Further Experiments in Localized Numerical Weather Prediction[1]

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ABSTRACT

Local numerical forecasts generated by interpolation from the National Meteorological Center primitive equation model are evaluated for the 1969–70 winter season in the eastern United States. A marked under-prediction of precipitation frequency appears to be due, at least in part, to the interpolation system.

1. Introduction

An experiment in localized numerical weather prediction based on the National Meteorological Center (NMC) primitive equation model (Shuman and Hovermale, 1968) has been described in an earlier publication (Spar, 1969, hereafter referred to as I). The method employed is spatial interpolation of the hourly grid-point predictions to specific city forecast points. The study is limited to a set of cities in the eastern United States, to the winter season, and to the problem of snow prediction.

In I results of verification were reported for the 1967–68 and 1968–69 winter seasons. This paper presents the corresponding results for the 1969–70 winter.

Forecasts were evaluated for the "winter" season, 1 November 1969 to 31 March 1970, for seven forecast "points": Albany (ALB), Cleveland (CLE), New York City (JFK), Philadelphia (PHL), Pittsburgh (PIT), Portland (PWM) and Washington (DCA). For New York City three separate verification points were examined: J. F. Kennedy Airport (JFK), Central Park (CP) and LaGuardia Airport (LGA). The latter was the sole verification point employed for New York in the previous evaluation.

The results of the verification for the past winter are presented in essentially the same format as in I to permit easy comparison. First, the critical predicted boundary layer potential temperature for rain-snow discrimination is presented in Table 1 for comparison with Table 4 of I. Second, the qualitative ("rain or no rain") precipitation forecast verification data are given in the form of contingency tables in Table 2, where "percent correct" is computed as the measure of skill, for comparison with Table 3 of I. Third, the quantitative precipitation forecasts are evaluated in terms of correlation coefficients in Table 3, which may be compared with the corresponding Table 6 of I. Finally, the verification of predicted onset time, shown in Table 5, is to be compared with the results for the earlier winters given in Table 5 of I.

In I it was noted that the original bilinear interpolation system for precipitation was replaced at NMC between the first two winters of the experiment by a more conservative interpolation algorithm. The latter, which places the zero isohyet halfway between grid points for which zero and non-zero hourly precipitation amounts are computed, does not spread the precipitation as far away from grid points at which precipitation is predicted as does the former system. As a result, precipitation tends to be forecast too late and too infrequently at the city forecast points. The conservative interpolation system was still in use in the 1969–70 winter season, and, as will be shown below, the same dry bias is found in the forecasts.

2. Rain vs snow

The method of computing the critical predicted boundary layer potential temperature θ_c [computed from the primitive equation (PE) model outputs, and averaged over the 12-hr "Tonight" and "Tomorrow" forecast periods] has been described in I. In Table 1 the results are shown for the past winter for individual and pooled stations, but only for pooled forecast periods, as little or no difference between the "Tonight" and "Tomorrow" forecast periods was found. Correct discrimination is based on a forecast of rain when the average predicted boundary layer potential temperature $\theta \geqslant \theta_c$, and a forecast of snow (verified by snow or mixed precipitation) when $\theta < \theta_c$. For the pooled results, only one New York station, LaGuardia Airport, has been used.

The most notable difference between the results shown in Table 1 and those for the previous two winters

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is in the value of θ_c, which fell from 282 to 279K, for the pooled data. This result appears to reflect a reduction of the warm bias, which was noted earlier in the boundary layer forecasts. Apparently this improvement in the temperature forecasts resulted from the change in the initialization procedure for boundary layer temperatures, which was introduced at NMC on 12 October 1969 (Weather Bureau, 1969).

In the relatively small data sample for 1969–70, there is a larger variation of θ_c from station to station than was found earlier, and a lower probability of correct discrimination (82% compared with 86%, for pooled data). Nevertheless, the use of θ as a criterion for rain-snow discrimination still appears to be justified statistically.

The poorest performance of θ as a rain-snow discriminator was apparently found in New York City in 1969–70. This behavior is not consistent with the results of the previous two years, and no explanation for it, other than sampling variablilty, is suggested. However, an examination of the performance of the system in a particular case may be illuminating.

The only heavy[2] snowfall of the winter in New York City fell on 25–27 December 1969, when total accumulations of 6.1, 6.8 and 7.4 inches were measured at Kennedy Airport, Central Park and LaGuardia Airport, respectively. Precipitation began about 0000 GMT on the 26th and continued until about 1800 GMT on the 27th, during which time the surface temperatures in the city varied between 28 and 43F[3]. In this period the precipitation began as snow, turned to rain 12 hr later, then changed back to snow. The average predicted boundary layer potential temperatures for this period at JFK, and the observed character of the precipitation in New York City (JFK, CP and LGA combined) are shown in the following table.

Initial data	Forecast period	θ	Weather
1200 GMT 25 Dec.	0000–1200 GMT 26 Dec. ("Tonight")	278	snow, ending with sleet
	1200–2400 GMT 26 Dec. ("Tomorrow")	281	sleet, turning to rain and drizzle
	0000–1200 GMT 27 Dec. ("Tomorrow night")	282	drizzle, freezing and changing to snow
1200 GMT 26 Dec.	0000–1200 GMT 27 Dec. ("Tonight")	277	(same)
	1200–2400 GMT 28 Dec. ("Tomorrow")	269	snow ending

The θ value (278K) for the first "Tonight" forecast period, based on the data for 1200 GMT on the 25th, clearly indicates snow, while that for the first "Tomorrow" period (281K) points to the change to rain. This is shown even more clearly by the hourly θ values which increase steadily from 276 to 281K during the first period, and vacillate between 280 and 282K during the second period. The forecast (282K) for the third period, "Tomorrow night", 36–48 hr after initial time, fails to anticipate the cooling trend and the return to snow. However, this error is corrected in the forecast for the second "Tonight" period, based on the new data for 1200 GMT on the 26th, which indicates the return to colder temperatures for "Tonight" (277K) and "Tomorrow" (259K). This is one case in which the forecaster would have been well-guided by the local numerical forecasts, at least for "Tonight" and "Tomorrow."

TABLE 1. Critical predicted boundary layer potential temperature θ_c(°K) for rain-snow discrimination for the period 1 November 1969 to 31 March 1970. [See Spar (1969) for explanation of method of computation.] N denotes the number of 12-hr precipitation periods in the data sample, and P the probability, in percent, of correct discrimination.

Station	N	θ_c	P
ALB	54	279	93
CLE	80	279	85
PHL	37	277	84
PIT	92	279	85
PWM	49	281	90
DCA	40	276	83
JFK	41	281	71
CP	45	281	78
LGA	44	281	73
Pooled*	396	279	82

* For the pooled data, JFK and CP are omitted.

3. Qualitative precipitation

In I it was shown that during the 1968–69 winter season the local numerical forecast system underpredicted the frequency of precipitation events at the city forecast points, apparently because of the conservative interpolation algorithm. That this was still the case in 1969–70 is shown by the contingency tables in Table 2 for the individual and pooled stations. In Table 2 the letter F denotes "precipitation forecast," NF "precipitation not forecast," O "precipitation observed," and NO "precipitation not observed." Traces are counted as precipitation not observed. Where stations are pooled, only LGA is used to verify New York City precipitation. Results are shown separately for the "Tonight" and "Tomorrow" forecast periods, and also for the total "24-Hours" period ("Tonight" plus "Tomorrow"). The numbers in the table represent number of cases and percent correct. Under column O, "% correct" refers to the percent of all the forecasts of precipitation that verified, etc.

The evaluation, shown in Table 2, of the 99 qualitative precipitation forecasts for 9 stations (7 cities) for the 1969–70 winter season leads to the following

[2] The second major snowstorm of the season, on 29 March 1970, deposited only 4 inches of snow within the city, although it did leave up to a foot of snow in the suburbs. That Easter Sunday storm is discussed later.

[3] At Central Park the maximum temperature reached only 37F, but at Kennedy Airport a maximum of 43F was recorded.

TABLE 2. Performance of qualitative local numerical precipitation forecasts. (See text for explanation of table.)

A. Albany (ALB)

	"Tonight" O	"Tonight" NO	"Tonight" % Correct	"Tomorrow" O	"Tomorrow" NO	"Tomorrow" % Correct	"24-Hours" O	"24-Hours" NO	"24-Hours" % Correct
F	11	0	100	11	2	85	16	2	89
NF	14	74	84	18	68	79	24	57	70
% Correct	44	100	86	38	97	80	40	97	74

B. Cleveland (CLE)

	"Tonight" O	"Tonight" NO	"Tonight" % Correct	"Tomorrow" O	"Tomorrow" NO	"Tomorrow" % Correct	"24-Hours" O	"24-Hours" NO	"24-Hours" % Correct
F	7	1	88	10	1	91	14	1	93
NF	34	57	63	29	59	67	45	39	46
% Correct	17	98	65	26	98	70	24	98	54

C. Philadelphia (PHL)

	"Tonight" O	"Tonight" NO	"Tonight" % Correct	"Tomorrow" O	"Tomorrow" NO	"Tomorrow" % Correct	"24-Hours" O	"24-Hours" NO	"24-Hours" % Correct
F	9	6	60	8	3	73	15	4	79
NF	8	76	90	12	76	86	15	65	81
% Correct	53	93	86	40	96	85	50	94	81

D. Pittsburgh (PIT)

	"Tonight" O	"Tonight" NO	"Tonight" % Correct	"Tomorrow" O	"Tomorrow" NO	"Tomorrow" % Correct	"24-Hours" O	"24-Hours" NO	"24-Hours" % Correct
F	10	1	91	11	4	73	16	2	89
NF	40	48	85	31	53	63	46	35	43
% Correct	20	98	59	26	93	65	26	95	52

E. Portland (PWM)

	"Tonight" O	"Tonight" NO	"Tonight" % Correct	"Tomorrow" O	"Tomorrow" NO	"Tomorrow" % Correct	"24-Hours" O	"24-Hours" NO	"24-Hours" % Correct
F	11	3	79	12	4	75	18	3	86
NF	14	71	84	12	71	86	15	63	81
% Correct	44	96	83	50	95	84	55	95	82

F. Washington, D. C. (DCA)

	"Tonight" O	"Tonight" NO	"Tonight" % Correct	"Tomorrow" O	"Tomorrow" NO	"Tomorrow" % Correct	"24-Hours" O	"24-Hours" NO	"24-Hours" % Correct
F	12	5	71	12	5	71	20	4	83
NF	9	73	79	7	75	91	9	66	88
% Correct	57	94	86	63	94	88	69	94	87

G. Kennedy Airport, New York (JFK)

	"Tonight" O	"Tonight" NO	"Tonight" % Correct	"Tomorrow" O	"Tomorrow" NO	"Tomorrow" % Correct	"24-Hours" O	"24-Hours" NO	"24-Hours" % Correct
F	8	3	73	9	2	82	15	2	88
NF	10	78	89	14	74	84	16	66	80
% Correct	44	96	87	39	97	84	48	97	82

H. Central Park, New York (CP)

	"Tonight" O	"Tonight" NO	"Tonight" % Correct	"Tomorrow" O	"Tomorrow" NO	"Tomorrow" % Correct	"24-Hours" O	"24-Hours" NO	"24-Hours" % Correct
F	10	1	91	9	2	82	16	1	94
NF	10	78	89	16	72	82	16	66	80
% Correct	50	99	89	36	97	82	50	99	83

I. LaGuardia Airport, New York (LGA)

	"Tonight" O	"Tonight" NO	"Tonight" % Correct	"Tomorrow" O	"Tomorrow" NO	"Tomorrow" % Correct	"24-Hours" O	"24-Hours" NO	"24-Hours" % Correct
F	10	1	91	9	2	82	16	1	94
NF	10	78	89	15	73	83	17	65	79
% Correct	50	99	89	38	97	83	48	98	82

J. Pooled Stations (excluding JFK and CP)

	"Tonight" O	"Tonight" NO	"Tonight" % Correct	"Tomorrow" O	"Tomorrow" NO	"Tomorrow" % Correct	"24-Hours" O	"24-Hours" NO	"24-Hours" % Correct
F	70	17	80	73	21	78	115	17	87
NF	129	477	79	124	475	79	171	390	69
% Correct	35	97	79	37	96	79	40	96	73

conclusions:

1) The system seriously underpredicts the frequency of precipitation. For pooled data, only 35–40% of the observed periods of measurable precipitation (traces being counted as no precipitation) were correctly anticipated.

2) There is no significant difference in skill between the "Tonight" and "Tomorrow" forecasts. For pooled data the "% correct" for all forecasts was 79% for both periods.

3) The forecast quality is markedly worse at Cleveland and Pittsburgh than at stations in the coastal plain. At Cleveland and Pittsburgh only 17–26% of the forecast periods with measureable precipitation were correctly anticipated, and only 52–54% of *all* the forecasts for the "24-Hours" period verified. The large number of precipitation days at the two stations (59 at Cleveland and 62 at Pittsburgh, out of 99 forecast days), with generally light precipitation amounts, clearly played havoc with the local numerical forecasts.

4) The results of the qualitative precipitation forecast evaluation are (except for Cleveland and Philadelphia, which were not included last year) essentially the same for 1969–70 as they were for 1968–69. When precipitation was forecast, it was very likely to occur (87% of the time for the pooled "24-Hours" forecasts this year), but it was not forecast often enough. If Cleveland and Philadelphia are excluded, the percent of all pooled "24-Hours" precipitation periods correctly anticipated in 1969–70 is found to be only 44%, compared with 49% in 1968–69.[4]

4. Quantitative precipitation

A potentially significant change in the primitive equation precipitation (PEP) forecast model was introduced on 19 March 1970 (Weather Bureau, 1970a), near the end of the 1969–70 evaluation period. However, no effect of this change in the sample of PEP forecasts was detected, and the data have therefore not been separated.

Correlation coefficients between PEP predicted and observed liquid equivalent precipitation amounts for the 1969–70 winter season are shown in Table 3. The following general conclusions may be drawn from the data in Table 3 and from a comparison with the results presented I:

1) The quantitative forecast skill declines markedly from the "Tonight" to the "Tomorrow" forecast periods. For pooled data the correlation coefficients decrease from 0.68 to 0.43. The decrease is greatest at those stations showing the highest correlations in the "Tonight" period. A similar pattern of behavior was found in 1968–69.

Table 3. Correlation coefficients between PEP* predicted and observed liquid equivalent precipitation amounts for the period 1 November 1969 to 31 March 1970 (99 forecast days).

Station	"Tonight"	"Tomorrow"	"24-Hours"
ALB	0.66	0.46	0.61
CLE	0.54	0.54	0.67
PHL	0.72	0.16	0.75
PIT	0.89	0.39	0.68
PWM	0.84	0.46	0.72
DCA	0.50	0.36	0.63
JFK	0.57	0.56	0.67
CP	0.76	0.53	0.75
LGA	0.73	0.60	0.71
Pooled**	0.68	0.43	0.66

* Primitive Equation Precipitation.
** Pooled data do not include JFK and CP.

2) In terms of correlation coefficient, the 1969–70 PEP forecasts exhibit greater skill than those of 1968–69 in the "Tonight" and "24-Hours" forecast periods. For example, based on the pooled data for the "24-Hours" forecast period, the 1969–70 PEP forecasts explain 44% of the variance of precipitation, compared with 30% in 1968–1969.

3) The differences among the correlation coefficients for the three New York City verification points, with explained variances differing by as much as 26% for the same numerical forecasts, illustrate both the mesoscale variations in precipitation and the difficulty of evaluating precipitation on the basis of only one raingage per city.

4) The poor qualitative performance of the PEP forecasts, specifically the failure to anticipate a majority of the precipitation periods, is only partly reflected in the correlation coefficients for precipitation amount. For example, based on the pooled forecasts, only 35, 37 and 40% of the "Tonight", "Tomorrow" and "24-Hours" precipitation periods in 1969–70 were correctly anticipated (Table 2); but the corresponding reductions in variance (from the squares of the correlation coefficients in Table 3) are 46, 18 and 44%. Although the quantitative forecasts are also unsatisfactory, they clearly reflect a different pattern of performance than that of the qualitative forecasts. This apparent discrepancy is most obvious in the "Tonight" forecasts for Pittsburgh and Portland. Only 20 and 44%, respectively, of the "Tonight" precipitation periods were correctly anticipated at these stations, yet the corresponding correlation coefficients are 0.89 and 0.84. The reason for this appears to be a relatively large number of light precipitation events, which affect the qualitative percent correct more than the quantitative correlation coefficient.

[4] On 30 October 1969 NMC introduced its "laminated" moisture concept for precipitation forecasting with the PE model. As noted by the Weather Bureau (1970b) this subsequently resulted in severe underprediction of precipitation, necessitating a corrective procedure which was introduced on 19 March 1970 (Weather Bureau, 1970a). However, the results of our evaluation were essentially the same for 1968–69, before the laminated model, as for 1969–70, after lamination, except for a slightly greater underprediction of precipitation frequency in the latter winter.

TABLE 4. Cumulative liquid equivalent precipitation (inches) at New York City, 25–27 December 1969. PEP denotes the local numerical forecast. The observations are for Central Park (CP), Kennedy Airport (JFK) and LaGuardia Airport (LGA). Type of precipitation is indicated by conventional symbols (see text). Only forecasts for the "24-Hours" forecast period, i.e., from 12–36 hr after data time, are used.

Date (December)	Time (GMT)	PEP	CP	JFK	LGA
26	0000	0	0.02 S	0.00 S	0.02 S
	0300	0	0.17 S	0.03 S	0.08 S
	0600	0	0.27 S	0.08 S	0.16 S
	0900	0	0.41 S	0.24 S	0.28 S
	1200	0	0.85 RE	0.74 E	0.38 SE
	1500	0.04	1.63 R	1.52 RS	1.19 R
	1800	0.27	1.75 R	1.56	1.26 L
	2100	0.53	1.77	1.56 R	1.26 L
27	0000	0.77	1.77 ZL	1.58 L	1.27 L
	0300	0.78	1.77 ZL	1.58 ZL	1.27 ZL
	0600	0.78	1.79 S	1.59 S	1.27 S
	0900	0.78	1.80 S	1.59 S	1.29 S
	1200	0.78	1.84 S	1.66 S	1.32 S
	1500	0.78	1.85 S	1.67 S	1.35 S
	1800	0.78	1.85 S	1.67	1.35 S

To illustrate the performance of the PEP forecasts in an individual case, the snowstorm of 25–27 December 1969 will again be cited. In Table 4 are shown the cumulative liquid equivalent precipitation amounts for the storm as predicted for New York City by the PEP model and as measured at the three New York stations, in 3-hr time steps. Also indicated is the type of precipitation with the conventional symbols: S = rain, L = drizzle, Z = freezing, E = sleet. The forecasts are those computed from 1200 GMT data, but only for the "24-Hours" period, 12–36 hr after initial data time.

Two features are apparent from the data in Table 4. First, the forecast onset time was at least 12 hr late, and second, the total precipitation measured was about twice the predicted amount. There was a marked variation in total precipitation among the stations, with most of it reaching the ground as rain during the warm phase of the storm. The model did correctly predict that most of the precipitation would fall within about a 9-hr interval, but the timing of that period of heavy precipitation was about 9 hr late, and the maximum intensity predicted (0.26 inch per 3 hr) was about one-third the observed intensity (0.78–0.81 inch per 3 hr). Nevertheless, despite the deficiencies of the forecasts (e.g., no precipitation was forecast for the first "Tonight" period), the model did succeed in anticipating the rather heavy precipitation over the "24-Hours" forecast period, 0000–2400 GMT on 26 December 1969.

In general, average precipitation amounts per predicted precipitation event exhibited no marked bias in 1969–70. Although the total precipitation amounts forecast were about half the observed totals, this error is almost entirely accounted for by the corresponding underprediction of the frequency of precipitation.

5. Onset time

The very low frequency of prediction of precipitation, together with the rather restrictive rules laid down (see I) for evaluation of onset time errors, left few cases for the study of the latter errors in the 1969–70 forecasts. Nevertheless, the analysis of the small data sample available, as shown in Table 5, leaves little doubt about the late onset time bias of the PEP forecasts. That this is a characteristic of the conservative interpolation algorithm now seems quite apparent.

In computing the errors shown in Table 5, "onset time" was defined as the beginning of the first hour in which *measurable* precipitation was recorded, and traces were ignored. For the 64 pooled cases available in 1969–70, the mean algebraic error is seen to be +4.1 hr compared with a mean absolute error of 5.9 hr. The mean absolute error is compatible with the value for pooled data (6.3) hr) found in 1968–69. However, the mean algebraic error indicates a much larger late (positive) bias in 1969–70 than was found in 1968–69 (+1.0 hr) for pooled data, traces being ignored. The sample of 64 non-independent pooled cases is rather small, and it is not certain that the increase in the late bias since last year is anything more than a result of sampling variablility. However, the fact that there is a late bias of 1–4 hr in the PEP forecast onset times now appears to be rather certain.

6. Conclusions

It would be misleading to end this paper without mentioning at least one case in which the local PEP forecasts failed utterly. Such a case is well represented by the following example.

On Easter Sunday, 29 March 1970, a "surprise" snowstorm struck the New York metropolitan area. Only 4 inches of snow accumulated in Central Park (less fell elsewhere in the city), and the snow was mixed with rain, producing a total liquid equivalent precipitation of ~1 inch in the city. In the suburbs of New York, however, snow depths up to a foot were measured.

Precipitation began at about 1200 GMT on the 29th and continued for about 12 hr in the city. This period of time corresponds almost exactly to the "Tomorrow" forecast period based on the 1200 GMT initial data of 28 March. Unhappily, the PEP forecasts for New York City (JFK) for this period (and indeed for the entire 36-hr period beginning at 1200 GMT on 29 March) indicated no precipitation.

It is quite possible that this forecast error may have been at least partly due to the interpolation system. Both Philadelphia and New York City lie within the same NMC grid-point "square," and at both stations no precipitation was predicted in the local PEP forecast. On the other hand, at Washington, which lies within the next grid-point "square" to the west, but only 40 mi northwest of the southwest corner of the Philadelphia-

New York "square," 0.22 inch of precipitation were predicted for the "Tomorrow" forecast period. Apparently a non-zero amount of precipitation was predicted for the southwest corner grid point referred to above, but the conservative interpolation system failed to spread it northeastward over Philadelphia and New York. Of course, a multitude of other errors, including errors in the quantitative precipitation forecasts for the grid points, undoubtedly contributed at least as much to the forecast error at New York City.

From the verification results of the 1969–70 winter season local PEP forecasts for the eastern region data sample, it must be concluded once again that the quality of these forecasts is not yet good enough for satisfactory local snow prediction. The most serious defect is the tendency to predict precipitation too late and much too infrequently. On the other hand, the local PEP forecasts (including the 6-hr operational version of these forecasts transmitted by the Weather Bureau via teletype under the heading FOUS) are often useful as guidance, particularly with respect to trends in the weather.

This year no attempt was made to derive statistical prediction equations (the so-called "synthetic" equations referred to in I) by regression methods from the local PEP forecasts. Clearly, the quality of these forecasts must first be significantly upgraded before statistical treatments can be profitably applied.

A major problem of the local PEP forecasts appears to be the interpolation algorithm. As noted in I, bilinear interpolation of precipitation, as practiced in the 1967–68 winter season, apparently led to overprediction of precipitation frequency and an "early"bias, while the more conservative system, which has been in use during the past two winters, leads to underprediction of precipitation frequency and a "late" bias. A program of empirical research is needed to determine the "best" interpolation system. As a temporary measure, until that research is carried out, it is recommended that steps be taken to spread the precipitation farther from the precipitation grid points than is now being done. This could be accomplished by returning to the original bilinear interpolation algorithm. The effect of this action would probably be to restore the "early-overprediction" bias, which would be least represent an error on the "safe" side from the viewpoint of heavy snow prediction.

TABLE 5. Mean absolute errors $|E|$ and mean algebraic errors E in PEP forecast onset time of measurable precipitation in hours. Errors are defined as forecast minus observed onset times, so that positive values indicate "late" forecasts. Traces are ignored. The only days used are those on which precipitation was forecast and verified to begin within the "24-Hours" forecast period, 0000–2400 GMT. In pooled results, CP and JFK are omitted as verification stations.

Station	N	$\|E\|$	E
ALB	8	5.1	+4.9
CLE	11	6.6	+4.1
PHL	6	7.8	+4.2
PIT	8	8.5	+4.5
PWM	9	4.2	+4.2
DCA	15	4.9	+3.2
JFK	6	7.5	+7.5
CP	6	6.8	+6.5
LGA	7	4.9	+4.6
Pooled	64	5.9	+4.1

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