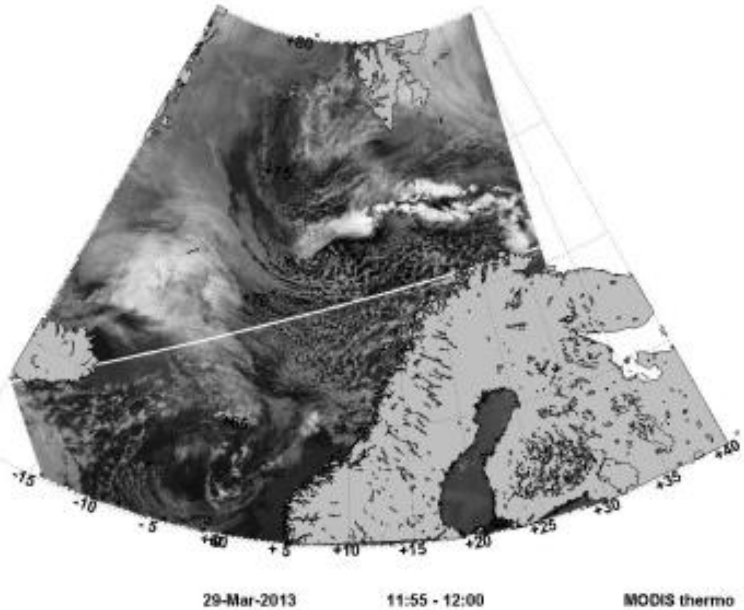
Outline

- Relevance
- Object of study
- Helicity. Definition and basic equations
- Selection of criteria for the study of polar lows. Choice of a criterion for evaluating helicity
- Diagnostic meaning of helicity
- Kinematic vorticity number
- Analysis of global helicity fields in the boundary layer based on ECMWF data and WRF modeling results using the example of March 2013
- Predictive meaning of helicity and kinematic vorticity number
- Results and conclusions

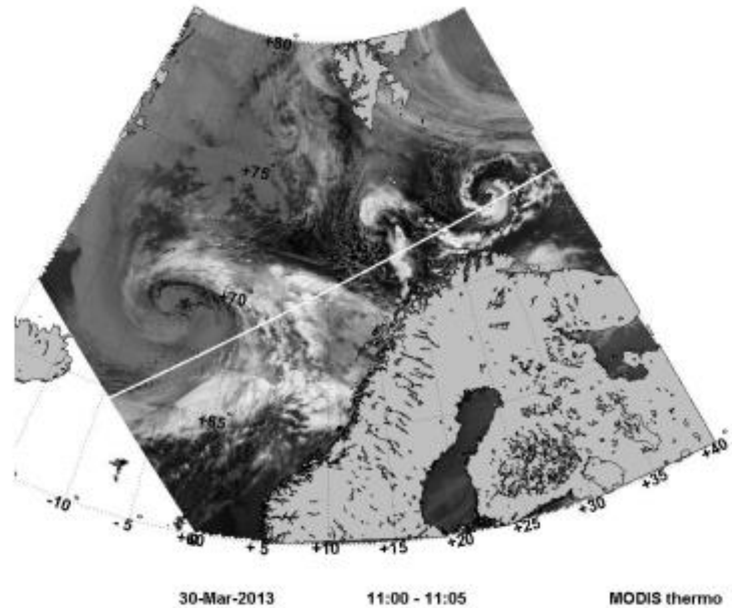
Motivation

Polar lows (PL) are mainly formed in the Arctic region and are capable of traversing about 100 km during their existence, reaching the coast of the mainland. According to various estimates [Romero R., Emanuel K., 2017], in the future, a decrease in the incidence of PL in these regions is predicted by 10-15% and a decrease in their intensity. At the same time, the area of occurrence of stable and intense PL in the Atlantic will move closer to Scandinavia, which will increase the risk of the impact of extreme climatic events, such as snow charges, storm winds and waves, icing, on infrastructure facilities. It is important to consider such phenomena to ensure transport operations in the design, construction and reconstruction of industrial facilities [Rasmussen E.A., Turner J., 2003; Lutsenko E.I., Lagun V.E., 2010]. Due to the lack of forecasting efficiency and the sudden nature of the occurrence, PL pose a significant danger to humans.

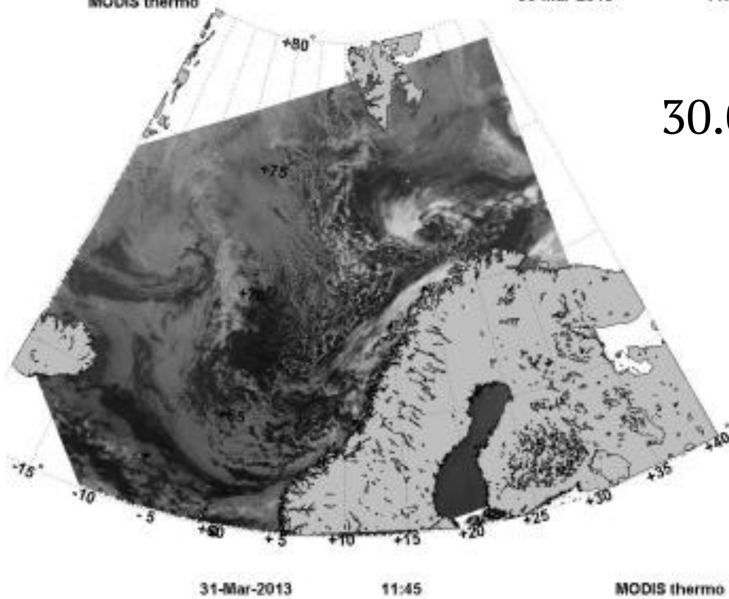
Research object (MODIS)



29.03.13 12:00 UTC



30.03.13 11:00 UTC



31.03.13 12:00 UTC
(Verezemskaya, 2014)

Motivation.
Research object

Mesocyclonic formations observed over the Norwegian and Barents sea surfaces from March 27 to March 31, 2013

Morphological characteristics of polar lows (Rasmussen and Turner, 2003):

- The approximate diameter of 150, 200, or 550 km (1000 km) is the diameter of the outer closed isobar;
- arises above the sea surface to the north of the main baroclinic zone (polar front);
- maximum wind speed at PL ⩾15 m / s;
- the velocity of the PMC - 50 km / h;
- lifespan - around the day

Relevance

- Harley D.G. 1960

Several publications in the last 15 years:

- Rasmussen E. A. , Turner J., «Polar Lows», 2003
- G. Fu, T. Kato, H. Niino and R. Kimura, 2003
- James A. Renwick, 2004
- Condron A. and Grant R. Bigg, 2005
- Mokhov I.I. and Akperov M.G., 2006
- Claud C., Duchiron B., and Terray P., 2007
- Claud C., Carleton A.M., Duchiron B. , Terray P., 2008
- Zahn M., H. von Storch, 2008
- Thomas J. Bracegirdle and Suzanne L. Gray, 2008
- Blechschmidt A.-M., 2008
- Golitsyn G.S., 2008, 2012
- Shkolnik I.M. and Efimov S.V., 2013
- Zappa G. and Shaffrey L., Hodges K. , 2014
- Shun-Ichi I. Watanabe and Hiroshi Niino, 2014
- Pegahfar N., Ghafarian P., 2015 ………

Similarity between polar mesocyclones and tropical cyclones:

- Polar Lows 2003
- G. Fu, T. Kato, H. Niino and R. Kimura, 2003
- Golitsyn G.S., 2008
- Shkolnik I.M. and Efimov S.V., 2013
- Akter F., Ishikawa H., 2014
- ………

Relevance.

Study of PL modes and their variability

- Businger, 1985 ; Forbes and Lottes, 1985 ; Emanuel, 1986 ;
- Turner et al., 1993 ; Lutsenko, 1999 ;
- Mokhov, 2000 ; Mokhov and Priputnev, 2001 ;
- Mokhov and Akperov, 2003 ; Condron et al., 2006 ;
- Mokhov et al., 2007; Gurvich et al., 2008 ;
- Zahn et al., 2008 ; Lutsenko and Lagun, 2010 ;
- Kolstad E., 2011 ; Noer et al., 2011 ;
- Chen et al., 2012 ; Lagun and Lutsenko, 2013 ;
- Laffineur et al., 2014 ; Zabolotskih et al., 2015 ;
- Rojo et al., 2015 ; Smirnova et al., 2016 ;
- Akperov et al., 2017

Selection of the integral diagnostic/prognostic criteria of PL

Integral characteristics of the atmosphere, key for the formation of extreme convective events

- Convective available potential energy

<u>CAPE</u>

an amount of buoyancy energy available to produce vertical acceleration of air particle;

- Convective inhibition

<u>CIN</u>

a numerical measure that indicates the amount of energy preventing an air parcel from rising from the surface to the level of free convection;

- • Storm-relative environmental helicity or storm-relative helicity and Storm-relative helicity (an alternative definition)

Diagnostic sense !!!

Fundamental dependence on information about the state of the upper troposphere !! (sparse aerological network / strong dependence on convection parameterization)

Selection of the integral diagnostic/prognostic criteria of PL

- (**Storm-relative environmental helicity, storm-relative helicity**)

$$\mathrm{SRE}H = \int_0^h \left[\left(\vec{V} - \vec{C}\right) \cdot \left(\vec{k} \times \frac{\partial \vec{V}}{\partial z}\right)\right] dz\,,$$ (*Onderlinde, Nolan, 1990*);

$$H = (v - v_{mean})\frac{\partial u}{\partial z} - (u - u_{mean})\frac{\partial v}{\partial z},$$ (*Davies-Jones, 1990*);

where $\vec{V}$- horizontal component of the wind velocity, u, v – wind velocity components in the cyclone, $\vec{C}$- the velocity of the cyclone, h is chosen between 1 and 3 km, u_{mean}, v_{mean} - velocity components of the cyclone center, $\vec{k}$ - the unit vector directed vertically

- **Helicity index** $S = \frac{8\pi}{3}\int_0^\infty V^3 dr,$ (*Kurgansky, 2008*);

where S – helicity index ($m^4\ s^{-3}$), V – tangentials component of the wind velocity ($m\ s^{-1}$), r – radius). S include the integral of the cube of tangential velocity and basically is the rate of helicity destruction in the surface layer proportional to the power produced by dynamic pressure force. Therefore this parameter is complicated for calculation and is ill-suited to operational forecast

Selection of the integral diagnostic/prognostic criteria of PL

- A criterion for formation of an intense atmospheric vortex

$$\frac{(2bt)^{1/2}}{hN} \geq 1,$$ (*Golitsyn, 2012*);

where b- buoyancy flux at the lower boundary of convective layer,

$h(t) = N^{-1}(2bt)^{1/2}$ – the height of the penetrative convection layer, $\vec{t}$- time, would be more than enough to reach the altitude h,

N – Brunt-Vaisala frequency

The criterion is necessary, but not sufficient condition for intense vortex formation.

It is integratal criterion that expressed through: the parameters of thermodynamic nonequilibrium state between ocean and atmosphere, the temperature, humidity, steady-state stability, development time. Such a criterion require much information collected and processed beforehand, great resources and much time

Selection of the integral diagnostic/prognostic criteria of PL

- **Kinematic vorticity number**

$$W_k = \frac{\|\Omega\|}{\|S\|} = \frac{\sqrt{\zeta^2}}{\sqrt{{D_h}^2 + Def^2 + Def'^2}}$$, (*Schielicke et.al., 2016*);

where ζ- the vertical component of the vorticity vector,

D_h– horizontal divergence,

Def – stretching deformation,

Def'– shearing deformation,

$\|\Omega\|$ – Euclidean tensor norm of the vorticity tensor,

$\|S\|$ – Euclidean tensor norm of the strain-rate tensor

In this case, when predicting it is necessary to know only the wind velocity field, complex and time consuming calculations are not required, which is a great advantage for an effective operational forecast

Helicity in ABL

Helicity is defined as the scalar product of velocity and vorticity:

$$\mathrm{H} = v \cdot rot(v).$$

- Etling D., 1985
- Hauf T., 1985
- Lilly D.K., 1986
- Kurgansky M.V., 1989, 2018
- Hide R., 1990
- Droegemeier K. K., Lazarus S. M., Davies-Jones R., 1993
- Markowski P.M., Straka J.M., Rasmussen E.N., Blanchard D.O., 1998
- Chkhetiani O.G, 2001, 2005
- Doswell C.A. and Schultz D.M., 2006
- Onderlinde M.J., Nolan D.S., 2014 …

Prognostic meaning:

- Pichler H., Schaffhauser A., 1997
- Tan Z., Wu R., 1994
- Glebova E.S., Levina G.V., Naumov A.D., Trosnikov I.V., 2009
- Lavrova A.A., Glebova E.S., Trosnikov I.V., Kaznacheeva V.D., 2010
- Levina G.V., Montgomery M.T., 2010
- Levina G.V., Montgomery M.T., 2011
- Pegahfar N., Ghafarian P., 2015 …

Helicity in ABL

$$\mathrm{H} = v \cdot rot(v).$$

Ekman flow:

$$U = U_G\left(1 - \exp\left(-\frac{z}{h}\right)\cos\frac{z}{h}\right) + V_G \exp\left(-\frac{z}{h}\right)\sin\frac{z}{h};$$

$$V = V_G\left(1 - \exp\left(-\frac{z}{h}\right)\cos\frac{z}{h}\right) - U_G \exp\left(-\frac{z}{h}\right)\sin\frac{z}{h}.$$

$h = \sqrt{\nu/\Omega}$ - Ekman scale,

V_G, U_G - geostrophic wind component.

Helicity (Kurgansky, Hide):

$$H = -U\frac{\partial V}{\partial z} + V\frac{\partial U}{\partial z}. \qquad (1)$$

Integral helicity (Kurgansky, 1993):

$$H_{int} = \int_0^\infty H = {}^1\!/_2\,({U_G}^2 + {V_G}^2). \qquad (2)$$

Helicity as a squared characteristic related to integral vortex formations

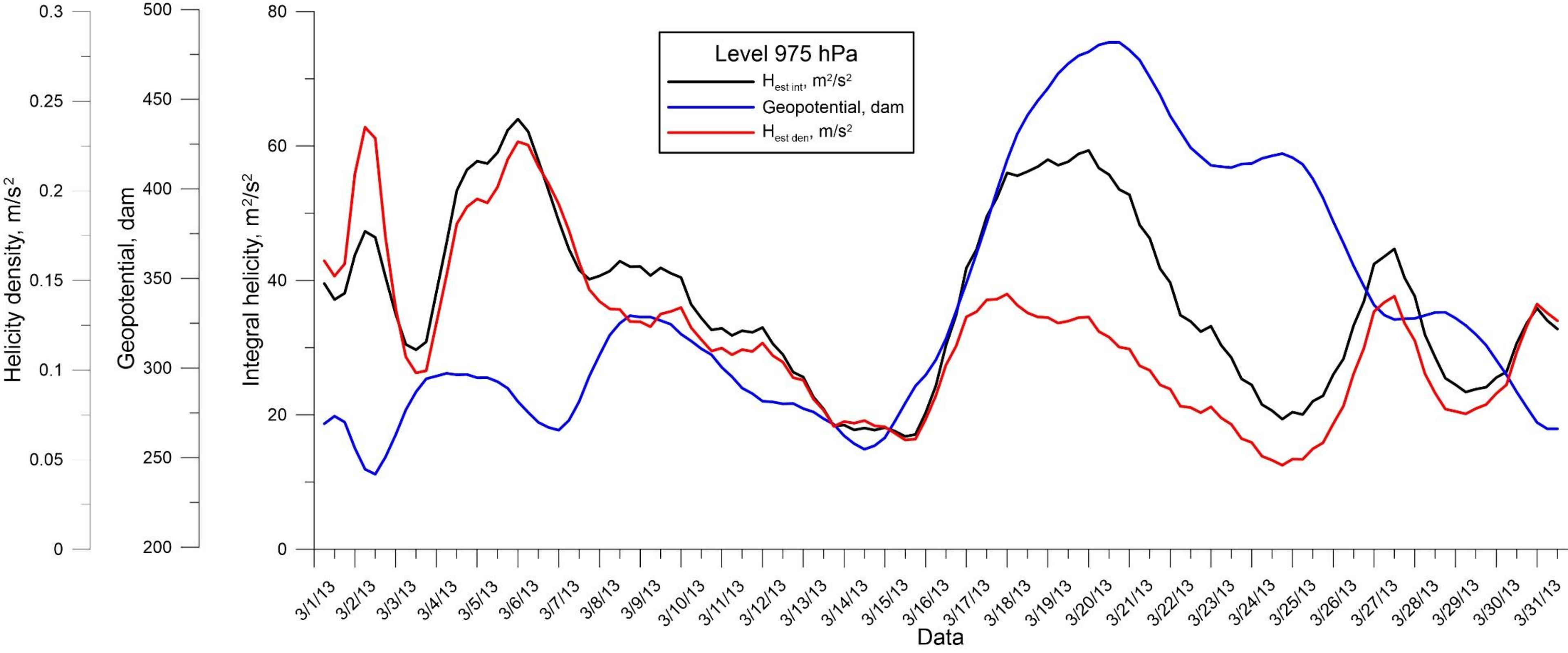
- h (U_G, V_G) - ? $\longrightarrow$ at 975, 850, 700 hPa
- $H_{int}(x_i, y_i) = \frac{1}{2}\left({U_G}^2 + {V_G}^2\right).$
- $H_{den}(x_i, y_i) = \frac{1}{2HGT}\left({U_G}^2 + {V_G}^2\right).$
- $H_{est} = \overline{H}_S = \overline{\sum_{x_i, y_i \epsilon S} H\ (x_i, y_i)}$ square averaged
-

where S: $\boxed{\text{square}}$ lon = 0-60°E; lat = 60-90°N

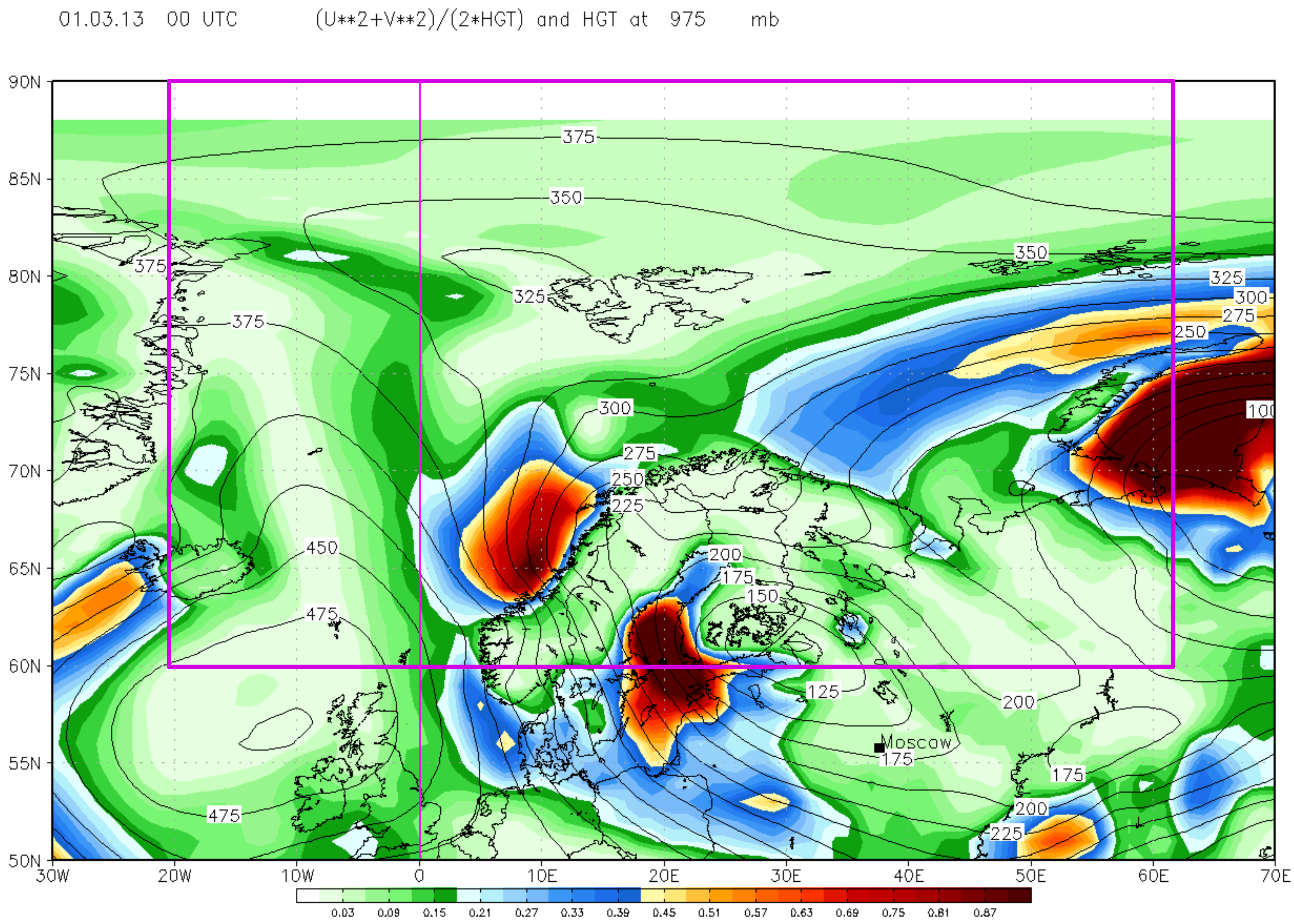
$H\ (x_i, y_i)$ then $H_{int}(x_i, y_i)$.

Integral helicity and helicity density.

Time behavior of the square average integral helicity (black line) and helicity density (blue) estimation according to the data from ECMWF, red line – geopotential. The Nordic seas. 29 – 31 March, 2013. Level 975 hPa



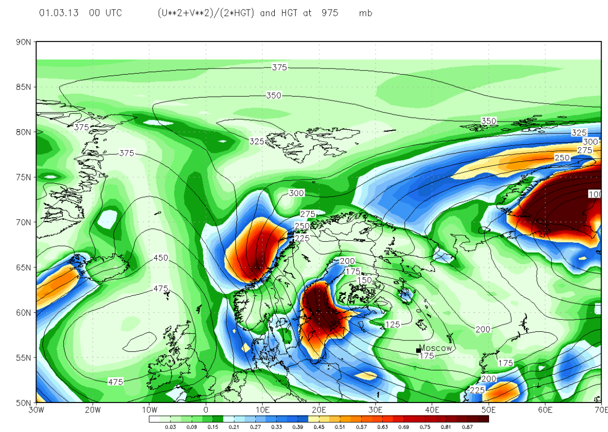
Averaging region for helicity and geopotential estimation for the period 01.03.13 – 31.03.13



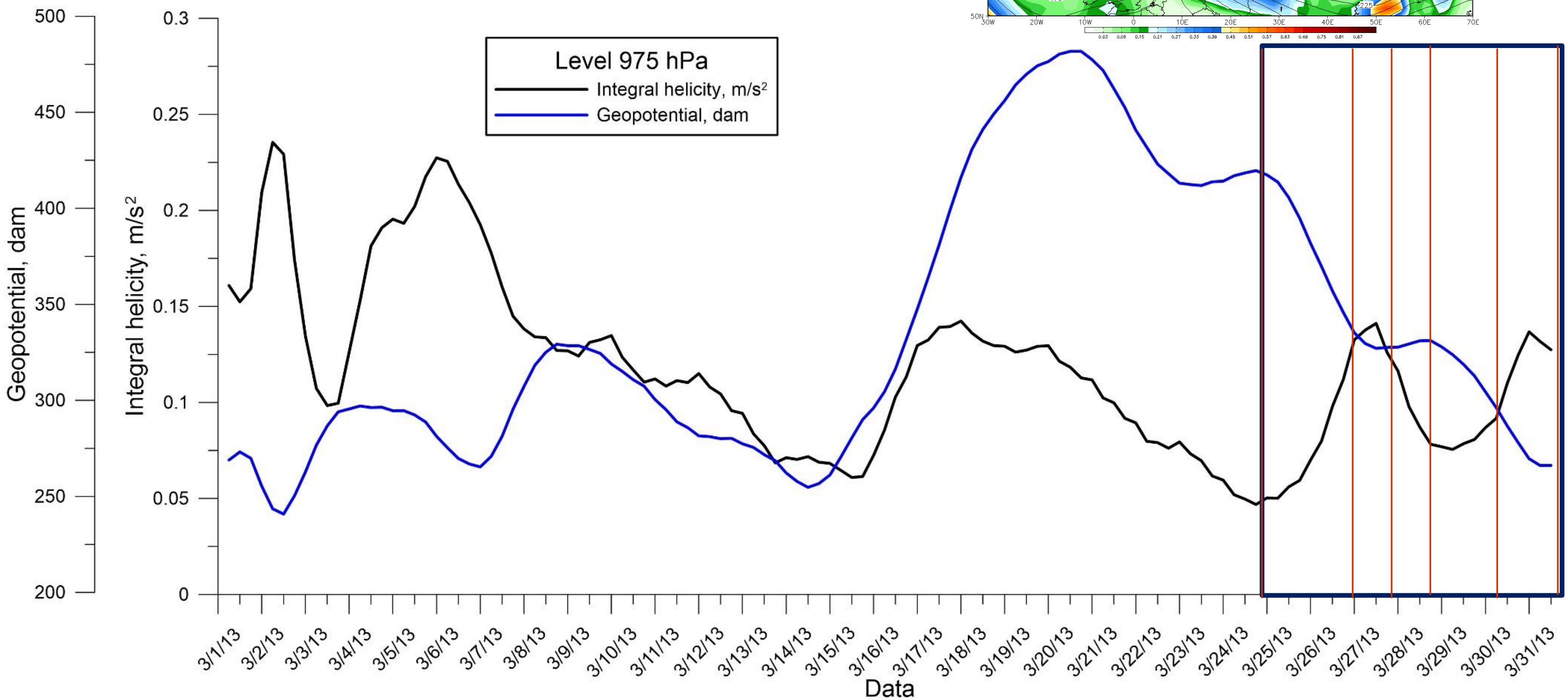
Helicity.

Integral helicity (m s^{-2}, filled colors on map) and geopotential (dam, blue line in graph, lines in map) in the atmospheric boundary layer. ECMWF. Nordic seas. Level 975 hPa

01.03.13 – 31.03.13



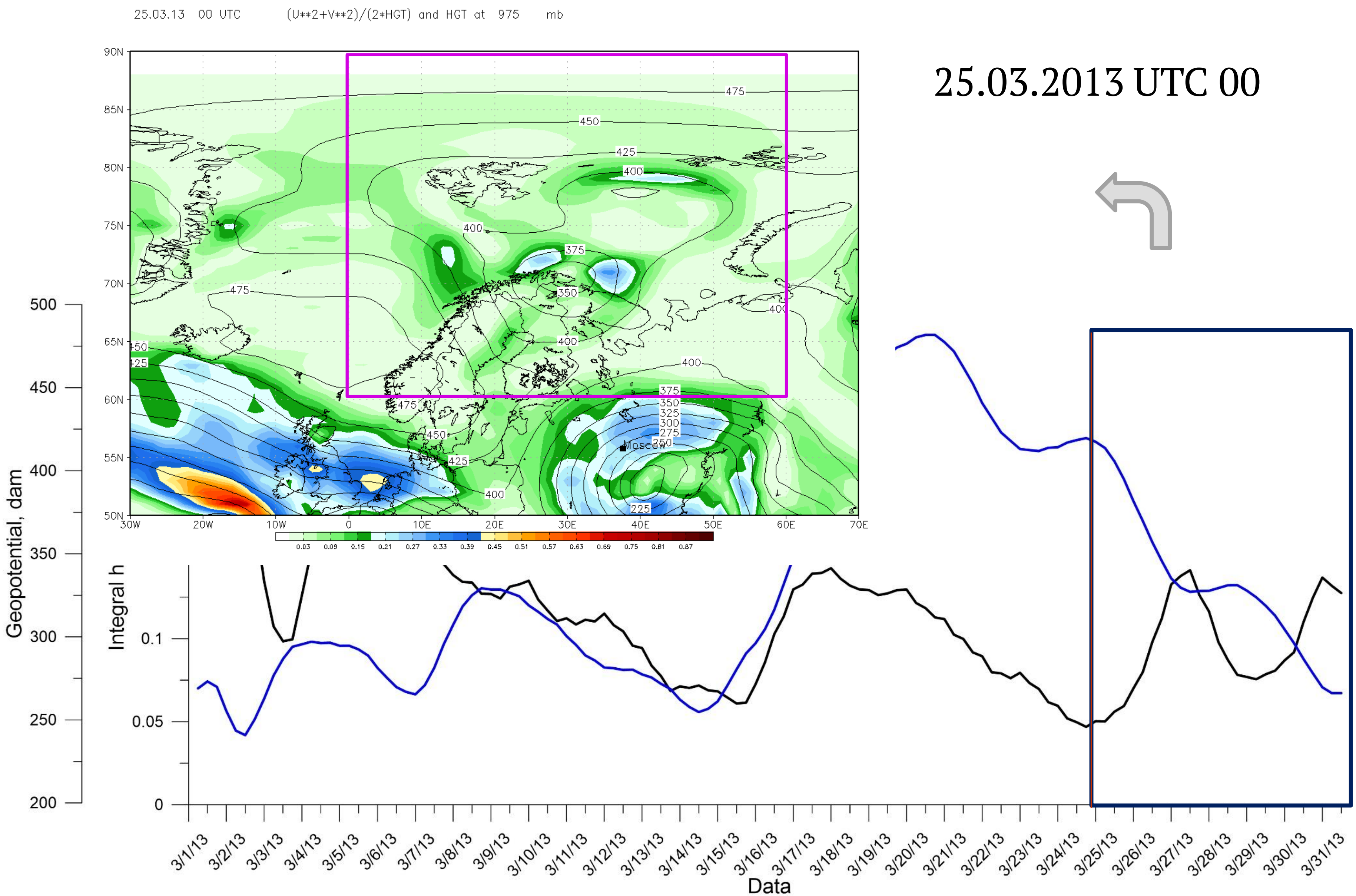
27.03.13 – 31.03.13



Helicity.

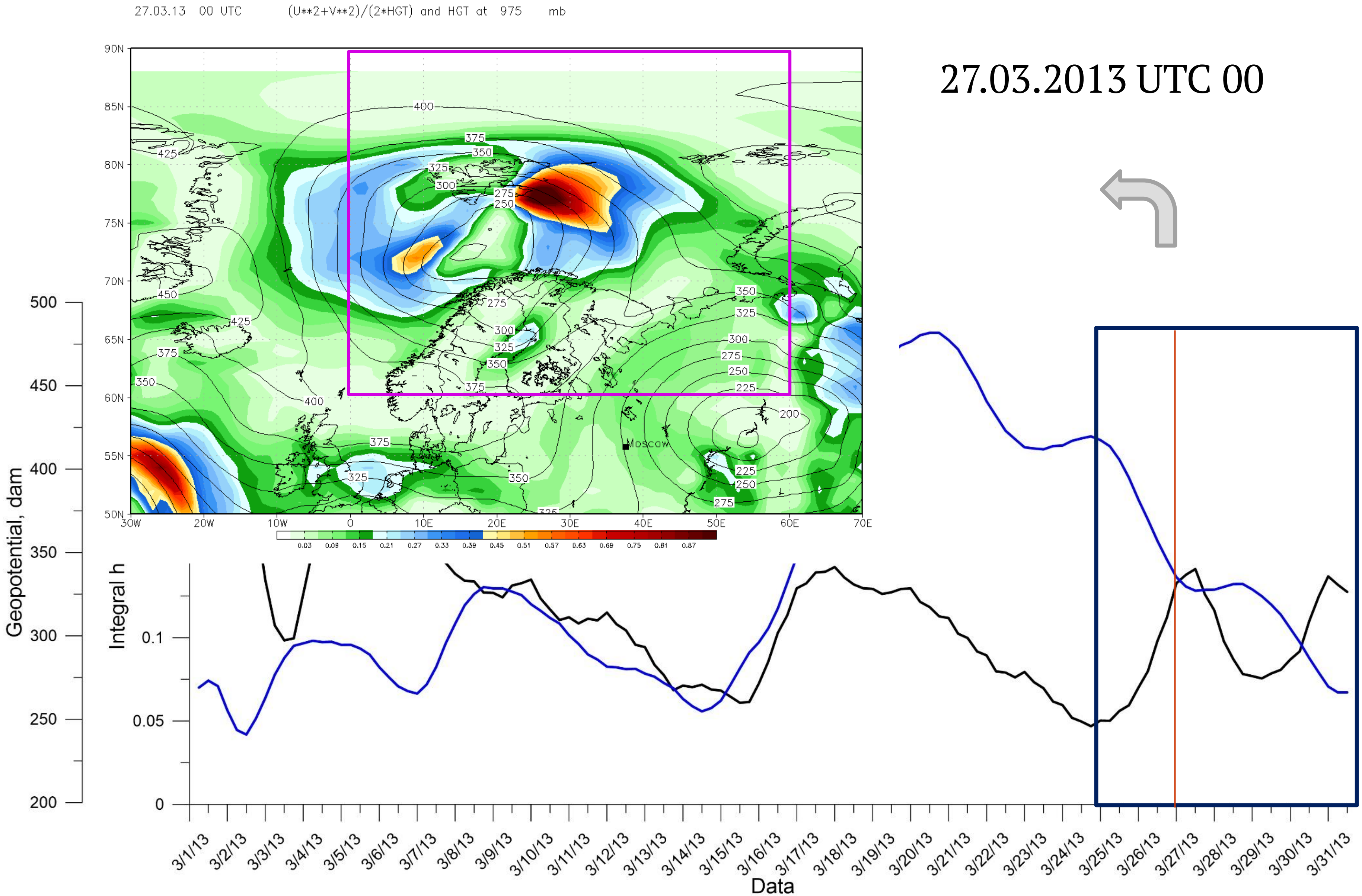
Integral helicity and geopotential. Level 975 hPa.
Diagnostic/prognostic meaning

25.03.2013 UTC 00



Helicity.

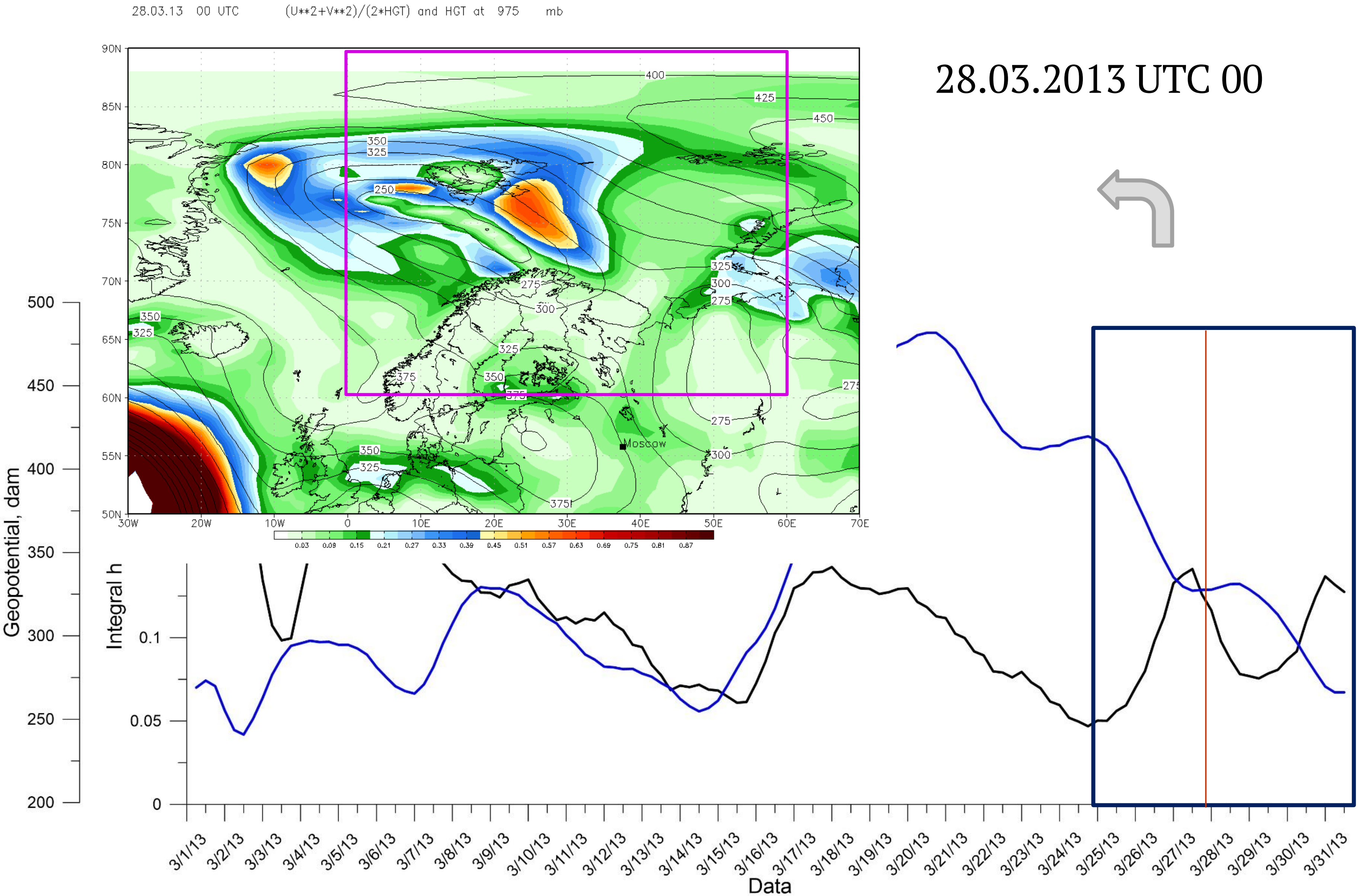
Integral helicity and geopotential. Level 975 hPa.
Diagnostic/prognostic meaning



Helicity.

Integral helicity and geopotential. Level 975 hPa.
Diagnostic/prognostic meaning

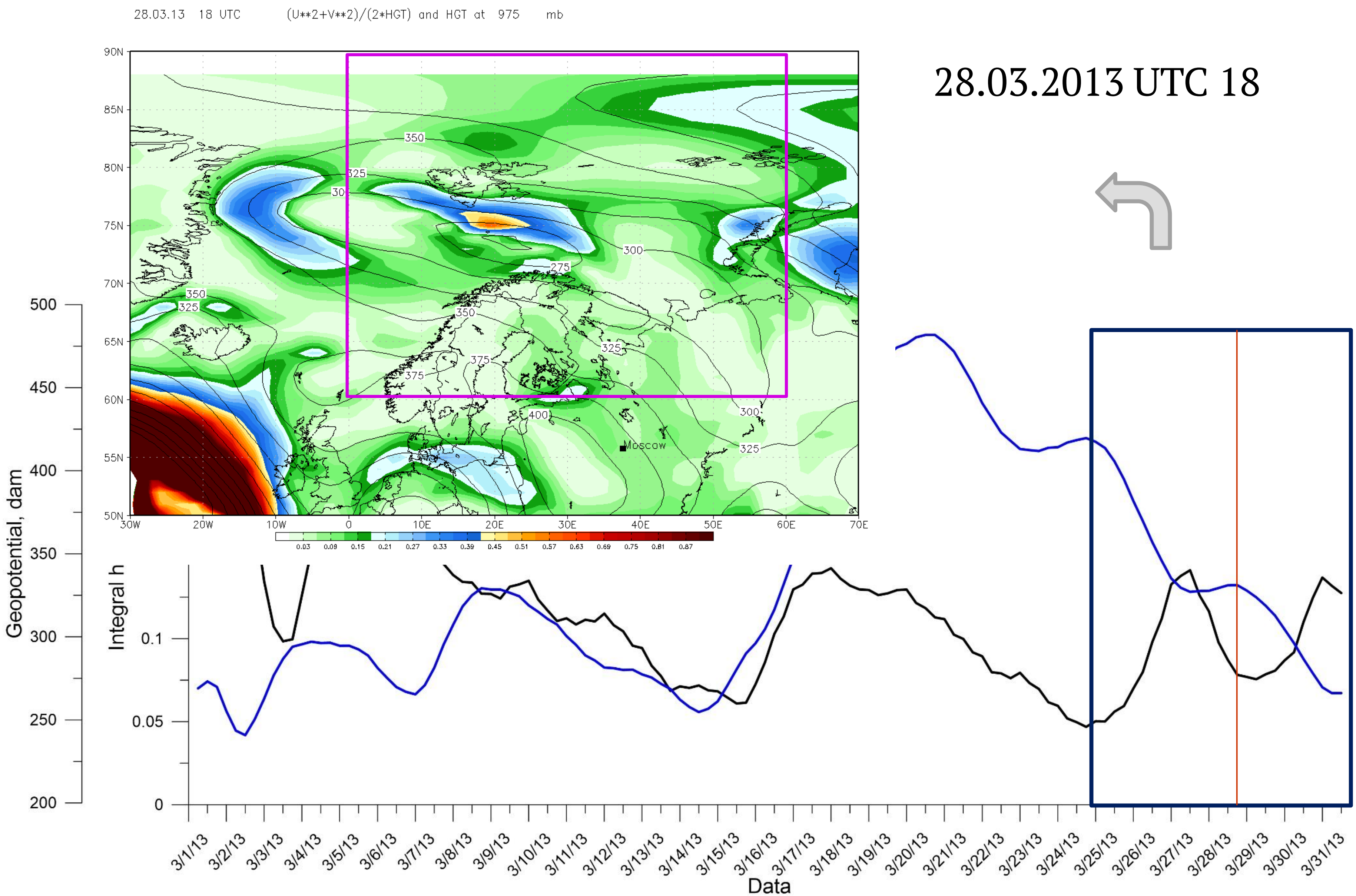
28.03.2013 UTC 00



Helicity.

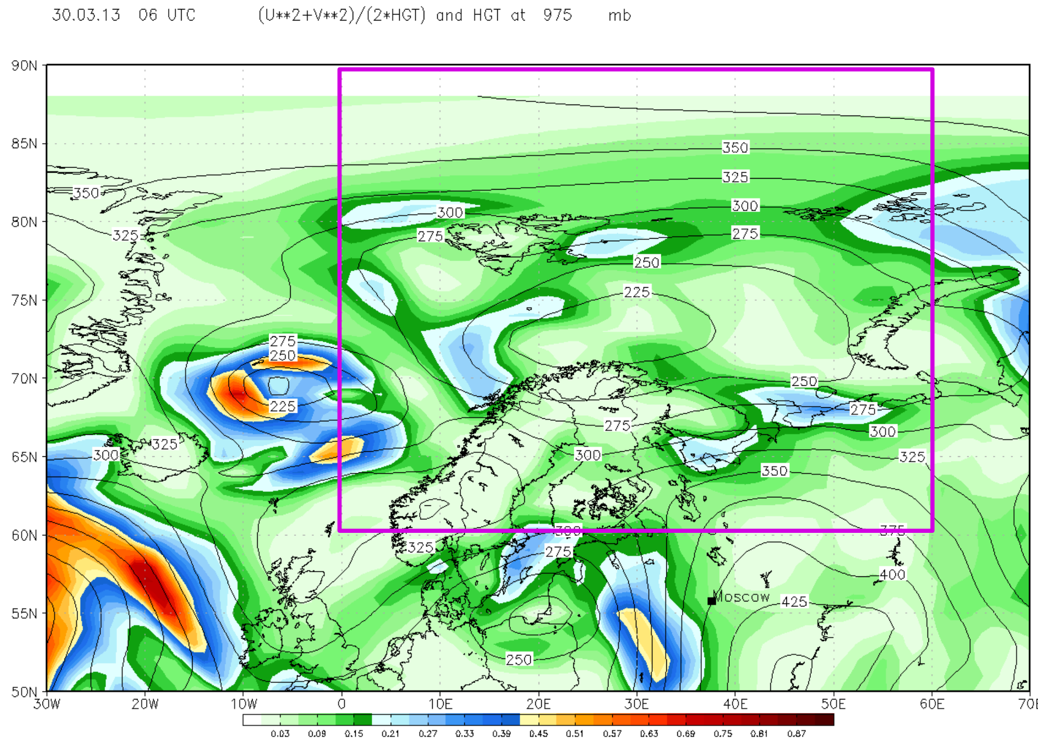
Integral helicity and geopotential. Level 975 hPa.
Diagnostic/prognostic meaning

28.03.2013 UTC 18

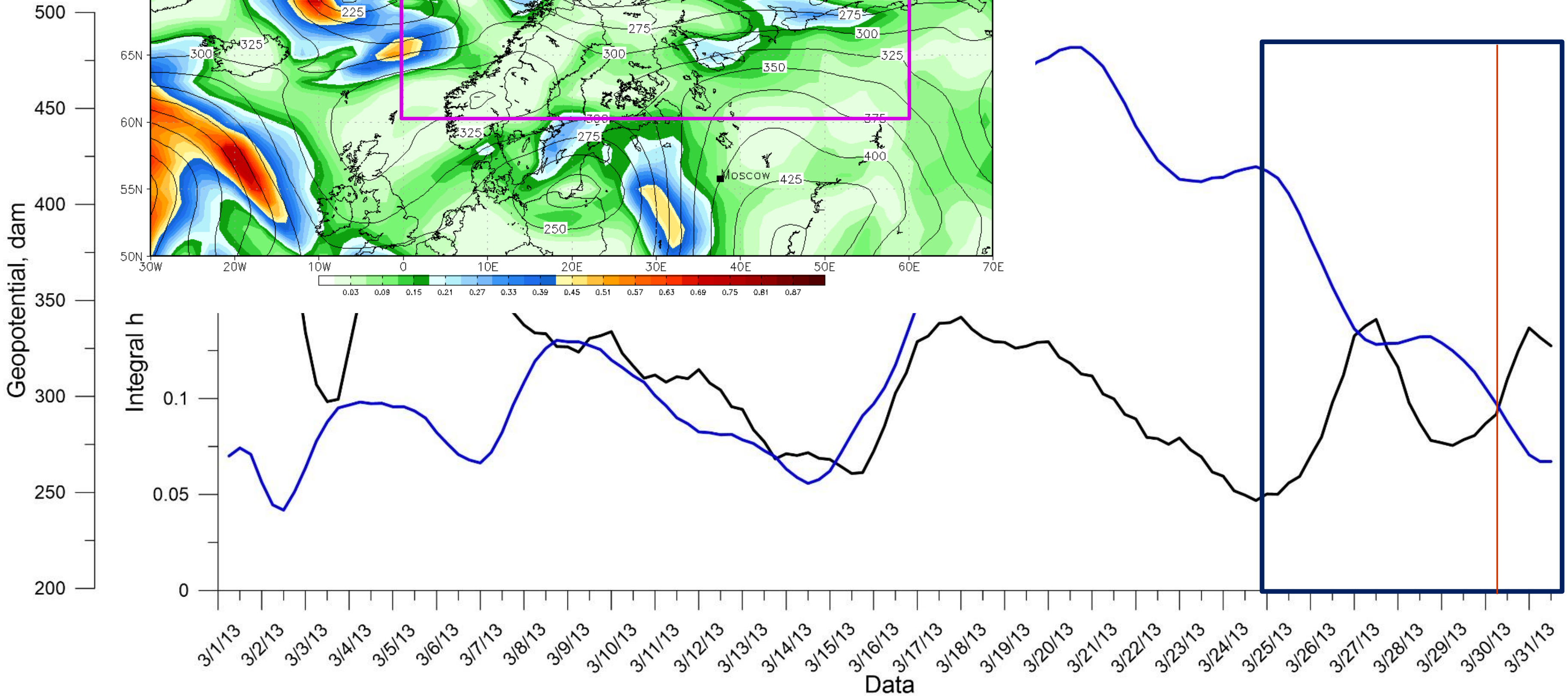


Helicity.

Integral helicity and geopotential. Level 975 hPa.
Diagnostic/prognostic meaning

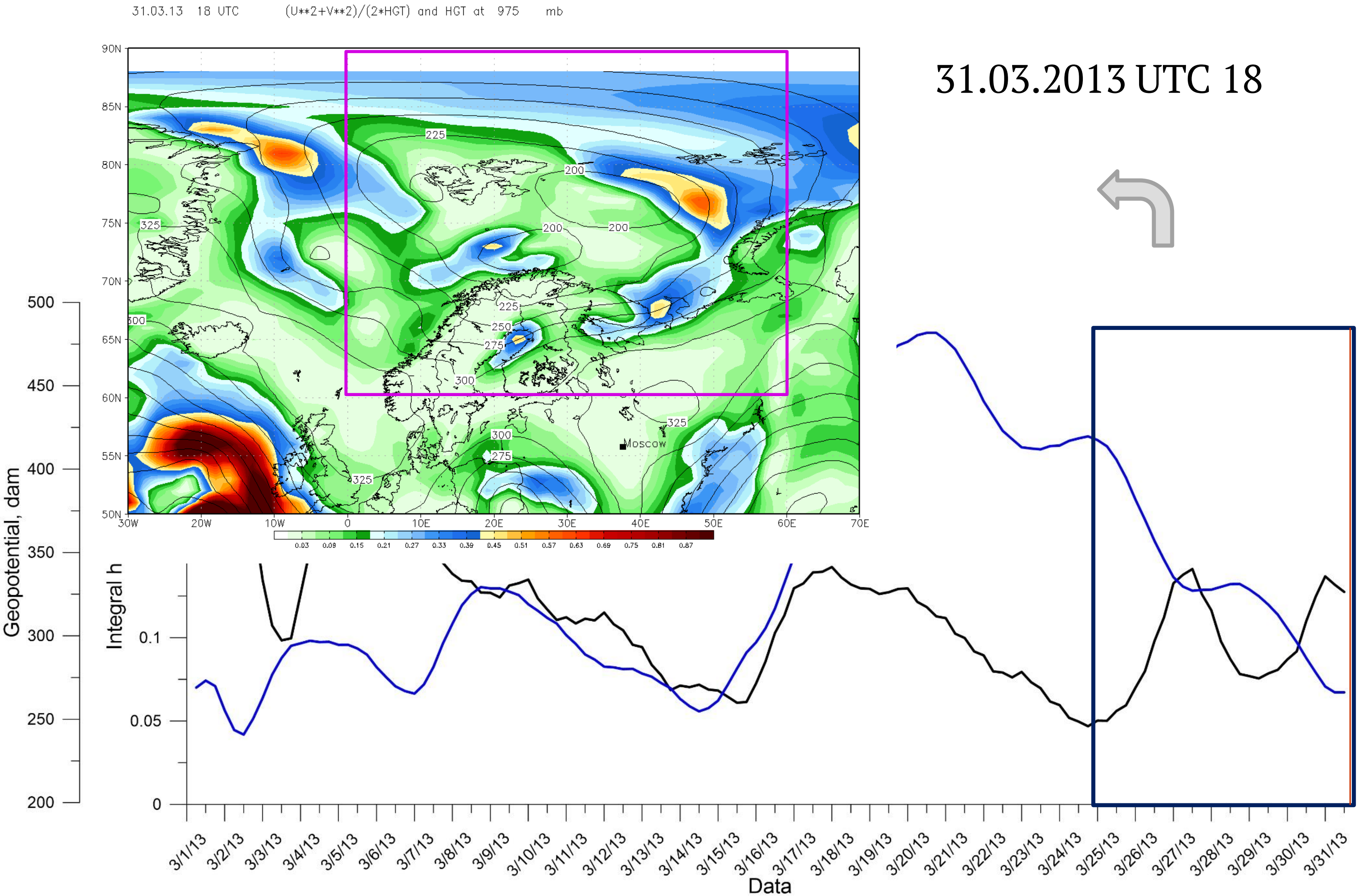


30.03.2013 UTC 06



Helicity.

Integral helicity and geopotential. Level 975 hPa.
Diagnostic/prognostic meaning

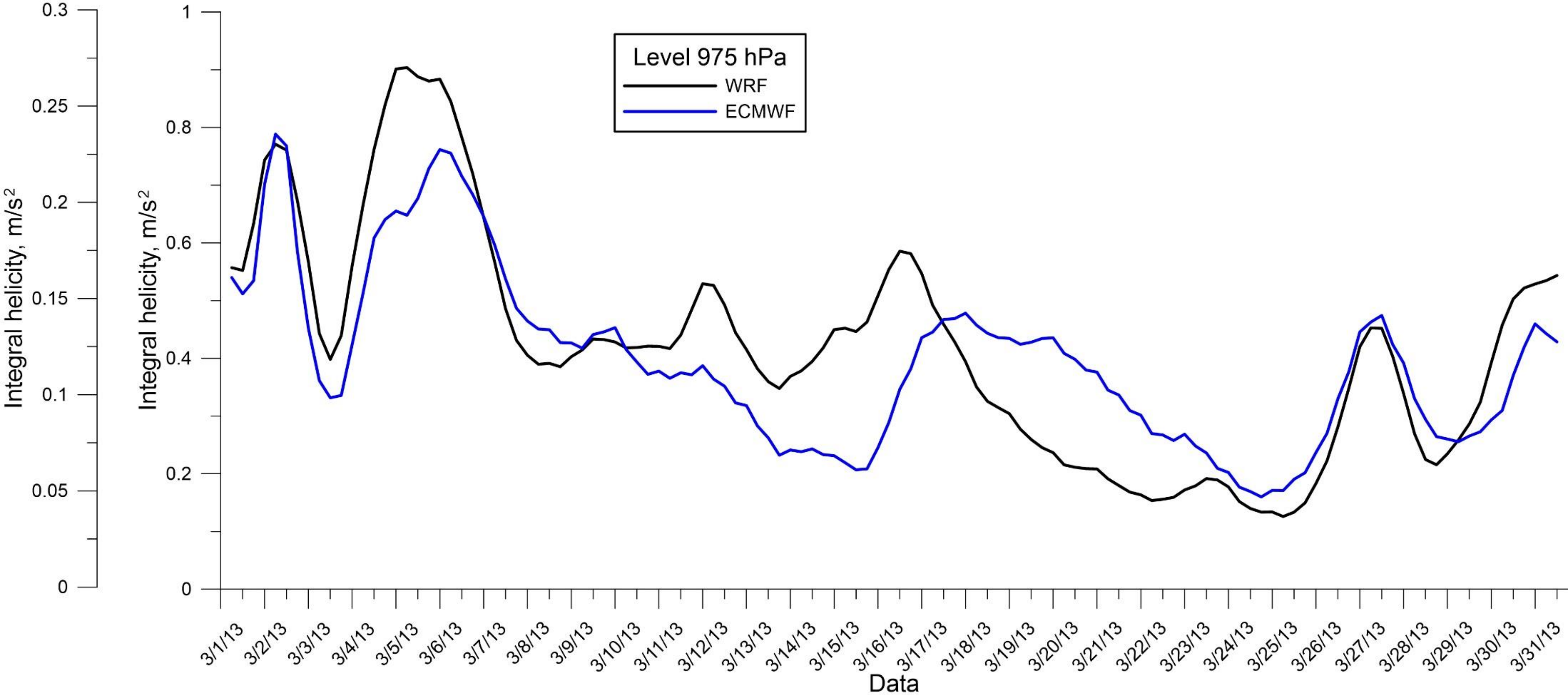


31.03.2013 UTC 18

WRF-ARW model. Grid and parameterizations

Run time	01.03.2013 00 UTC-31.03.2013 18 UTC
Number of domains	2
Map projection	Polar
Grid distance	10 000 m (10 km) / 3333 m (3,333 km)
Full south-north dimension	327/109
Full east-west dimension	207/90
Full vertical dimension	50
Time step	60 s
Longwave Radiation	CAM/CAM (Community atmosphere model, W. D. Collins et al., 2004)
Surface Layer	Monin-Obukhov (Zilitinkevitch)
Land Surface Model	Noah, (Chen et al., 2001)
Planetary Boundary Layer	Mellor-Jamada-Janjic scheme (Janjic, 1994, MWR)

Time behavior of the square average integral helicity according to the data from ECMWF and to the results of numerical simulations on the WRF-ARW model. The Nordic seas. 975 hPa

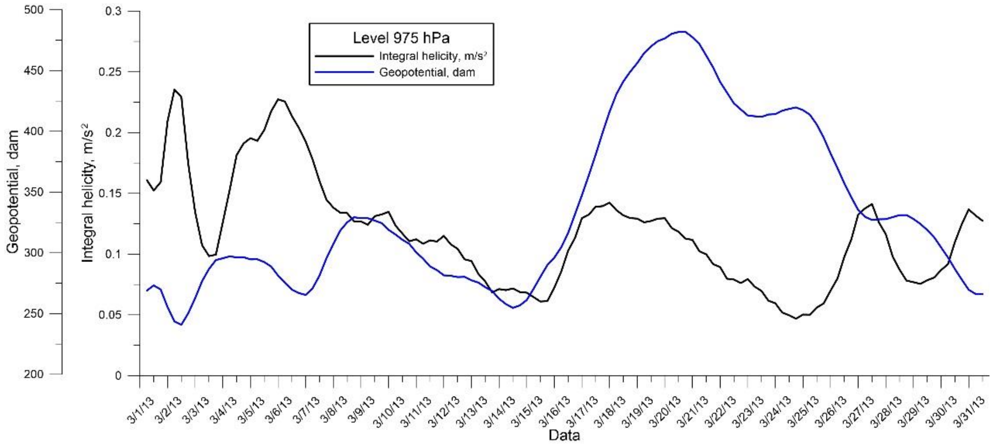


01.03.13 – 31.03.13

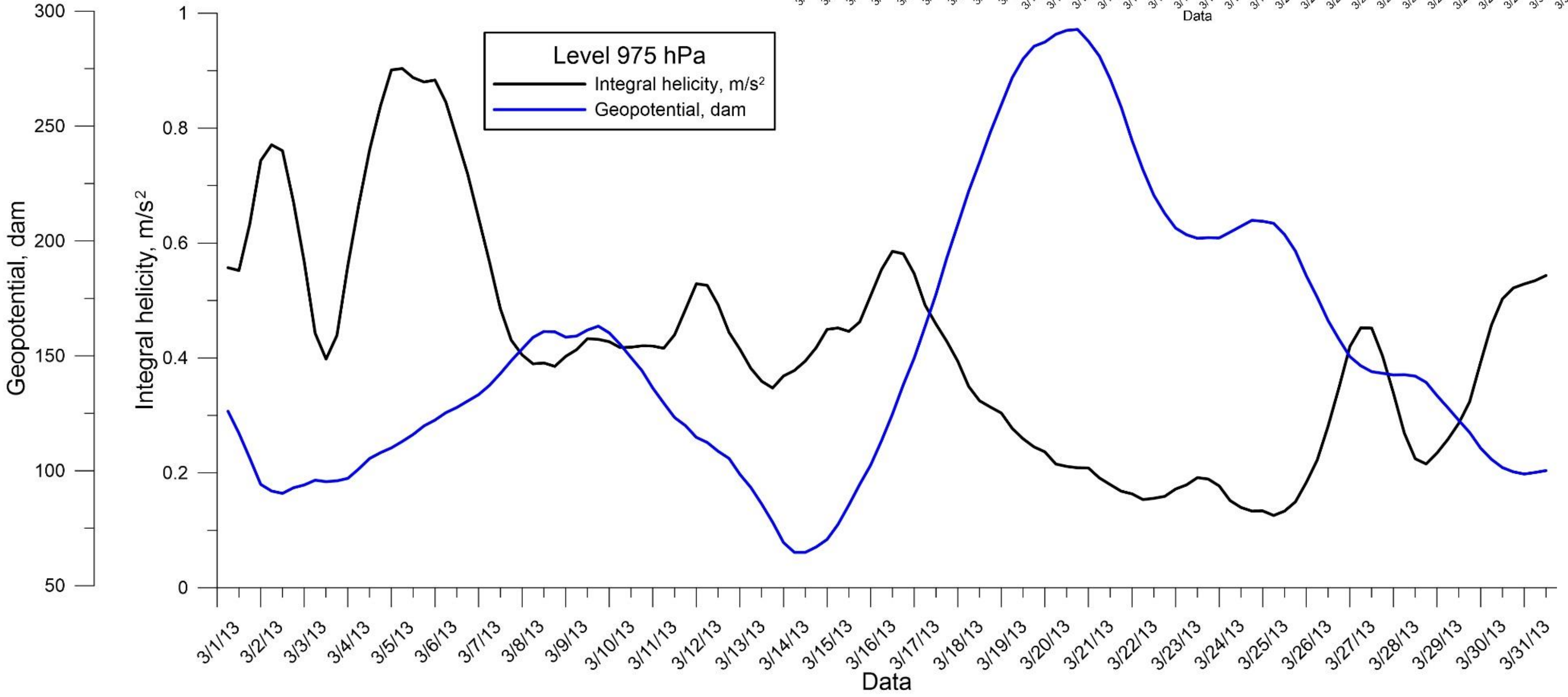
Helicity.

Integral helicity and geopotential in the atmospheric boundary layer The Nordic seas. 27 – 31 March, 2013. ECMWF and WRF. Level 975 hPa

ECMWF

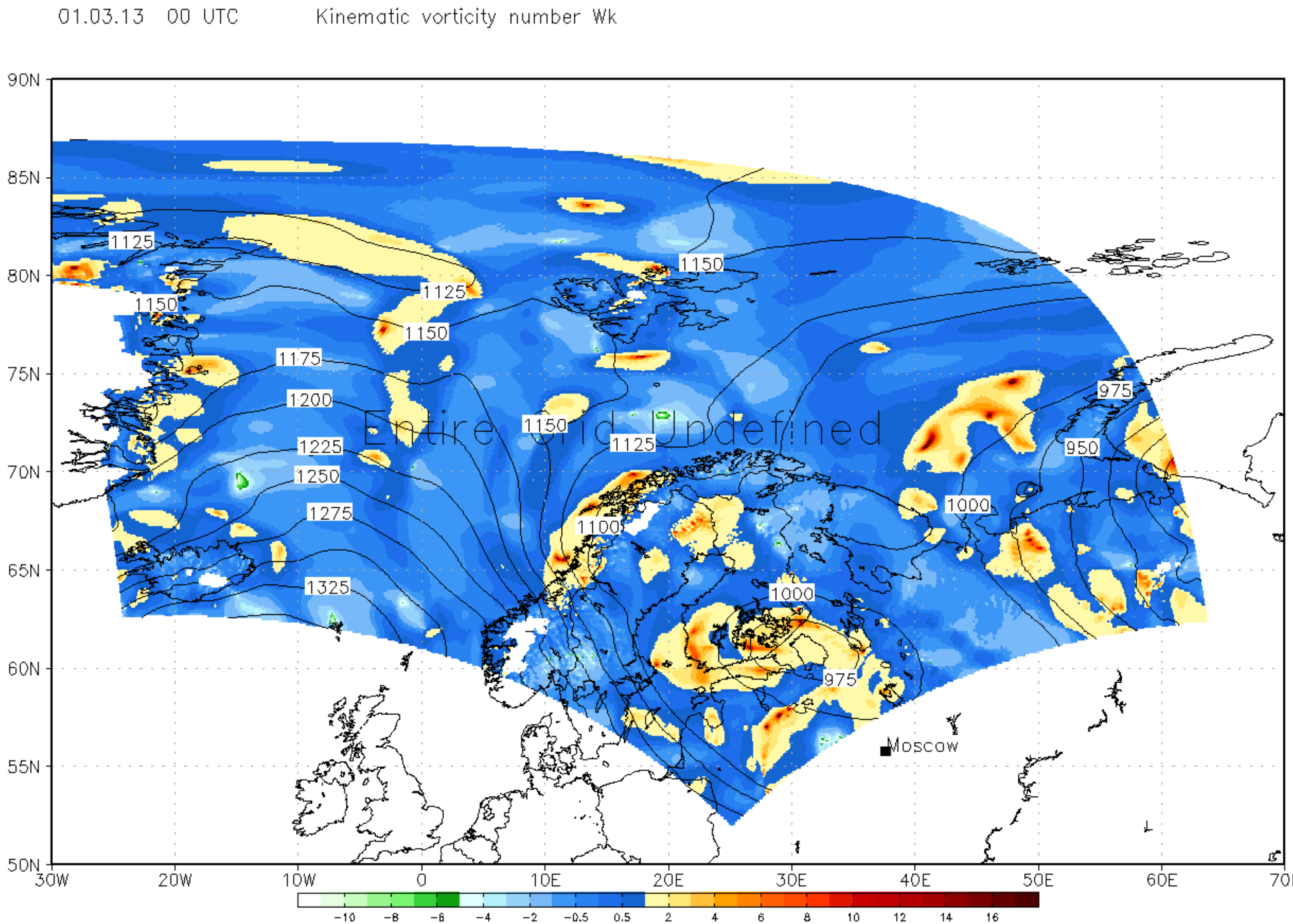


WRF

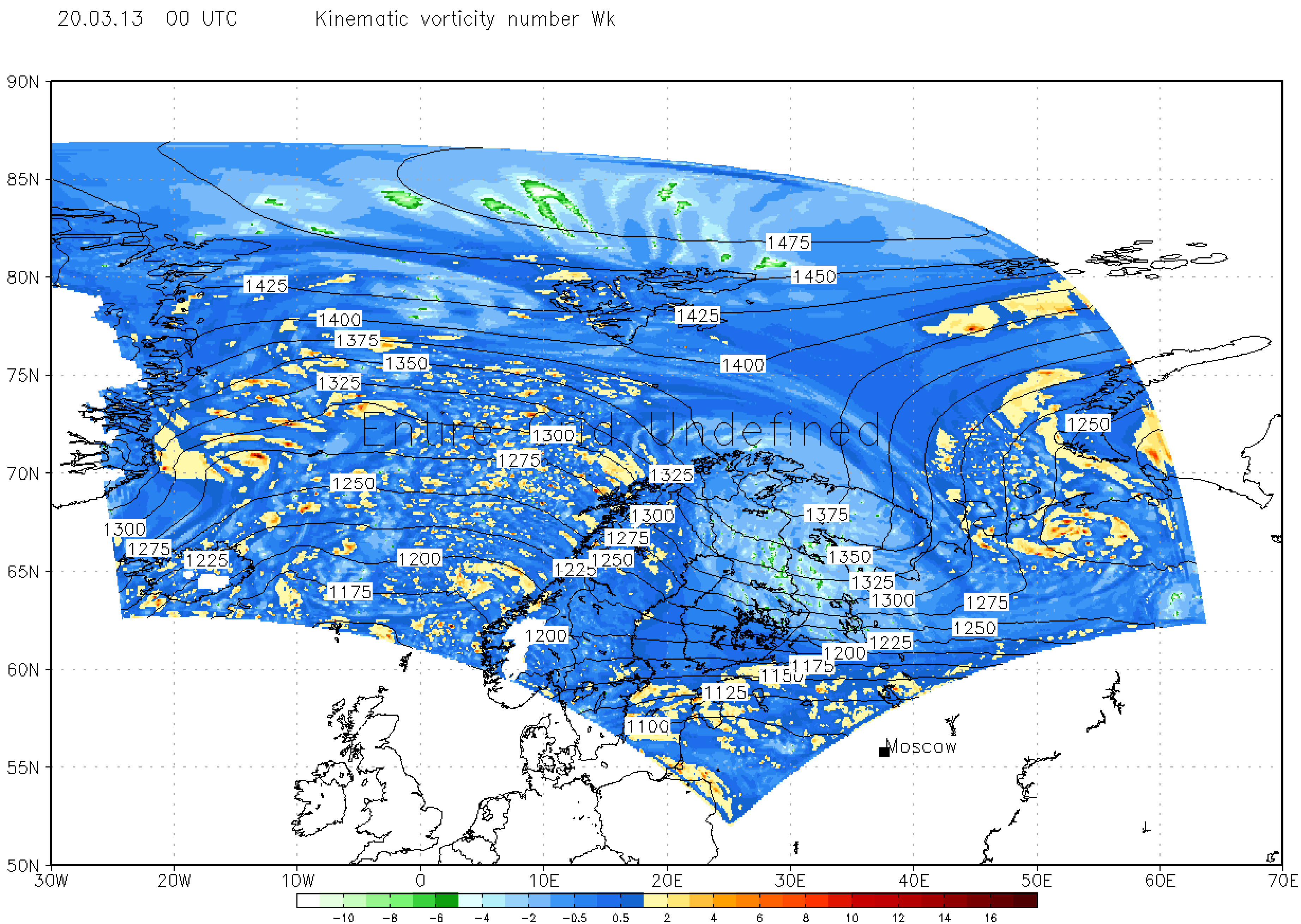


Kinematic vorticity number

And geopotential in the atmospheric boundary layer. 27-31 March, 2013. ECMWF. Nordic seas. Level 975 hPa



Kinematic vorticity number



Summary and conclusions

- The main challenge of our work is to make the operational forecast of PLs possible by selecting the diagnostic and prognostic integral characteristics of PLs, sufficient for PLs identification and analysis of their size and intensity in a convenient, usable and understandable form.
- In this study the combination of the estimation of the helicity as the integral square characteristic related to aggregate vortex formations (helicity hereafter) and kinematic vorticity number has been picked up.
- To indicate the main findings we have used reanalysis data and the results of numerical modeling in the WRF-ARW model for the PLs over the Nordic Seas in 2013.
- It has been noted that local minima of the geopotential correlate well with local maxima of helicity during the PL (a negative correlation coefficient of -0.706 for 27-31 March and of -0.945 for 29-31 March, 2013).
- Local changes in helicity are adjacent to the front of the PL. One day before the formation of PL, a significant increase of helicity was observed. The average helicity density of large-scale motions have the values of 0.3 – 0.4 $m\ s^{-2}$.

Summary and conclusions

- Kinematic vorticity number is the PL size and intensity additional indicator. It helps to single out individual polar low occurrences. At the moment of maximum intensity of PL the kinematic vorticity number can reach values of 12 – 14 units. These results are consistent with what we have reported above.
- Consequently, criteria associated with vorticity and helicity quite clearly manifested through the PL genesis and development and can be used to increase the efficiency and accuracy of complex forecasting techniques. It should be mentioned that at this time such a statement is only a hypothesis, which needs to be tested using a larger ensemble of cases.
- Future work will need to extend these analyses to other PLs active basins. Furthermore, it would be of interest to compare the representation of PLs by the use of any other criteria. Moreover, the spectral nudging technique would facilitate the obtaining of less intense PLs and enhance accuracy and quality of obtained statistic and integral characteristics and validate the structure and number of polar lows in high-resolution climate model either. Finally, an intention exists to use our combined criterion as a precursor of machine learning PLs identification procedure where currently analysis of satellite imagery and capturing particular cloud patterns (e.g. comma-shaped) apply in the majority of cases. It would eliminate the time consuming first stage of datasets collection.

Papers and funding

- This work was supported by the Russian Science Foundation (project No. 19-17-00248)

- The results have been published here:

Vazaeva, N. V., Chkhetiani, O. G., & Kurgansky, M. V. (2020, November). On integral characteristics of Polar Lows. In *IOP Conference Series: Earth and Environmental Science* (Vol. 606, No. 1, p. 012065). IOP Publishing.