Thermal Communication Between the Sea Surface and the Lower Troposphere

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ABSTRACT

Seasonal mean sea surface temperatures and 1000–700 mb thicknesses are correlated by pattern and also for 5° squares over the eastern North Pacific in order to find out more about bulk heat exchange between ocean and atmosphere. The results bring out the importance of static stability as a primary variable in heat exchange—the stability being varied by air mass modifications associated with advection, by cyclonic and frontal lifting, and by heating or cooling of the ocean surface. Geographical and temporal effects are described against this background.

1. Introduction

The new emphasis on large-scale interactions between atmosphere and ocean suggests a reexamination of existing sea surface temperatures (SST) and upper air data in a search for clues to the large-scale heat transfer process. Where the flow of heat from sea surface to atmosphere is strong, we might expect a high correlation between SST and temperature in the lower layer of the atmosphere. Where the flow of heat is effectively shut off with near zero or negative heat flux (air warmer than water), the temperatures of the atmosphere and ocean might be expected to vary independently of one another and yield low correlation coefficients.

If we can learn where, when, and under what conditions SST is most closely correlated with the temperature of the overlying lower tropospheric air column, we will advance our understanding of the heat exchange process and perhaps improve our ability to use observed SST patterns as a tool in long-range forecasting.

2. Data sources and physical concepts

Use is made of a vast file of climatological data gathered over the North Pacific since 1947. These data are SST's averaged by months and seasons over 5° squares from about 10,000,000 ship reports and also 700-mb heights and sea-level pressures originally obtained from the Extended Forecast Division, National Meteorological Center, NOAA. The latter data make possible thickness calculations which, if desired, are easily converted into mean virtual temperatures. This paper will be concerned only with seasonal fluctuations in 1000–700 mb thicknesses and SST's in the area of the North Pacific east of 180°.

Since we are here dealing with a complex-coupled air-sea system, it is difficult to separate cause and effect. However, certain elementary physical concepts ought to help in this respect:

1) The heat released to the overlying air column is largely a function of the difference between air and sea temperatures, vapor pressure differences, and wind velocity. Radiation terms also enter, but these are not so directly dependent on air-sea temperature differences, being more a function of clouds and moisture in the atmosphere and not a concern of the present line of investigation.

2) The heat of evaporation and the sensible heat extracted from the water must partly depend upon the static stability of the air, since unstable air permits greater heat loss than stable air. Stable air over the sea may be produced by warm air moving over a cold sea surface or over a mass of colder air or (aloft) by atmospheric subsidence. Cold air moving over a warm sea surface leads to instability as does general ascent. The lapse rate is also steepened by vertical eddy mixing.

3. Correlation fields and their interpretation

If we correlate the *patterns* of SST with thickness using 5° squares east of 180° and north of 20N over the North Pacific, we obtain the values given in Table 1. These pattern correlations were computed by using corresponding values of thickness and SST at 5° squares for the area from 180° eastward. Each point was weighted by using the area enclosed by a 5° square at the latitude of that point. The resulting correlations thus give an effective idea of the degree of similarity of the SST pattern and the overlying atmospheric 1000–700 mb thickness pattern.

Table 1 shows that the seasons when cold continental air is frequently forced over relatively warmer water (namely, fall and winter) have higher correlations than spring and summer when air-sea temperature differences are smaller and sometimes reversed (as at northern latitudes).

If the *point* values of SST vs thickness correlations

TABLE 1. Average of the seasonal pattern correlations of SST and 700 mb-surface thickness for the years 1947–71.

Season	Correlation
Winter	0.45
Spring	0.39
Summer	0.37
Fall	0.45

for the 25 years are plotted areally as in Figs. 1–4, it is clear that major large-scale geographical differences exist. Shaded areas, where correlations exceed the 5% level of significance,[1] are found in all seasons in and south of the Aleutian and Gulf of Alaska lows. Another large area of high positive correlation is found in the northeast trades. In winter, strong correlation is found off the west coast of the United States. Between the northern and southern strong positive areas is a zonally-oriented zone of low correlations. This zone appears in each season and seems to migrate northward from winter to summer. The above facts imply that the heat in northern waters is readily provided to the lower troposphere by virtue of the fact that normally cold continental air masses are fed into the Aleutian and Gulf of Alaska lows, particularly during the cold seasons. Reasonably high correlations are also found there in summer and fall because of vertical stirring introduced by the frequent cyclones (Klein, 1957).

Heat from the surface waters in the northeast trades is readily provided to the lower troposphere as cool air moves over warmer water surfaces in the fashion detailed in the classical studies of Riehl and Malkus (1958). Along the west coast of the United States the development of the west coast inversion, especially in the warm season, reduces the net heat transport from the surface water to the lower troposphere, effectively acting as a heat shield. In winter, when the inversion is frequently destroyed by fronts and by cold air advected over relatively warm water, the shield is not present and the correlations are high.

The zone of minimum correlation found between the northern and southern maxima lies in the northern flank of the ridge of the North Pacific high. In this area the stabilizing effects of subsidence are enhanced by prevailing winds from warm (southerly) waters to colder water, thereby reducing the thermal communication between surface and lower troposphere.

If we examine those particular seasons with extremely high or low overall pattern correlations of SST and thickness, the above general concepts become elucidated and other facts emerge. In Tables 2 and 3 are listed the six seasons of the 25 years which had the lowest correla-

[1] Significance assumes serial independence of pairs of seasonal values. This assumption is not strictly valid, but here we are using the significance level only as an indication of the strength of the relationship.

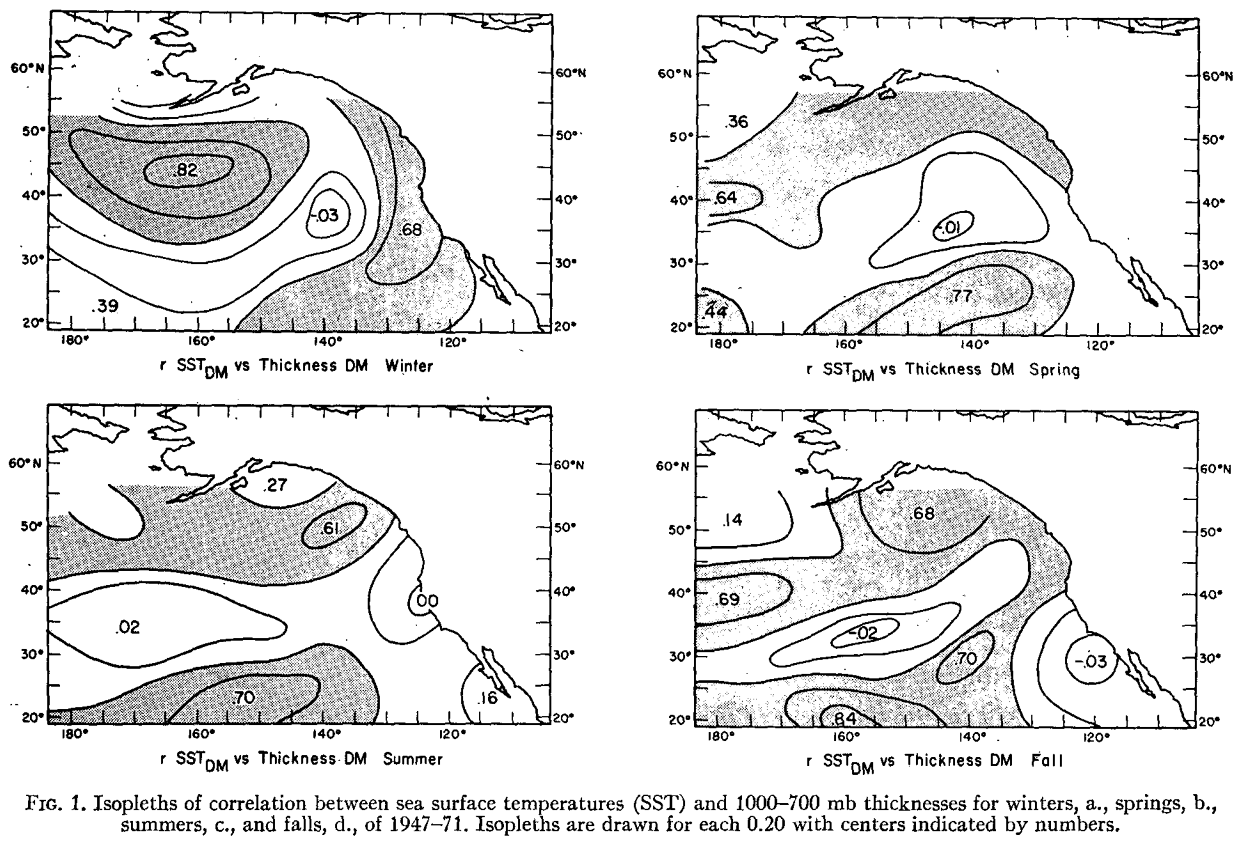

FIG. 1. Isopleths of correlation between sea surface temperatures (SST) and 1000–700 mb thicknesses for winters, a., springs, b., summers, c., and falls, d., of 1947–71. Isopleths are drawn for each 0.20 with centers indicated by numbers.

Table 2. Lowest pattern correlations between SST and 1000–700 mb thickness with absolute and algebraic means of SST_{DM}.

	$r(SST,\Delta Z)$	SST_{DM} Absolute mean	SST_{DM} Algebraic mean
Spring 1949	0.008	1.04	0.32
Fall 1949	−0.074	0.73	−0.04
Spring 1951	−0.104	0.62	−0.10
Winter 1955	−0.205	0.57	−0.36
Summer 1967	0.019	1.09	0.25
Winter 1968	−0.028	0.67	0.12
Average	−0.064	0.79	0.13

Table 3. Highest pattern correlations between SST and 1000–700 mb thickness with absolute and algebraic means of SST_{DM}.

	$r(SST,\Delta Z)$	SST_{DM} Absolute mean	SST_{DM} Algebraic mean
Winter 1949	0.787	1.70	0.25
Fall 1957	0.783	1.42	0.74
Winter 1959	0.819	1.13	0.34
Spring 1960	0.776	1.05	−0.01
Fall 1968	0.805	1.25	0.10
Winter 1970	0.848	1.09	−0.66
Average	0.803	1.27	0.13

tions and the six with the highest, along with the mean absolute and mean algebraic values of SST departure from the 1947–66 mean (abbreviated as SST_{DM}) for the 5° squares east of 180°. While there is not much difference in the algebraic mean SST departures between the two groups of seasons, the absolute mean SST departures are uniformly higher for the group where SST and thickness patterns are highly correlated. In other words, strong SST anomaly patterns are apt to be more highly correlated with temperatures of the lower troposphere than weak anomaly patterns. This result

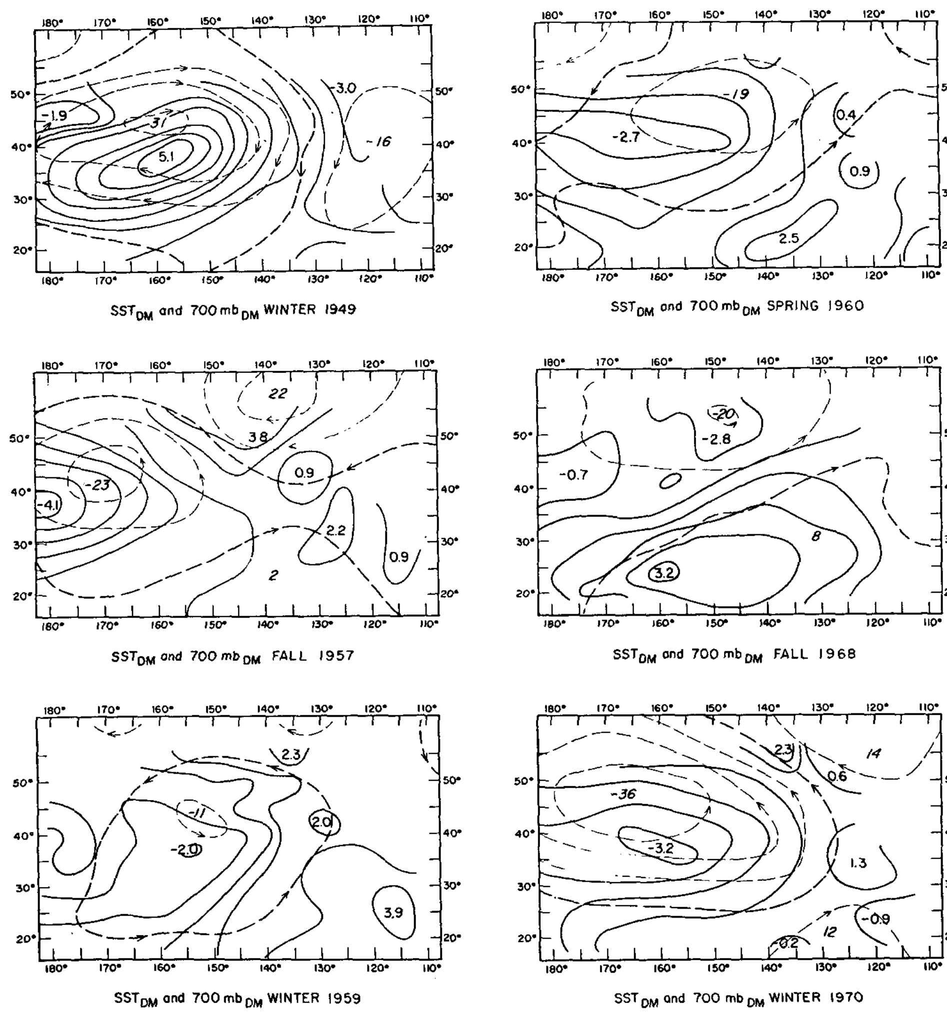

Fig. 2. SST anomalies (solid lines) and 700-mb anomalies (broken) for the six seasons of highest pattern correlation between SST and thickness anomalies. Isopleths of SST anomaly are drawn for each Fahrenheit degree and isopleths for 700-mb anomaly for each 100 ft. Centers of maximum values are given as numbers. Arrows on 700-mb anomalies represent geostrophic anomalous flow.

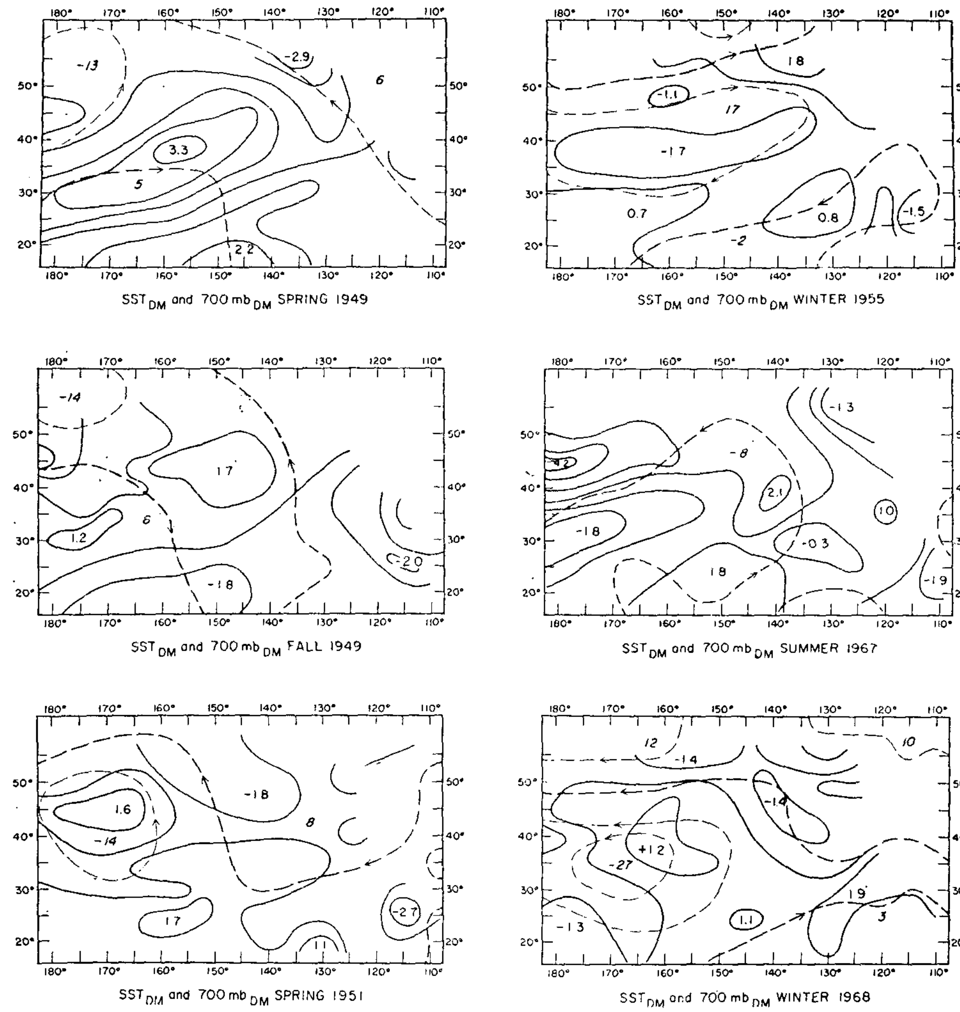

FIG. 3. As in Fig. 2 except for the six seasons with lowest pattern correlation between SST and thickness anomalies.

is not changed if one computes standardized SST absolute and algebraic means (not shown) so that there is no seasonal bias introduced. The above results are further illuminated by referring to the SST anomaly charts for the specific seasons indicated in Tables 2 and 3 and displayed in Figs. 2 and 3.

With one exception, namely winter 1949, all the SST charts associated with high SST-thickness pattern correlations have anomalously cold water westward and northwestward of anomalous warm pools. On the other hand, the low correlation cases have no clear-cut prevailing pattern. The association between these SST patterns and thicknesses becomes clearer when one considers in addition the corresponding mid-tropospheric circulation anomalies. These circulation anomalies are sketched on the SST anomaly charts as broken lines which represent isopleths of anomaly of 700-mb height, the arrows flying in the direction of the anomalous geostrophic component of flow. In general, in the high correlation cases, areas of negative 700-mb height anomaly are found over cold SST pools and positive height anomalies over warm pools, not surprising because of our selection of extreme cases. Frequent cyclones and fronts traverse the area between positive and negative anomalies (Namias, 1959).

Some of the good correlation can be ascribed to warm and cold air masses advected by atmospheric long waves which also produce corresponding cold and warm ocean water through anomalous Ekman advection and heat exchange (Namias, 1959). The comparisons also suggest

TABLE 4. Average pattern correlations of SST vs thickness east of 180° for terciles of SST standard deviations in this area.

Season	SST standard deviations Low	Medium	High
Winter	0.24	0.44	0.67
Spring	0.35	0.34	0.49
Summer	0.35	0.39	0.37
Fall	0.34	0.44	0.59

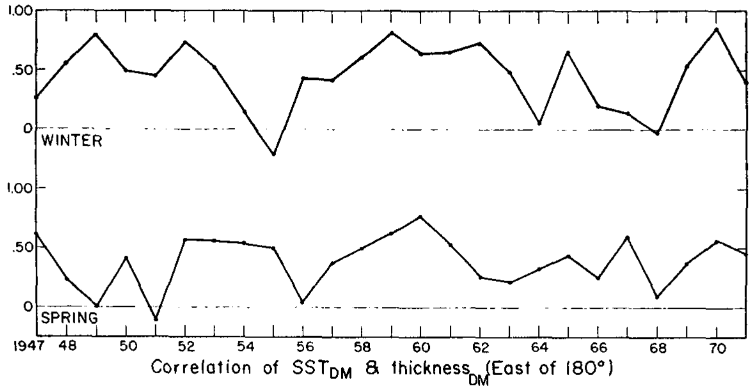

Fig. 4. Winter (above) and spring (below) pattern correlations between SST and thickness over the North Pacific east of 180°.

that the coupled air-sea system operates so that atmospheric cyclonic activity cooperates with the SST anomalies to destroy inversions and thereby reduce the stability of the lower troposphere over much of the area. This would, in turn, facilitate an increase in the transport of heat from ocean to atmosphere. It is, of course, not possible to say from these charts or statistics whether the atmosphere is being forced by the ocean thermal contrasts or vice versa. Probably there are interactions both ways. In the low correlation cases, there is little or no apparent relationship between the SST and 700-mb patterns.

In order to show that the above results for the 12 extreme cases apply in a general way to the entire sample of 100 seasons, I have arrayed the SST standard deviations from the mean and divided them into terciles for each season. The pattern correlation of SST vs thickness was then tabulated in accordance with whether the SST standard deviations were low, medium or high. The summary results, given in Table 4, show that the correlations between SST and thickness patterns are for the most part distinctly higher when SST patterns are strong than when they are weak (low absolute values of SST deviations from mean). The summertime similarity of correlations for low, medium and high standard deviations may indicate the dominant role played by radiation (through cloudiness) rather than other factors in affecting the shallow mixed layers and thermoclines observed in the ocean at this time of year.

It therefore seems that greater vertical stirring of air induced both by cyclonic activity and by destabilization of air masses seems to be an effective way to produce coupling between atmosphere and sea surface. When SST positive anomalies are very large, as in winter 1949, the destabilization seems to be introduced by direct heating from below and not necessarily by increased cyclonic activity as may be seen from the anomalies of 700-mb height. Preliminary computations of stability up to the 700-mb level in the winter of 1949 show that the lapse rate was appreciably steeper than the long-term normal [0.6C $(100\ \mathrm{m})^{-1}$ vs 0.5C $(100\ \mathrm{m})^{-1}$] despite the fact that the 700-mb height anomalies were strongly positive (see Fig. 2), a circumstance which usually indicates more than normal subsidence. Apparently, in the winter 1949 case the anomalous Ekman

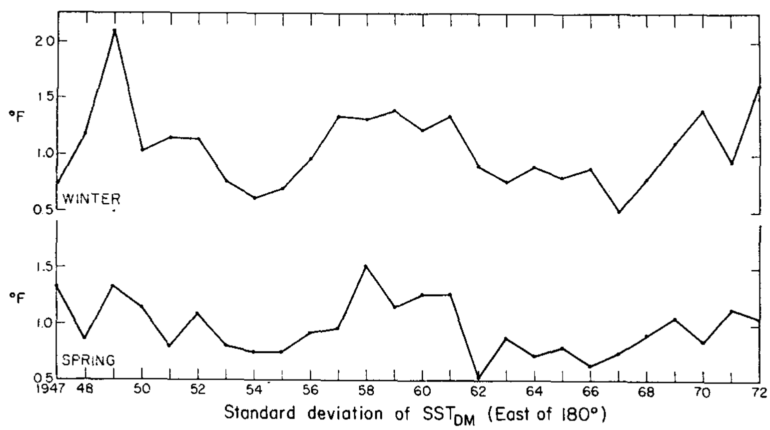

Fig. 5. Winter (above) and spring (below) standard deviations of SST anomalies for all points in the North Pacific east of 180°.

drift resupplied warm water from the south, as suggested by the height anomaly pattern (Namias, 1970). This plus the implied anomalous downwelling were able to keep the pool warm.

4. Long-period trends

Graphs of the seasonal pattern correlations between SST and thickness, and of the standard deviations of SST in the area east of 180° (Figs. 4 and 5, for winter and spring) indicate long-period swings on the order of 5–10 years. As indicated earlier there is a distinct relationship between the magnitude of the correlations and the standard deviations (see Table 4). There is also some suggestion of correspondence between winter and the subsequent spring. In other words, large variability of SST in winter is apt to continue into the following spring, as will high correlations between SST and thickness. These results are probably yet another manifestation of the great persistence of SST patterns (Namias and Born, 1970) and their interactions with the atmosphere.

Similar graphs for summer and fall (not reproduced) do not display such coherence, probably because of the small-scale chaos introduced by variable radiative effects associated with cloud and variable ocean mixing in the shallow mixed layer found at these seasons.

5. Conclusions

Seasonal pattern correlations between SST and 1000–700 mb thickness over the eastern North Pacific indicate areas of high ocean-to-air heat exchange south of the Aleutian low in all seasons, over a large portion of the northeast trades, and (in winter) off the west coast of North America. A zone of low (non-significant) correlation is found on the northward flank of the North Pacific anticyclone. These findings suggest the strong influence of air mass modifications by air advection over water masses of different temperatures and point to varying atmospheric stability as a principle component of large-scale heat exchange.

Lower tropospheric thicknesses are also influenced by abnormal warm or cold water temperatures which may in turn be generated by complex effects of atmospheric centers of action or by ocean currents.

SST-thickness pattern correlations are high when the standard deviations of SST are large and low when they are small.

There appear to be long-period swings of the order of 5–10 years in winter and spring correlations between SST patterns and 1000–700 mb thickness patterns.

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