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CONTEMPORARY PROBLEMS OF OBJECTIVE ANALYSIS OF METEOROLOGICAL FIELDS

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U. S. BOARD ON GEOGRAPHIC NAMES TRANSLITERATION SYSTEM

Block	Italic	Transliteration	Block	Italic	Transliteration
А а	*А а*	A, a	Р р	*Р р*	R, r
Б б	*Б б*	B, b	С с	*С с*	S, s
В в	*В в*	V, v	Т т	*Т т*	T, t
Г г	*Г г*	G, g	У у	*У у*	U, u
Д д	*Д д*	D, d	Ф ф	*Ф ф*	F, f
Е е	*Е е*	Ye, ye; E, e*	Х х	*Х х*	Kh, kh
Ж ж	*Ж ж*	Zh, zh	Ц ц	*Ц ц*	Ts, ts
З з	*З з*	Z, z	Ч ч	*Ч ч*	Ch, ch
И и	*И и*	I, i	Ш ш	*Ш ш*	Sh, sh
Й й	*Й й*	Y, y	Щ щ	*Щ щ*	Shch, shch
К к	*К к*	K, k	Ъ ъ	*Ъ ъ*	"
Л л	*Л л*	L, l	Ы ы	*Ы ы*	Y, y
М м	*М м*	M, m	Ь ь	*Ь ь*	'
Н н	*Н н*	N, n	Э э	*Э э*	E, e
О о	*О о*	O, o	Ю ю	*Ю ю*	Yu, yu
П п	*П п*	P, p	Я я	*Я я*	Ya, ya

* ye initially, after vowels, and after ъ, ь; e elsewhere. When written as ё in Russian, transliterate as yё or ё. The use of diacritical marks is preferred, but such marks may be omitted when expediency dictates.

FOLLOWING ARE THE CORRESPONDING RUSSIAN AND ENGLISH DESIGNATIONS OF THE TRIGONOMETRIC FUNCTIONS

Russian	English
sin	sin
cos	cos
tg	tan
ctg	cot
sec	sec
cosec	csc
sh	sinh
ch	cosh
th	tanh
cth	coth
sch	sech
csch	csch
arc sin	$\sin^{-1}$
arc cos	$\cos^{-1}$
arc tg	$\tan^{-1}$
arc ctg	$\cot^{-1}$
arc sec	$\sec^{-1}$
arc cosec	$\csc^{-1}$
arc sh	$\sinh^{-1}$
arc ch	$\cosh^{-1}$
arc th	$\tanh^{-1}$
arc cth	$\coth^{-1}$
arc sch	sech^{-1}
arc csch	csch^{-1}

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rot	curl
lg	log

Contemporary Problems of Objective Analysis of Meteorological Fields

L. S. Gandin

1. An objective analysis of meteorological fields belongs to that group of studies which have only recently surfaced in present day meteorology. Occasioned by the demands for realization of numerical forecast methods, this aspect of meteorology was developed less than 20 years ago. In 1961, during the IV Meteorological Conference, the development and introduction of objective analysis methods were in the initial stage of development. V. V. Bykov and G. P. Kurbatkin [4] proposed an analysis methodology based on an approximation of geopotential fields with algebraic polynomials and similar to the method of Gilchrist and Cressman [48] which, at that time, was employed in the United States. An approach was developed in the Main Geophysical Observatory which was based on the methodology of optimum interpolation [6], [7], which makes use of information concerning the statistical structure of the fields for the meteorological elements under analysis. This method was introduced into practice by I. A. Chetverikov [42] under the direction of S. L. Beloyusov.

Further investigation [9] established the fact that the method of optimum interpolation possesses a number of fundamental advantages over other objective analysis methods, particularly the method of successive correction which is widely employed abroad [44, 45].

The basic advantage consists in the lesser sensitivity, in comparison with other methods, of the optimum interpolation method to the network thickness and the accuracy of the initial data. It is therefore not surprising that even though development of the method of polynomial approximation also was continued in the Soviet Union [5, 30, 41] that Soviet scientists paid great attention to the optimum interpolation method in the field of objective analysis.

Currently, operative numerical forecasts, constructed in various forecasting centers in the Soviet Union, use the results of objective analysis produced by the optimum interpolation method. In the USSR Hydrometer Center programs written by S. L. Beloyusov and S. A. Mashkovich are used for this purpose [1]. These same programs, with slight apparent changes, are used in numerical forecasts which are made jointly by the Main Geophysical Observatory im. A. I. Voyeikov and the North-Western Administration of hydrometeoroligical services. Both the meteorological elements and the dissociation coefficients of the vertical profiles with respect to biorthogonal functions were subjected to optimum interpolation as they were developed in the methodology realised at the Computer Center of the USSR Academy of Sciences Siberian Branch (VTs SO AN SSSR) in conjunction with the Novosibirsk regional center. Methods based on optimum interpolation have been introduced or have been prepared for introduction in Tashkent, Khabarovsk, and Tbilisi.

Not only the geopotential fields but also other meteorological elements are subjected to this optimum interpolation. This question has been studied in particular in the investigations of V. P. Meleshko and A.Ye. Prigodich [26] according to an analysis of temperature and dew point, and by M. O. Krichak [19] and M. V. Kartashov [16] according to an objective analysis of wind and other factors.

Development of methods for objective analysis of mesoscale distribution of meteorological elements has special meaning. If an analysis of air fields on hand can still be accomplished in a reasonable period of time, then when conducting an analysis of the earth layers by synoptics, it makes sense to ignore that portion of information already accumulated except that which pertains to the period in question. Construction of mesoscale distributions when using the entire body of information available can be done in operative order only by automated means, i.e., by objective analysis.

The first research in this direction was done by L. N. Strizhevskiy [33] who developed this correlation method using the so-called smoothing. S. L. Beloyusov and L. N. Strizhevskiy [2] wrote a program for operative analysis of earth-based barometric tendencies using optimum interpolation with corrections made by smoothing. This program is applicable, in particular, in the forecasts for Leningrad, which are done according to the L. V. Rukhovts-B. M. II'in method which makes great use of trend information.

Finally, a methodology has been developed for objective analysis of fields of four elements at the earth surface (pressure, trend, temperature, and dew point) which is based on the very same principles. The introduction of this methodology has allowed the transition to automatic construction of both ring-type charts and synoptic charts encompassing large regions. A system of rational maintainence and information searching on a computer, as proposed by Ya.M. Kheifetz, plays a significant role [40].

Ten years ago the initial data of objective analysis were written and monitored by hand. Now methods which permit automatization of all stages in the preliminary processing of operative information have been developed and out into practice. S. L. Beloyusov, K. A. Semendyaev and others [1] have researched methods for automatic searching, recognition, and codification of information.

Automatic control of operative information is of special importance. Only through automatic control can all information on hand be regulated and not just that individual datum which appears to be, for some reason or another, suspicious. Besides, as the tests show, it is necessary to avoid subjective elements specifically when processing through or correcting dubious data.

S. L. Beloyusov [18] was the first to develop a method of automatic data control for geopotential in the Soviet Union. Over a period of years his method was used as a matter of course in operational practice for processing error-studded data. Later on, other methods were devised which allowed not only the disregarding but also the correction of mistaken information. Some research [9, 28, 31] shed light on the construction and improvement of static control of geopotential and temperature data based on static equations. S. A. Mashkovich and S. I. Gubanov [25] developed a method of optimum interpolation at each station with the surrounding stations (horizontal regulation) as proposed in [8]. B. M. Il'in and L. V. Rukhovets, based on M. I. Yudin's concept, constructed a method of static vertical regulation using optimum interpolation at each level according to the data of other levels [43]. All these methods were put into operational practice. M. C. Krichak has studied questions regarding the monitoring of wind data [20].

Currently a complex method of air information regulation is being worked out [11]. The essence of this notion consists of the fact that a determination of excluding or correcting information is made after analysing the results of employing several independent control methods. It makes sense that all operations, including determination making, are conducted automatically. Research has shown that complex control is able to insure a considerably higher correction degree and information readjustment in comparison with the subsequent use of several regulation methods, as is now being done.

As previously stated, considerably different objective methods for meteorological fields are employed in different nations. It is interesting that despite the clear-cut advantages of optimum interpolation this method over a long period of time is used only in the Soviet Union. Only in recent years has a crisis developed. Thus, the American scientist Eddy [47] proposed an objective analysis method based on one of the optimum interpolation methods. Another variant, specifically optimum interpolation of the deviation from the forecast values, was worked out by Kruger in Canada [49] and used in practice by the Canadian meteorological survey. The research of Miyadoda and Talagrand [50] on the problems of four-dimensional analysis [50] should also be mentioned, in which they make wide use of the notion of optimum interpolation.

A deciding factor in terms of propagandising these ideas came about several years ago when a comparison was made between the results of operative objective analyses as conducted in various nations [13]. This comparison revealed that the analyses conducted using optimum interpolation in the USSR Hydrometry Center was in all cases of better quality than those made abroad, despite the fact that the optimum interpolation method requires at least half the volume of initial data as compared with the data needed when using the other methods.

2. It is a well known fact that the density of the aerological station grid distributed over the earth's surface is more or less

homogeneous. This question was examined from a qualitative point of view in one of the works of YeM. Dobrishman [14]. He showed that over large areas (oceans, deserts, a large portion of the southern hemisphere) the density of aerological station networks was many times less than what is necessary. For these regions, analysis of the field of a meteorological element at a particular level, at a particular moment according to the observation data only on this same element and at the same level and for the same time period is not able to insure the required precision of analysis. To increase the precision in these areas of light grid density it is necessary, in distinction from thick grid regions, to bring in additional information - data from other levels, for other periods and about other meteorological elements. This supplementary information must be used along with the initial data. In other words, there must be a coordination of the meteorological fields.

Many ways for this type of matching have been tried over the last ten years.

One of these ways is the use of the data from observations at many different levels, particularly calculation of the earth-based observations of stations for analysing aerological fields. The network density of the meteorological station is greater than that for the aerological stations. This constrast is particularly great over the oceans where the aerological observations are taken only by a few island stations and weather ships at a time when meteorological observations at the ocean surface are taken on all kinds of non-weather ship cart. A. A. Petrov [29] has developed the means of calculating this additional information; he uses an approach similar to that proposed by Doos and Eaton [46], and by V. D. Sovetov [32] and G. Kh. Khatamkulov [38, 39] who used different variations of optimum interpolation and matching for solving this problem. The latter of the above mentioned works shows both with theoretical evaluations and by using numerical experiments with actual fields that using earth-based information allows us to considerably increase the analysis accuracy of the 850 mb surface field geopotential.

The use of the data of neighboring lower levels is useful also for an analysis of fields at higher altitudes where the information flow is greater but its error also higher than on the lower-laying levels. For these two reasons an analysis of fields at higher levels can be considerably more precise by matching with data from much lower levels. This type of matching method was devised by V. P. Boltenkov [3] as an addendum to analysis of temperature fields and by M. S. Tatarskiy [34] for geopotential fields. V. D. Sovetov [32] used for an analysis of data at great altitudes the data for geopotential of neighboring levels and that for temperature by combining the optimum interpolation and static matching methods. The greatest detail in the works cited above is in the research of Tatarskiy whose results lead to a methodology suitable for operational practice.

B. V. Ovchinskiy [27] has proposed an interesting method for using the observations from previous time periods as supplementary information for the purpose of optimum interpolation in three measuremenets: along the two space coordinated and also with respect to time. It follows that in comparison with the direct application of observation data from previous periods the results of numerical forecasts constructed from these data are preferable. This supplementary information is more useful to the same extent that dynamic short-term forecasting is more effective than static extrapolation with respect to time.

M. S. Fuks-Rabinovich [36, 37] researched the appeal of forecast information and generalized the so-called dynamic analysis method as proposed by Thompson [52] in a number of aspects, particularly regarding its application of the results of spatial forecasting instead of two-dimensional. In addition, besides the artificial division of the so-called "empty" region i.e. the region of dense linear observation, Fuks-Rabinovich developed a methodology for matching the diagnostic and forecast information. This question today assumes tremendous importance as it concerns the problems of so-called four-dimensional analysis which we shall discuss below.

A large cycle of research has been completed concerning the questions raised by using data on wind when analysing geopotential fields. In objective analysis methods used abroad wind data are employed using comparatively crude instruments. They are useful chiefly because the information they contain regarding geopotential data is not fully utilized by these methods. In distinction to this, research conducted in the USSR uses the more strongly theoretically based information and , therefore, offers much more promising methods for matching fields of geopotential and wind.

One of these methods is statistical matching which is based on the method of optimum differentiation which, in turn, is a natural generalization of the optimum interpolation method. Theoretical evaluations conducted by R. L. Kagan and G. Kh. Khatamkulov [15] permit an evaluation of the possibility of this type of approach. I. Klug conducted detailed numerical experiments using the optimum differentiation method on which bases he developed an objective analysis methodology for the field of geopotential bringing in data on wind which is suitable for introduction into operational practice. The special feature of this methodology is simplicity of application which permits elimination of re-evaluation of wind data in the region of the jet stream. This work shows that the given methodology allows considerable improvement qualitatively of the objective analysis when the air station grid is dense as is characteristic for the Northern Atlantic.

Another approach is based on diagnosed differentiation of the equations derived by Sasaki [51] from the variation principle obtained from the other concepts of G. I. Marchuk [23]. Having solved this equation it is possible to find, in a known sense, the minimum changes of field of geopotential and wind which connect variable fields with each other in a given way. This type of approach to matching geopotential and wind fields is a subject of investigation being conducted at the USSR Hydrometry Center in the Computer Center of the USSR Academy of Sciences (Siberian Branch), and [21, 22] in the Leningrad Hydrometeorological Institute [17]. It should be mentioned that Sasaki derived this equation leaving open the question not only of solving it but introducing into it weight factors. In numerous works means were proposed for solving these equations with which this approach has been associated. In particular, I. Klug [17] proposed the use of weight factors variable with the territory and which are dependent on the precision of optimum interpolation of geopotential and wind by generalizing the Sasaki method. He showed that this type of generalization leads to a noticeable improvement in precise definition of the analysis results. The works of the Computation Center Siberian Branch of the USSR AS made great improvement in the quality of numerical forecasts by using the results of matching fields of geopotential and wind as the initial data.

It is interesting to note that in distinction from the majority of meteorological research the economic effectiveness of work to perfect methods of objective analysis is comparatively easy to judge. The method of such an evaluation consists of the following. Increased precision of analysis in regions where the station network is sparse can be achieved without perfection of the methodology by organizing new stations. By using the method of optimum interpolation it is not difficult to estimate beforehand the average precision which will be obtained as a result of the operation of these additional stations [9], [24] and others). Consequently, it is possible to explain the organization of what number of new stations is equivalent to this or that improvement of the analysis methodology, and to evaluate its economic effect.

It stands to reason that what has been said does not mean that the works directed towards making the methods of objective analysis more precise are more effective from an economic standpoint than research being done in other branches of meteorology. It can be confirmed that this effectiveness is easier to evaluate when applicable to works on objective analysis.

In passing it should be stated that increasing the accuracy of analysis is not for the purpose of matching meteorological fields and, in particular, matching geopotential and wind. Tests showed that to obtain successful numerical forecasts with respect to non-geostrophic models only one type of matching is necessary which in foreign literature has been called initialization. The purpose of initialization is to obtain the initial fields which are found in dynamic agreement with the equations for the forecast models. Investigations into initialization of fields of geopotential showed that initialization by alternative integration of the forecast equations both prior and ahead in time permits elimination of hypothetical changes in the integral characteristics of the model during numerical forecasting, leading, at the same time, to extremely small changes in the initial fields of geopotential and wind. The works on initialization are only in the beginning stages and, indoubtedly, the procedures developed will be perfected at some later date.

3. Many of the investigations conducted which were mentioned above deal with the possibility of noticeable improvement of objective analysis results, particularly those for regions where the station network is sparse. The introduction of corresponding improvements into operational practice provided slight advantages. However, in order that this introduction can be made most effectively, it is necessary to define more clearly the functions of the various subdivisions which are associated with the questions of objective analysis.

Researchers who are developing new analysis methods don't have the opportunity to actively introduce their findings and, therefore, they, as a rule, are insufficiently associated with operational work, for one reason or another, which present problems for them. On the other hand, groups of researchers, who are directly occupied with operational work on numerical analysis and forecasting can fully introduce algorithms worked out in all details and cannot, to one degree or another, be obliged to occupy themselves with "dual" results of research below operational application and operation testing of corresponding methods.

It is necessary, therefore, that there be functioning of an "intermediary link" - subdivisions which are directly concerned with introduction of research results in the field of objective analysis into operational practice. In essence, these subdivisions do exist. It is important only to clearly define the problems and to show that these problems consist not only in the new methods under formulation and in continuing development of them, but also in introducing these methods into operational practice.

Another problem is associated with the use of the results of objective analysis. These results are helpful to the degree that they are used for numerical forecasting. However, the needs which modern numerical forecasting requires are relatively limited. However, the requirements which modern numerical forecastings place on volume and detail of initial data are comparatively limited. The possibilities of objective analysis methods are much greater. They are in a position to provide detailed diagnostic information for direct, unassociated with numerical forecasting, application and, in the first place, for use in synoptic-forecasting.

Technical limitations preclude the realization of these possibilities for a long time; these limitations are associated with the insufficient power of the computers and peripheral hardware. Currently the position has changed. With the technical means available it is possible to not only free synoptics from other chart analysis work but to supply them with considerably more information than which is used now. This is not done for only one, but, a very good reason: this information could not be used.

The reason for this position is the fact that not only in synoptic practice the means for using more complete information have not been developed. The point in fact is that synoptics bring in forms of information which are entirely natural for constructing hand charts but are difficult to obtain and are entirely unnecessary when this process is automated. Thus, synoptics are attracted to using analysis and forecasting according to synoptic charts on which data for portions of stations have been imposed although, undoubtedly, the objective analysis charts were constructed on the basis of all without exclusion of data, objectively regulated, containing more complete and precise information. Synoptics are made on frontal charts. Instead of this they can be used for objectively analysing and automatically constructing the field of such elements as humidity, cloud cover, precipitation, barometric tendency. It stands to reason that this would put more information in the hands of synoptic researchers.

It would be entirely incorrect to explain this position by the conservatism of synoptics. Existing methods of synoptic analysis in forecasting have been merged over a period of many years when the possibilities of objective analysis did not yet exist. The reconstruction of these methods applicable to the opportunities for automatic processing of information is not at all a technical problem but requires serious scientific investigations which have not yet been undertaken in either the Soviet Union or any other nation in the world. This problem must be accorded primary importance. Otherwise, we shall soon witness the sad contradictions between all the boastful promises of objective analysis of meteorological fields and the poor quality of these claims.

4. The prospects for the further development of research in objective analysis are associated with, mainly, the so-called four-dimensional analysis (or assimilation) of meteorological information. This problem is being given great attention abroad. Its essence is contained in the following (see, for example [12]).

Modern analysis and forecast methods rely on the use of observation data referring to previously determined periods which are separated from one another by comparatively large time intervals of not less than several hours. These types of observations are acceptable for unifying synoptic observation terminology (although they include air terms) as distinct from asymptotic observations which do not have the indicated time discretion.

Nowadays the volume, quality, and possibility of using asymptotic observations is growing very fast. In the first place, observations from space satellites applies to this category. The role of these observations has grown rapidly in recent times in connection with explication of the opportunities of setting up vertical profiles for temperature and geopotential with respect to data of spectral measurements of exiting radiation. To the category of asymptotic observation applies observations using high pressure aerostats. Finally, measurements on automatic stations both earth-based and in the oceans (bouys) can be done in asymptotic order.

To use asymptotic information for objective analysis it is necessary to move on from a spatial (three-dimensional) analysis to a space-time relationship, i.e. four-dimensional. This transition, which has already been discussed, signifies the great use of numerical forecasting data during analysis. Thus, methods of four-dimensional analysis must be a synthesis of the methods of objective analysis and numerical forecasting.

Two significantly different four-dimensional analysis charts can be envisioned. In the first, a so-called discrete chart, the asymptotic data is initially extrapolated with respect to time over asymptotic periods using forecast models in such a way that matching of the synoptic and asymptotic information is done only in the synoptic periods. In the second chart, a continuous chart, the asymptotic information is contained in the forecasting model for that moment in time when it is obtained. In this case, the forecast model, integrated in real time (i.e. with the rate at which the actual processes transpire) is continuously or almost continuously abundant in observation data. The matching of observation data with forecast information is also done, continuously.

In passing we should state that within the framework of both schemes it is necessary from time to time to conduct initialization to escape the above mentioned mismatching in the behavior of the forecast models.

From the two- four-dimensional analysis schemes the discrete chart is easier to produce and, therefore, easier to realise. Also, investigation of the four-dimensional analysis is conducted as it applies to both charts. These investigations are only the stage of numerical experiments. Under these experimental situations which are characteristics for four-dimensional analysis, an artificial means is created. In particular, the behavior of one or another forecast model is applied for finding the truth; in addition, the data from forecast models are examined as observation data but only a measured way.

The beneficialness of the method of numerical experiments is doubtless. Numerical experiments are widely used in domestic research of objective analysis about which we spoke in particular above. In addition, it is necessary to see to it that when transferring from model situations to actual situations a number of factors must be also taken into consideration which effect the actual set-up of the numerical experiments. Therefore, besides model experiments it is necessary to conduct development of four-dimensional analysis of real processes.

In principle, the solution of this problem is clear. The solutions consist of applying these same notions which refer to the matching of fields which have already been developed for spatial objective analysis. However, very significant work remains to be attempted on these lines and difficulties surmounted. Specifically, detailed study must be made both of the properties of various types of information (synoptic, asymptotic, forecast) and the relationship between the informations presented by various sources. Only on the basis of these studies can a sufficiently well-based method of four-dimensional analysis of meteorological fields be produced.

Works in this direction are just now beginning. It is understood that they should be gone ahead with sufficiently great intensity so that the cardinal changes in the character of the operative meteorological information, changes which have occurred in comparatively recent time, can be dealt with from all sides and with full force.

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