Post-processing of numerical weather prediction for aviation meteorological service

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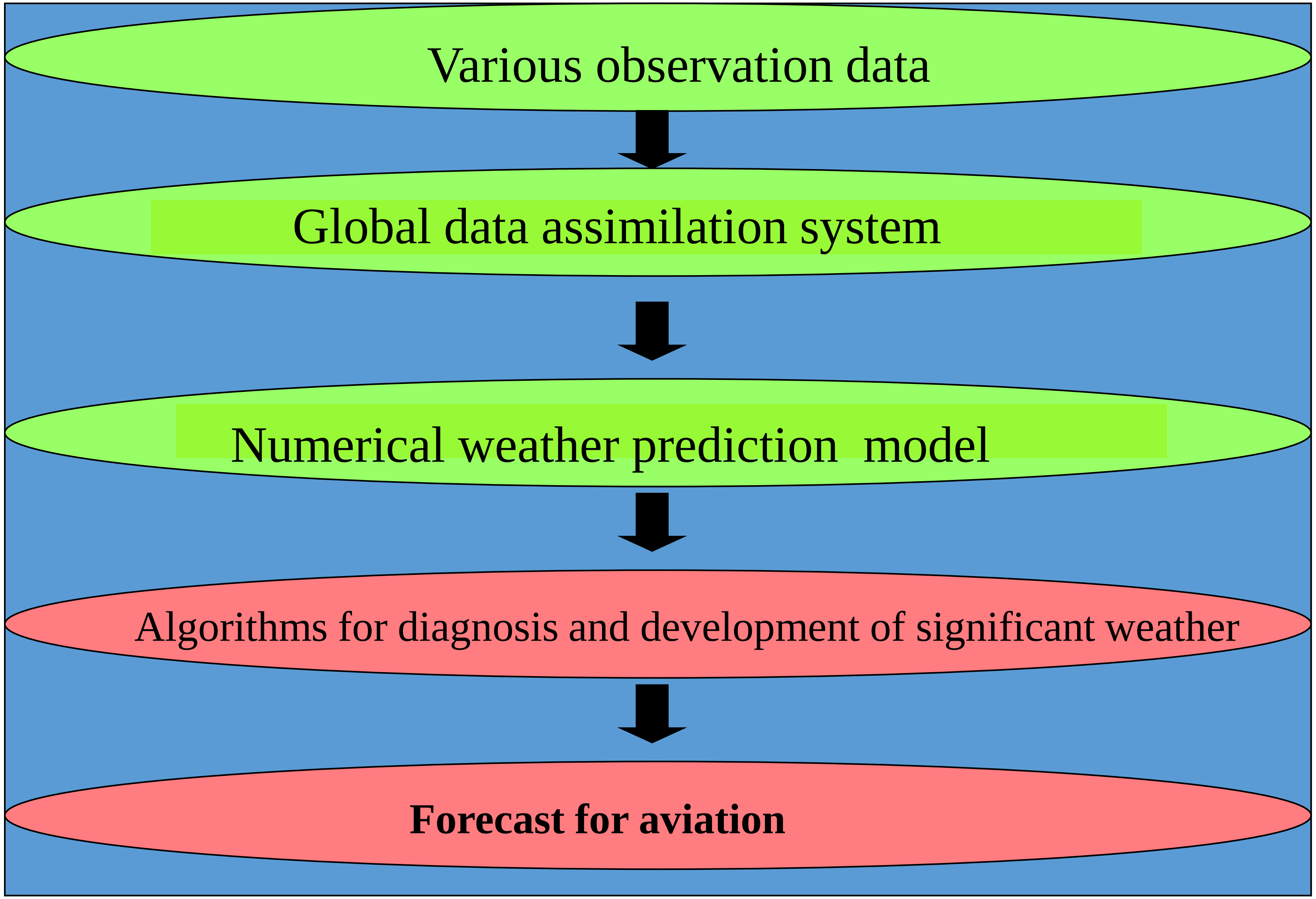
Weather forecasting for aviation



Forecasts for aviation

Forecasts	**Area, flight and route**	**TAF (terminal aerodrome forecast) TREND, for take-off**
Production	Atmospheric parameters **at flight levels** (H, T, V, RH…) **Significant weather : jet stream parameters, tropopause height and temperature, intensity of turbulence, icing, mountain waves, characteristics of convection**	Atmospheric parameters at surface (T, V , **QNH**…) **Видимость, высота нижней границы облачности**, явления погоды (гроза, туман, пыльная буря, осадки…)
Projection	6-120 h	Up to 30 h
NWP model	Global	For limited area, local
Details	data can be used as a sufficient source of information	It is necessary to add observation data for nowcasting range

Desirable accuracy of forecasts used for aviation meteorological service

- Much more high vertical resolution in upper troposphere and stratosphere (reduced vertical separation minima – 10 hft)
- Much more high accuracy as compared with the same for routine weather forecasts for population:

Parameter	For take-off	Routine
Temperature, ^{0}C	± 1 90% of cases	± 2
Wind speed, ms^{-1}	± 2.5 90% of cases	± 5

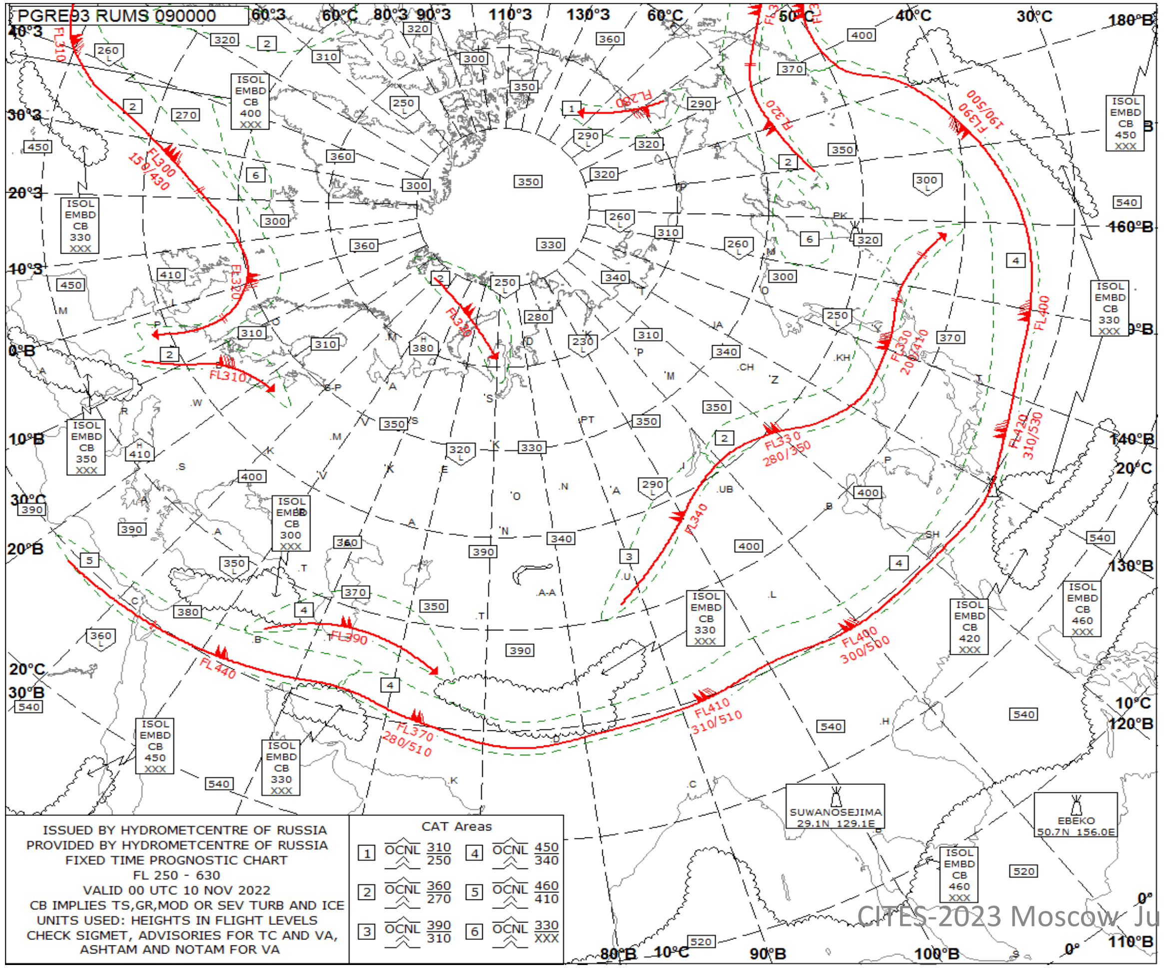
NWP for area (en-route) forecasting

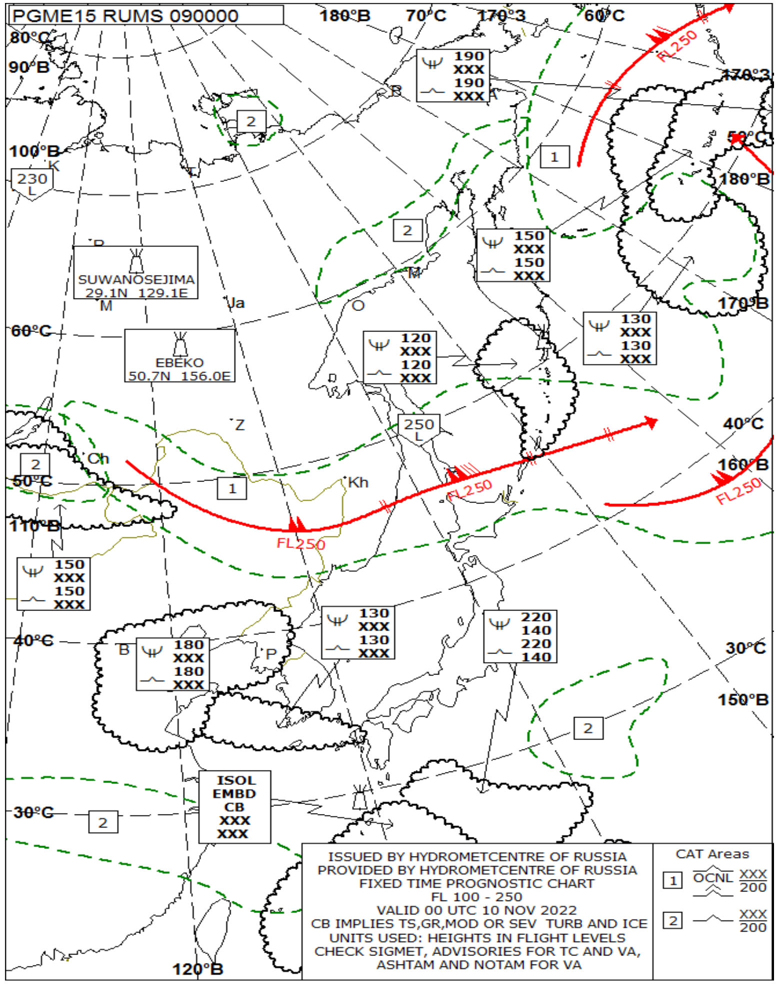
Urgency of an issue

- **ICAO World Area Forecast System (2 global centers, WAFC London and WAFS Washington) –** stopped providing meteorological en-route information for Russia since March 11, 2022 (Global grid data of atmospheric characteristic et flight levels and SigWX charts)

- **Russian Area Forecast System (RAFS)** – was established by order of Roshydromet Head on May 3, 2023 with the approval of the Ministry of Transport and the Ministry of Natural Resources. It bases on the SL-AV model data (yet SL-AV20).

Significant weather charts SigWX for medium and heigh level are made by forecasters using post-processing grid data on the base of NWP model:
characteristics of jet streams, tropopause, turbulence, icing, convection, mountain waves

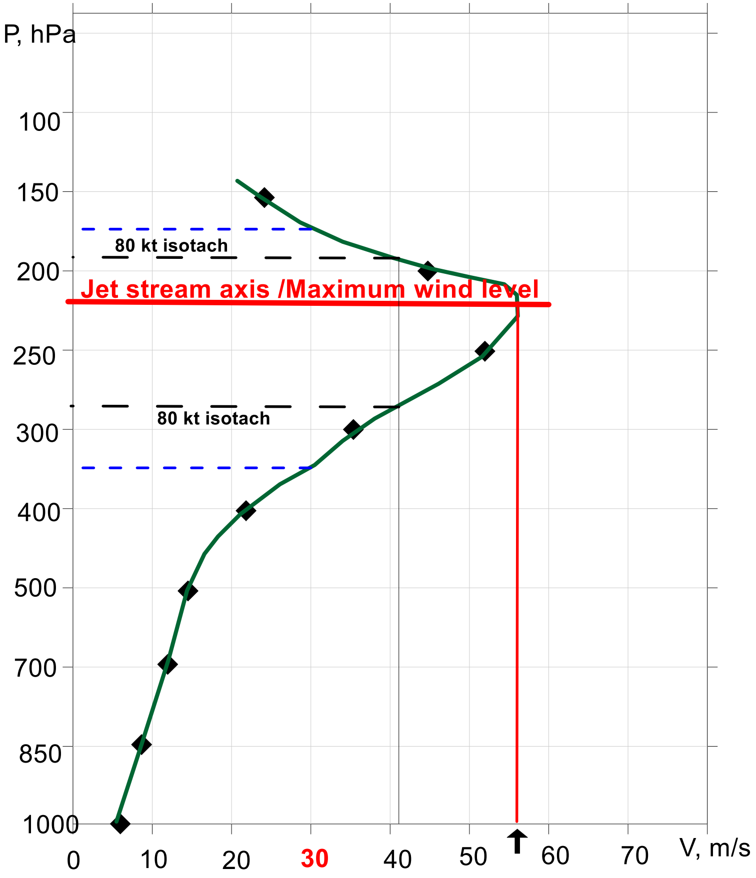


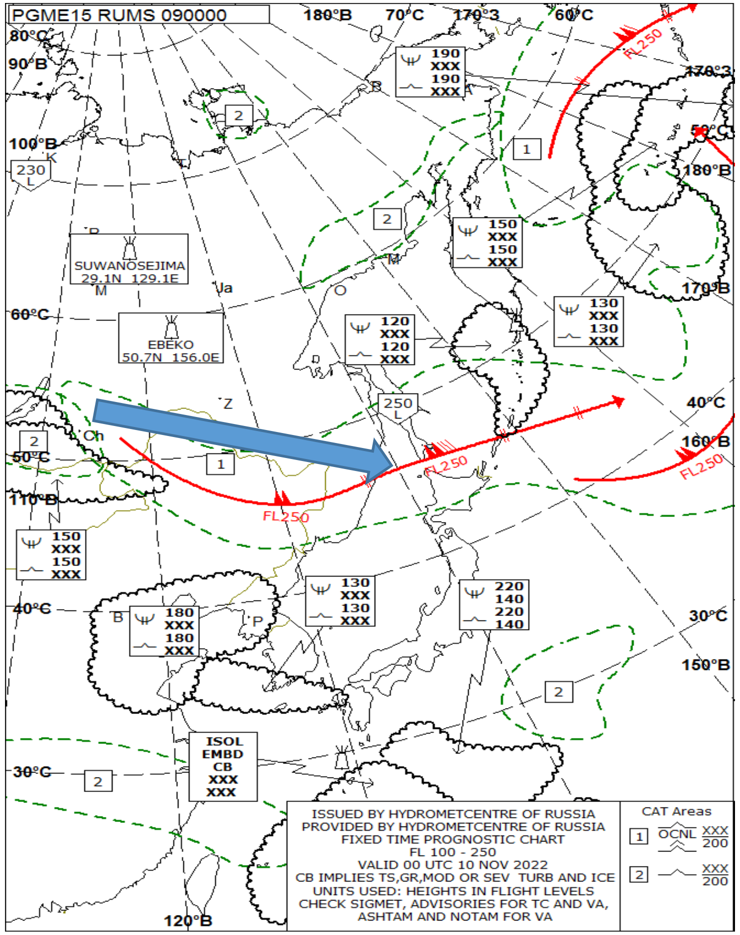


Post-processing for jet stream prediction

Wind profile with a jet stream at grid point
according to wind output data at standard (model) levels

Standard algorithm to predict jet stream (maximum wind) attributes:
speed ,
direction,
level height





Jet stream simulation as a marker of NWP model shortcomings

- Globally averaged estimation (for example, the wind speed forecast error) are often not very informative, while the selection of the most physically significant sections of the field allows one to detect "weak points" of the model dynamics (which can be occur at the stage of initial conditions formation).

Estimation of the forecasting quality for maximum wind speed in the Northern Hemisphere by the global model SL-AV20 . April 2023

MW, m/s	<30	30-40	40-50	50-60	>60	>30	Aver
BIAS	-0.5	-1.1	-1.5	-2.0	-3.4	-1.5	-0.9
MAE	**1.9**	**2.7**	**3.0**	**3.4**	**4.4**	**3.0**	**2.3**
SQRT	2.5	3.6	4.0	4.8	6.2	4.2	3.2
±5m/s,%	94	86	82	78	68	82	89.8

Estimation of the forecasting quality for maximum wind attributes in terms of ICAO requirements in the Northern Hemisphere by the global model SL-AV20. April 2023

Attribute	Limit	ICAO	SL-AV20
Speed	5 m/s	90% of cases	82% of cases
Direction	20 deg	90% of cases	98% of cases
Level height*	300 m	80% of cases	57% of cases

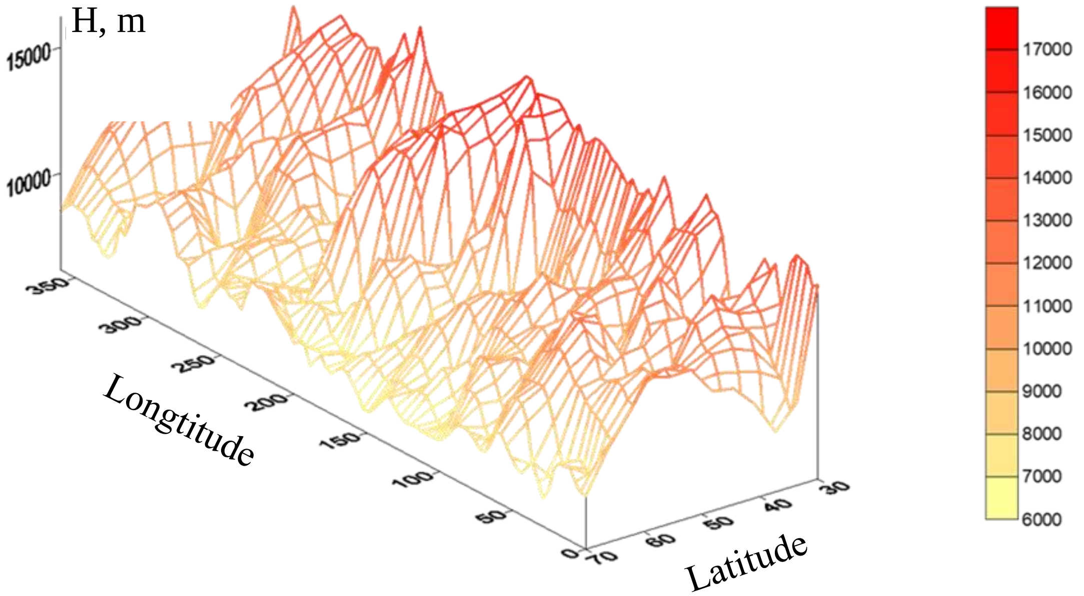
*SL-AV10 – vertical resolution in the upper troposphere will be doubled. This fact allows to hold out a hope of better results.

Tropopause forecasting

- “Dynamic” tropopause concept – tropopause as a surface of equal values of Ertel's potential vorticity (3.5 pvu)

$$\vec{Q} = \frac{1}{\rho}(f\vec{k} + \nabla \times \vec{v})\nabla \theta$$

DYNAMIC TROPOPAUSE LOOKS AS A QUASI-MATERIAL SURFACE, UNIQUELY DETERMINING IT AT EVERY POINT (IT EXCLUDES THE PROBLEM OF MULTIPLE “THERMAL” WMO TROPOPAUSES)



Difficulties of tropopause simulation in NWP models

- **Underestimation of deep tropospheric-stratospheric vertical circulations in high front zones by the NWP model is the cause of a noticeable smoothing of the tropopause (largest errors in the areas of tropopause folds and domes)**

Estimation of the forecasting quality for tropopause height in the Northern Hemisphere by the global model SL-AV20 . April 2023

Htrop, km	<6	6-8	8-10	10-12	12-14	14-16	>16	Aver.
BIAS	393	107	20	51	-4	287	-123	26
MAE	**466**	**246**	**243**	**294**	**475**	**841**	**649**	**433**
SQRT	709	361	383	576	815	1308	1028	777
±300 м, %	48	72	72	71	53	36	44	60

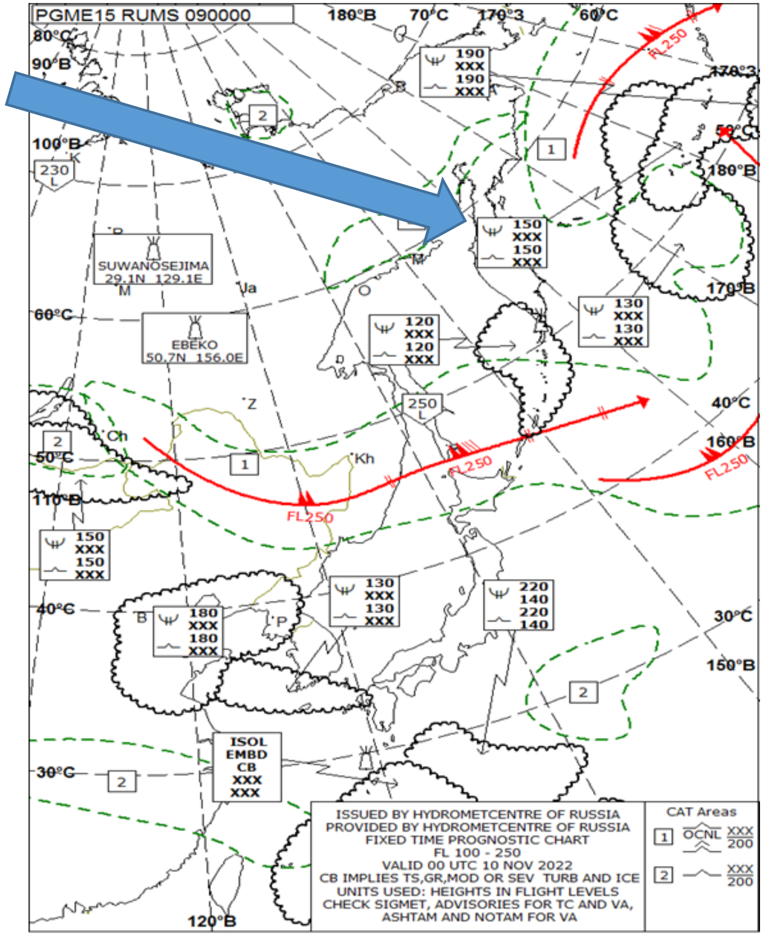
ICAO requirement to tropopause height prediction

Limit	ICAO	SL-AV20
±300 m	80%	60-70%

Icing forecast

Current algorithm for SigWV chart : occurrence/non-occurrence of icing layer is determined by the ranges of temperature values and relative humidity. There are no gradations of intensity, just border of layer.

Research algorithm (local area model COSMO-Ru6.6): taking into account vertical speed and liquid water content to estimate icing intensity

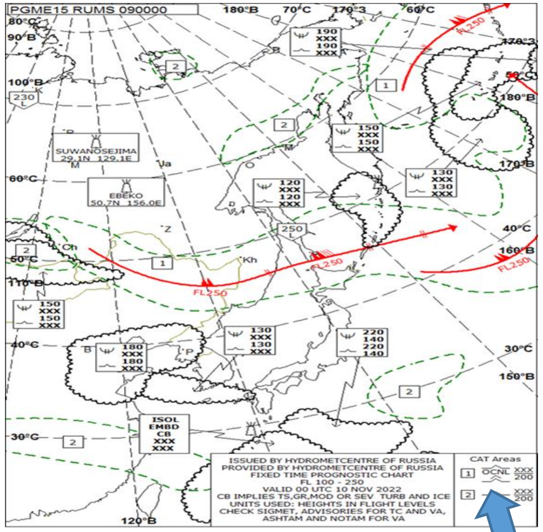


Correct prediction of aircraft icing conditions requires a dramatic change in the description of model microphysical processes associated with transition of water states and distribution of droplet sizes over the spectrum. Unfortunately, even if the result is achieved, these are extremely costly calculations in terms of computational resources which are currently unrealizable for routine forecasting

Impact of turbulence on aircraft

<u>Turbulence sources:</u>

- **Convection**
- **Mountain waves**
- Roughness of surface
- **Jet streams**



Turbulence is the cause of bumpiness. Intensity of bumpiness depends on size of turbulence eddies .

Maximum effect is caused by eddies with typical scale from 100 to 1000 m

It is necessary to improve the dynamical core of global NWP model - model should be eddy-resolving

Current approach for turbulence forecasting – search of following characteristics:

- Large vertical and horizontal gradients of wind and temperature
- Transient flow
- Dramatic change of value and sign for temperature gradients
- Low static stability
- Jet stream meandering
- …

Examples of turbulence indices

Brown index

$$\Phi_n = \sqrt{0,3\zeta_a^2 + D_{sh}^2 + D_{st}^2} \ .$$

Ellrod-Knapp index

$$TI2 = \left(D + C_{vg}\right)\left|\frac{\partial \vec{V}}{\partial z}\right|,$$

$$D = \sqrt{D_{sh}^2 + D_{st}^2} = \sqrt{\left(\frac{\partial u}{\partial x} - \frac{\partial v}{\partial y}\right)^2 + \left(\frac{\partial v}{\partial x} + \frac{\partial u}{\partial y}\right)^2},$$

$$C_{vg} = -\left(\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y}\right).$$

$$DVSI = D \cdot VS \cdot \frac{V}{45},$$

$$VS = \sqrt{\left(\frac{\partial u}{\partial z}\right)^2 + \left(\frac{\partial v}{\partial z}\right)^2} \ .$$

Frontogenesis function

$$F = 0,5\left|\nabla_h \theta\right|\left(D\cos 2\beta + C_{vg}\right),$$

где $|\nabla_h \theta|$ – величина горизонтального градиента потенциальной температуры на поверхности h; β – угол между осью растяжения изогипс и изолинией потенциальной температуры.

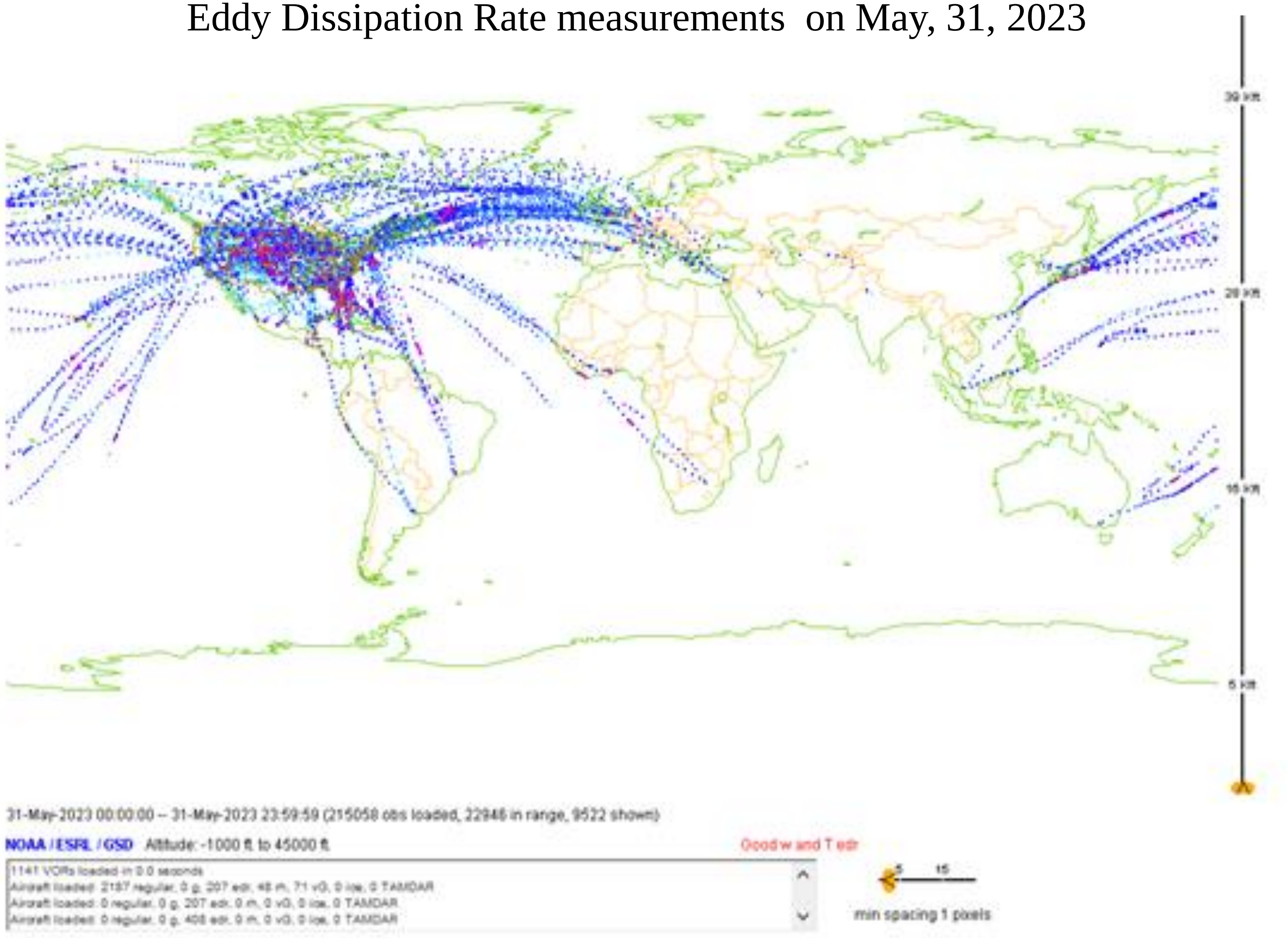
Lunnon index

$$Lunnon = \left[\left(\frac{\partial v}{\partial p}\right)^2 - \left(\frac{\partial u}{\partial p}\right)^2\right] \cdot \left(\frac{\partial u}{\partial x} - \frac{\partial v}{\partial y}\right) - 2\frac{\partial u}{\partial p}\frac{\partial v}{\partial p}\left(\frac{\partial u}{\partial y} + \frac{\partial v}{\partial x}\right)$$

The main challenge: a search of thresholds

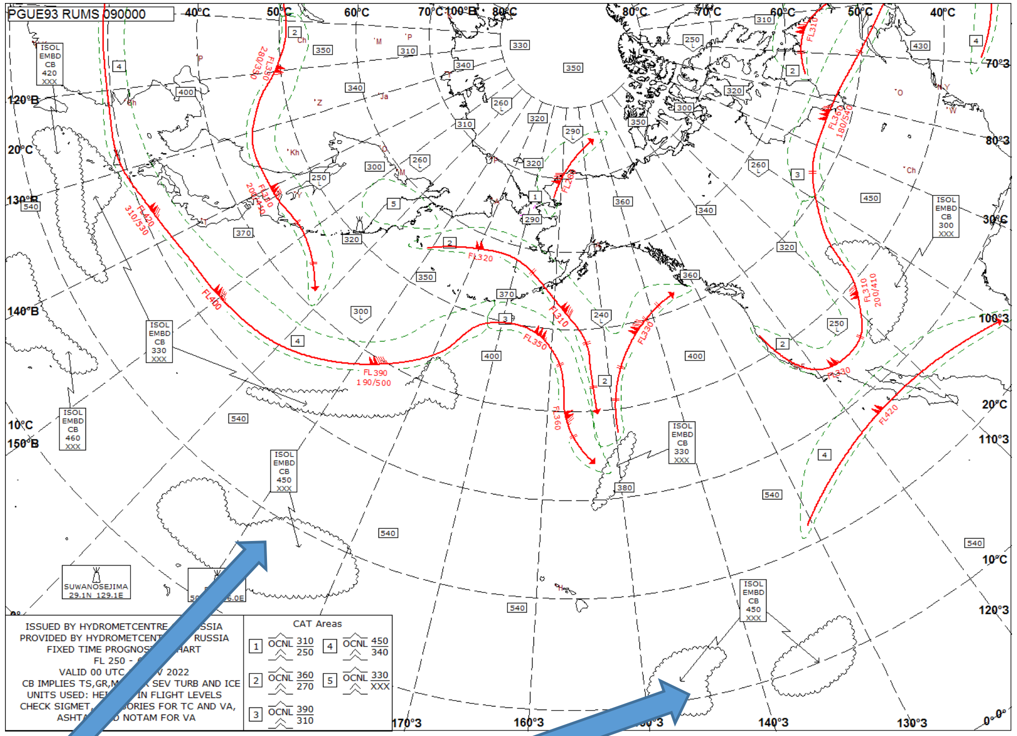
- Calculations of occurrence and intensity of turbulence based on model output data may by verified just by observation/measurement data
- Data lack over Russia
- Post-processing results based on global model data may be checked using data information over any area.

Eddy Dissipation Rate measurements on May, 31, 2023



Convection prediction – TCU, Cb, coverage, top height, type

- Implementation of “parcel method” using global model output data (temperature, humidity, height)
- Introduction in algorithm “mixing layer” (thickness depends on season)
- Thresholds of instability indices to detect thunderstorm.
- Forecasting of CB type “embedded” imply an adequate model simulation for other cloudiness at high levels



Cb

Mountain wave forecasting

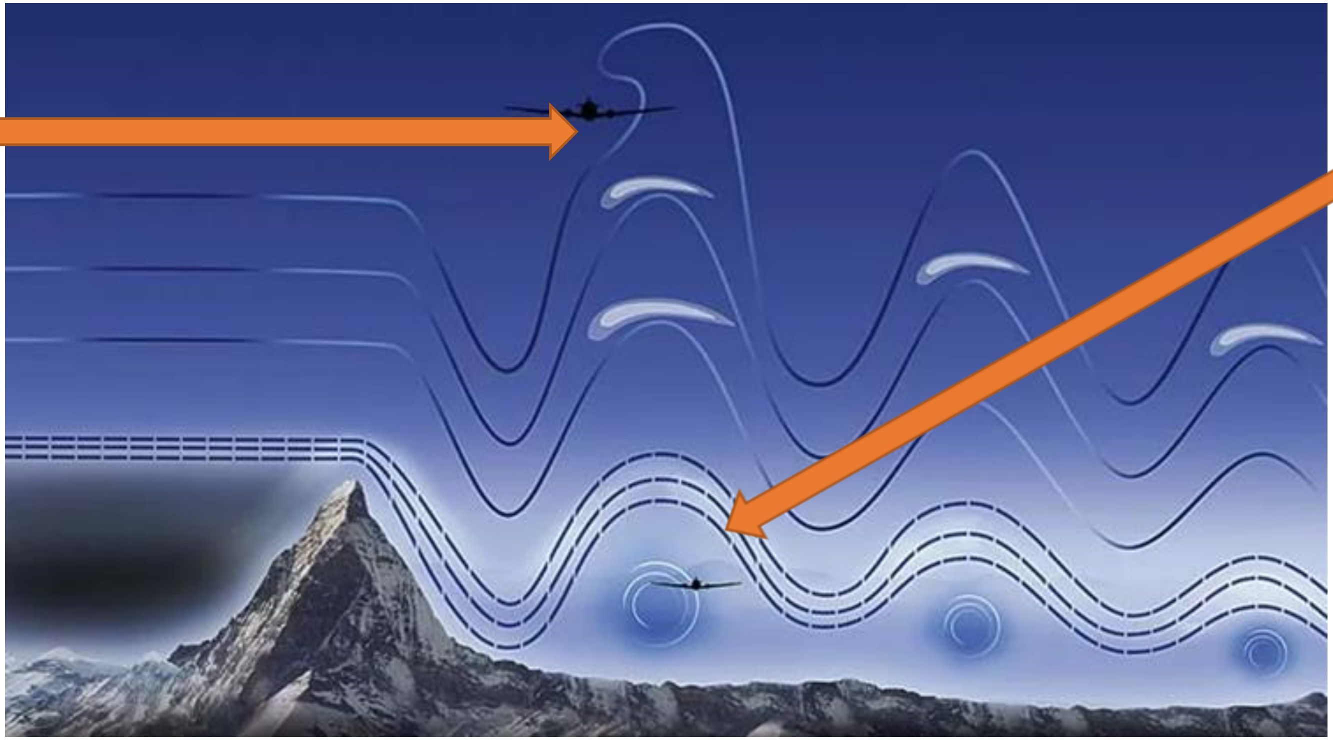
ICAO requirement - Severe /moderate mountain wave (MW SEV/MWMOD) forecasting:

- **Vertical downward stream beyond convective : speed is 3 /1.75 $m \cdot s^{-1}$**

OR

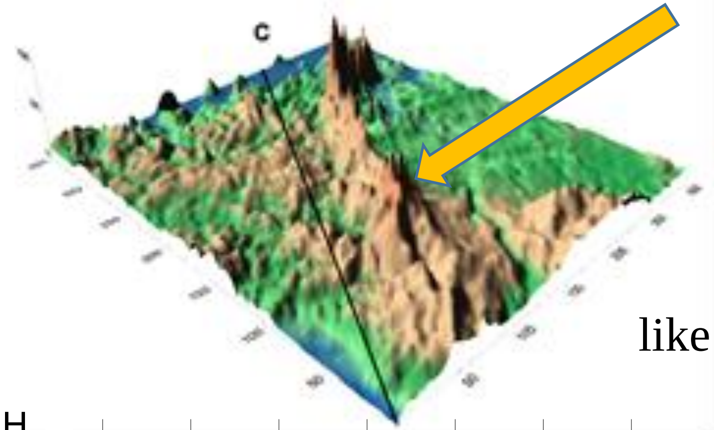
- **Severe /moderate turbulence forced by orography**

Turbulence as a result of MW breaking

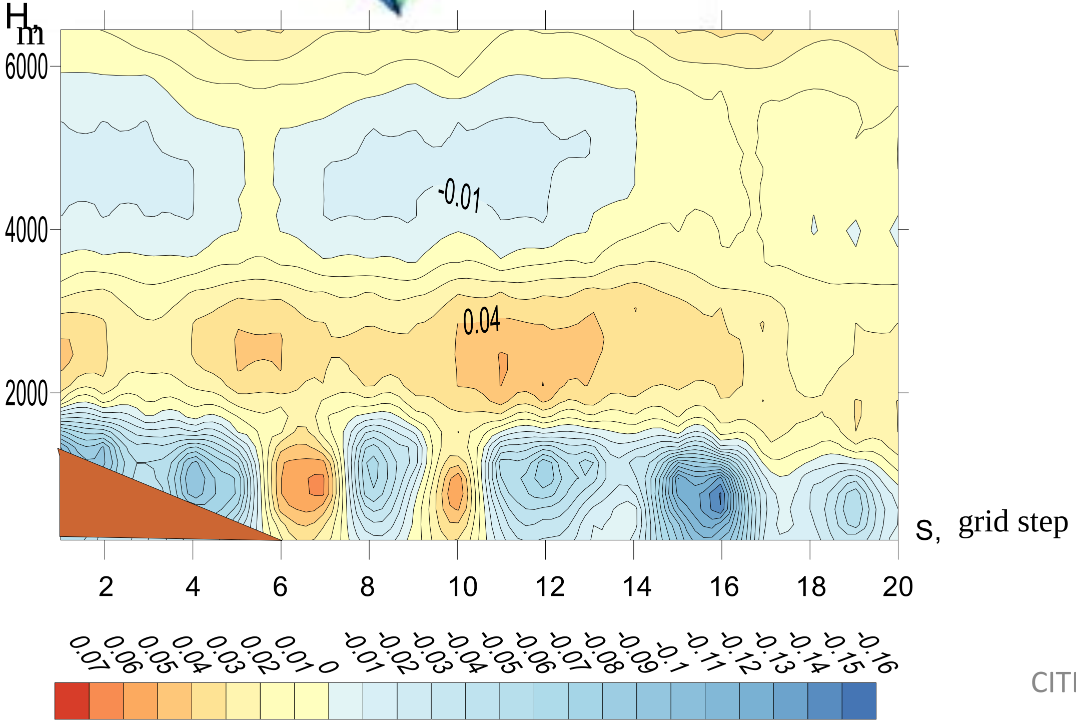


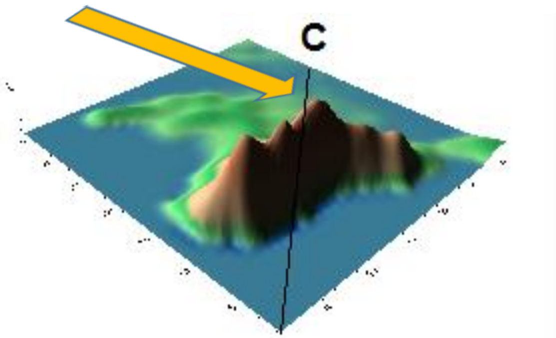
«Rotor» turbulence under wave crest

Mountain wave simulation in COSMO-RU-ENA 6.6 model

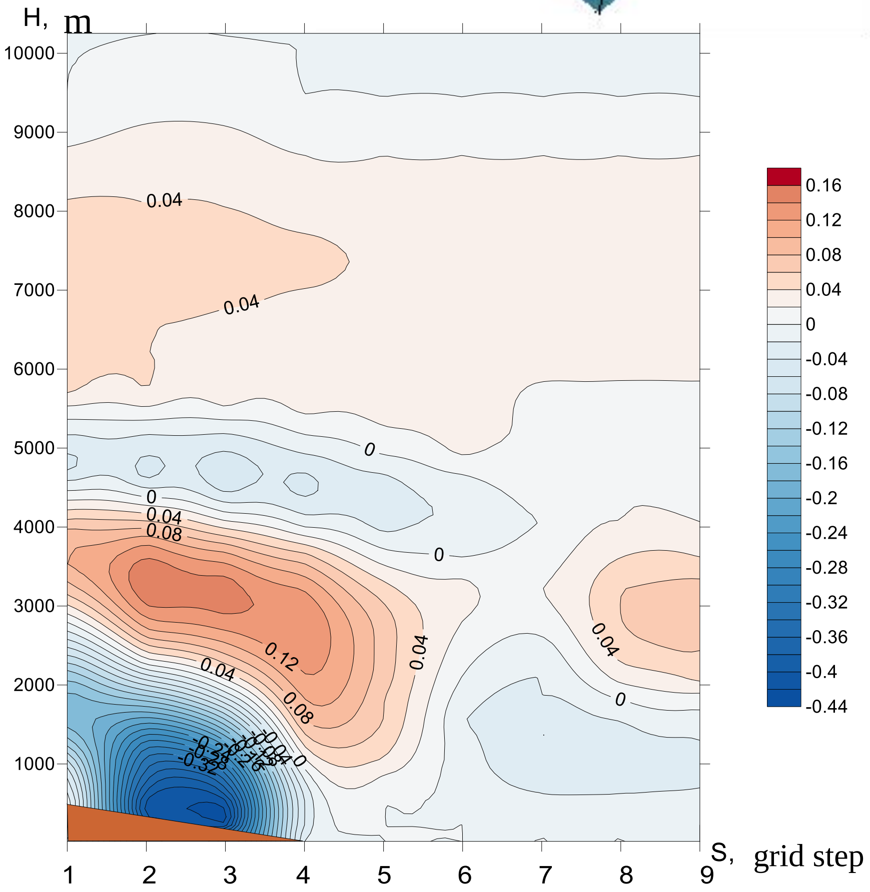


Urals,
like a «trapped» MW





Crimean Mountains,
upward gravitation
wave

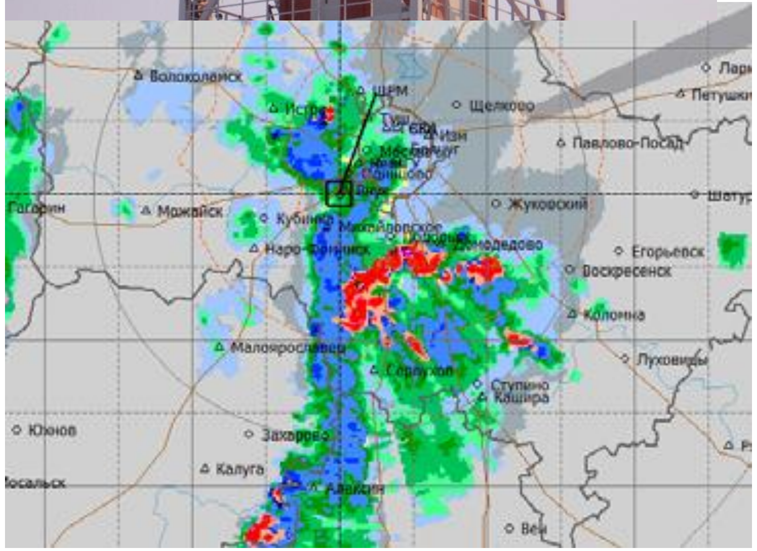


NWP for aerodrome forecasts

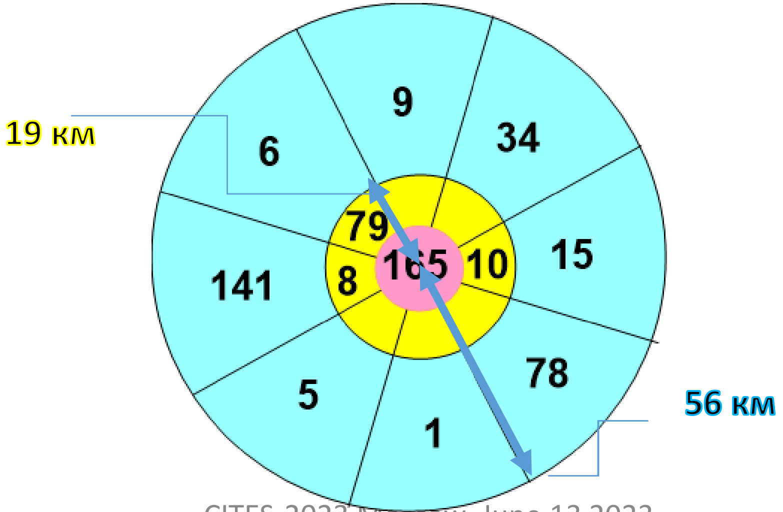
Nowcasting of the **arrival time** of the thunderstorm at the aerodrome

Calculation with update of observation and forecasts every 10 min

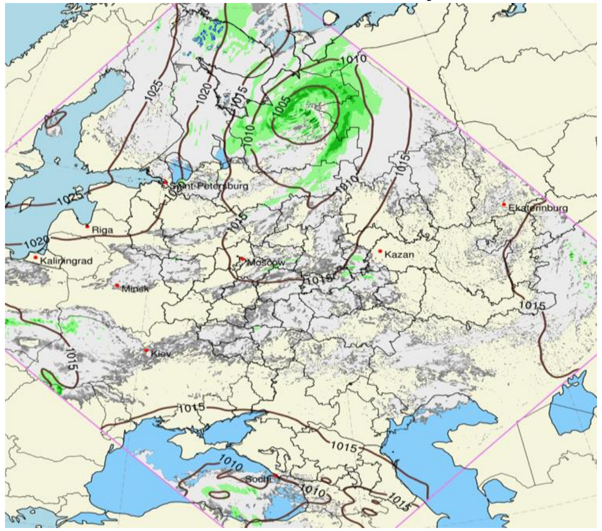
DMRL-C, 1x1 km, Hazardous weather

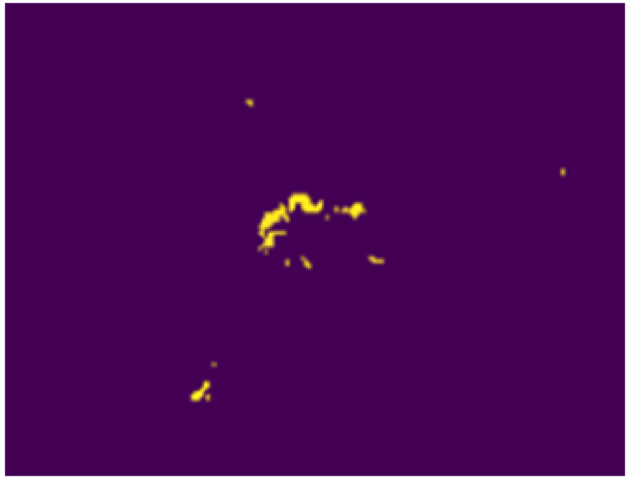


TSS-928, sectors, lightning discharges



COSMO-Ru2.2, instability indices, wind





Forecasting of **visibility change** at aerodrome

- RVR visibility
- Prevailing visibility at aerodrome

Ideal NWP model (for visibility prediction):
in addition to high resolution (hundreds/tens of meters) with the real-time assimilation of data from numerous sensors, a detailed description of the processes in the surface layer is necessary - the transition from parameterizations with an explicit description of the exchange processes between the surface and the atmosphere, accounting for turbulence (including wake vortexes), changes in the model microphysical block for precise prediction of precipitation types.

Thank you for your attention