ON AN ALGORITHM OF CONVECTIVE WEATHER POTENTIAL IN THE EARLY FLOOD SEASON OVER PEARL RIVER DELTA IN CHINA

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1. INTRODUCTION

Other than precipitating weather, the convective weathers in this paper refer to the severe convective weathers such as strong wind gusts, hails and tornados that are induced by thunderstorms. The nowcast of these convective weathers is difficult because of their sudden occurrence, strong intensity and short duration. At present, the techniques for convective weather nowcast include three aspects: (i) the techniques of identification, tracking and extrapolation forecast of thunderstorms; (ii) the mesoscale numerical model forecasting techniques; and (iii) the interpretation techniques combining both (i) and (ii). The interpretation techniques are the primary nowcasting techniques which have been developed in many countries and represent the trend of nowcasting technique development (Chen Mingxuan, et al., 2004). The interpretation techniques generally incorporate a variety of meso- or micro-scale observations including radar and satellite data for developing the conceptual models for the initiation, growth and dissipation of thunderstorms. These interpretation models integrate numeric weather prediction (NWP) model and other extrapolation products to build the nowcasting system of thunderstorms by means of statistic interpretation approaches of some kinds. Many operational applications showed that these interpretation nowcast models/systems usually outperform other techniques with more accuracy and longer lead time. In recent years, such nowcasting systems have been developed in many countries, for instance, the ANC (Auto-Nowcaster) (Mueller et al., 2003) by the National Center for Atmospheric Research (NCAR), the Gandolf (Generating Advanced Nowcasts for Deployment in Operational Land Surface Flood Forecast) (Pierce et al., 2000) by Met Office, UK, the SCAN (System for Convective Analysis and Nowcast) (Smith et al., 1998) by the U.S. National Weather Service (NWS), and the SWIRLS (short-range warning of intense Rainstorms in localized System) by Hong Kong Observatory (Li et al., 2000).

Studies on nowcasting of mesoscale severe weathers have been carried out in China in recent years. Wang Xiaofang, et al. (1994) analyzed the collocation of mesoscale systems associated with hail weathers in Beijing area and proposed a conceptual model for hail fallout zone forecast. Du Bingyu et al., (2000) developed a nowcasting system for convective weathers in Shanghai, based on atmospheric dynamics, moisture, stability and trigger mechanisms from outputs of mesoscale numerical models, Doppler radars, geostationary satellites, MICAPS (Meteorological Information Comprehensive Analysis and Process System), the automated precipitation observation network, as well as the forecaster experiences. The system had been proved to be much effective in nowcasting severe weathers in Shanghai area.

In recent years, rapid improvement of observation techniques, data communication and mesoscale numerical prediction models in China provides advanced means to develop operational systems for objective and quantitative nowcast of thunderstorm weathers. Convective weathers take place frequently in the Pearl River delta each year in the early flood season (EFS) April-June. Many studies have focused on the convective processes in this area. Luo Huibang et al., (1994) conducted specific studies on the local severe storms in Pearl River delta (PRD), obtaining many understandings of storm’s behaviors. Xu Lihang (1994) analyzed the meteorological conditions that triggered the occurrence of the convective weathers in a subtropical high controlled...
situation. Wang Peiling (1994) concluded that the local storms were apt to generate under the condition of low pressure, atmospheric instability, high temperature and humidity in the lower layer and high humidity in the middle and upper layers. Liu Yunce et al. (2001) described the characteristics of severe convective processes initiated by sea breeze front. These studies revealed that the initiation and development of convective weathers in the PRD region are closely related to the larger-scale dynamic and thermodynamic conditions. Therefore in our study, not only echo-based variables derived from radar information but also environment-based parameters provided by mesoscale numerical prediction model were incorporated into the nowcasting algorithm.

2 DEVELOPMENT DATASET

The Guangzhou next generation Doppler radar situated at 23.01N, 113.21E had been put into operation in 2001. The radar can provide 6-minute interval volumetric scanning capability for the whole PRD region. In our study, we had collected radar reflectivity imageries for the 230 km scan radius at 0.5 degree elevation during April-June, 2004. The echo intensities were subdivided into 15 categories with different values assigned according to the reflectivity, e.g., 1 was assigned to category one whose reflectivity range was 1-5DBz; 2 was assigned to category two whose reflectivity range was 6-10DBz; and so on. The intensity data of 1°×1km grid mesh was derived from each reflectivity imagery along azimuth ranging 1−360° and radial ranging 1−230km, forming a total of 360×230 pixel data on a radar imagery.

In the last five years, Guangdong has built more than 600 automatic weather stations (AWS’s) which spaced 10-20km. Most of the AWS’s observe 4 meteorological variables (wind speed, wind direction, temperature, and precipitation). Some observe 6 meteorological variables (additionally two extra variables, air pressure and humidity). In our work, the thunderstorm wind gust data were gathered from the AWS observations for those gust speeds greater or equal to 17.0m/s. Other convective weather records such as hail and tornadoes came from local field observation stations. A total of 358 convective weather events were corrected during April-June, 2004, within the 230 km range of radar scanning.

Another type of predictors (known as environmental predictors) was collected from numerical weather prediction (NWP) model products. The environment predictors were derived from 12-36-h forecasts of the Guangzhou Institute of Tropical and Marine Meteorology, China Meteorological Administration (CMA) mesoscale numeric prediction model (GZH M model), as archived by the Guangdong Meteorological Observatory. The GZH M model is a mesoscale non-hydrostatic model that runs two times per day (0000, 1200 UTC). The model’s 1-h temporal and 14-km spatial resolution data in 12-36-h prediction valid period were objectively assigned to the individual storm cells by simply setting the values of the storm cells the values of the grid points closest to them.

3 CELL IDENTIFICATION AND CELL-EVENT CORRESPONDENCE

The process for developing the CWP algorithm included three steps: 1) identification of individual storm cells; 2) determination of cell-event correspondence, and 3) development of nowcast algorithm to provide the probability of cell-produced convective weather events.

A strong convective system should appear as a strong echo system on a radar reflectivity imagery reaching certain intensity and occupying certain area. We refer to such strong echo system as a thunderstorm cell because they generally could produce severe convective weathers. It is critical that a convective cell could be automatically identified on a reflectivity imagery. The definition of a cell is such that the echo intensity and area must meet some criteria. Feng Yerong and Kitzmiller(2004) in the development of the neural network severe weather potential (NN-SWP) and Kitzmiller and Saffle(1995) in the development of the linear regression severe weather potential (LR-SWP) utilized VIL (Vertically Integrated Liquid) as an indicator to define a storm cell. They defined that a cell should occupy at least two 4×4 km grids and has VIL greater than or equal to 10kg m−2. In our effort, a cell is defined when the all the pixels’ intensity within an echo system is greater than or equal to 50 dBz and this echo
system should spatially cover an area greater than or equal to 64 square kilometers. The cell’ 64 square kilometer area definition is similar as such that a cell should at least be 8km long on a size. This size approximates the lower limit of the average spatial scale for individual thunderstorm cells (10 to 30 km) as defined by Byers and Braham (1949).

We tried to establish a correspondence relationship between an individual cell and relevant convective weather events. This correspondence is defined to exist when the spatial and temporal relationship between a storm cell and a convective event meet. Such relationship is that the convective event occurred within the range of 60 km from the cell centroid within one hour. When a convective event is found to meet these correspondence criteria with an identified cell, the convective event is considered to be produced by the cell. A correspondence relationship then exists between the cell and the event. If several correspondences exist with one cell, for example, one cell corresponds with several convective events, the closest and the latest event will be selected to build the cell-event corresponding relationship.

It should be pointed out that proper combination of spatial and temporal thresholds for identifying a cell must be carefully constructed to avoid over-identification of storm cells. An optimal threshold combination is that it should increase the ratio of the number of event-corresponding cells to the total number of identified cells, i.e., the event-detection ratio. Table 1 lists several threshold combinations for the data of April 2004. Different spatial and temporal threshold combinations could result in significant difference in the number of identified cells. The last raw indicate the threshold combination that produce the largest event detection ratio. So this threshold combination, reflectivity $\geq 50$ dBz and area $\geq 64$ km$^2$, was used in our study to define a storm cell. Such cell identification approach can identify 1060 cells in April 2004 of which 32 could bring in convective weather events.

<table>
<thead>
<tr>
<th>Cell reflectivity(dBz)</th>
<th>Cell area(km$^2$)</th>
<th>Number of identified cells</th>
<th>Number of event-corresponding cells</th>
<th>Event detection ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\geq 40$</td>
<td>$\geq 81$</td>
<td>6135</td>
<td>45</td>
<td>0.007</td>
</tr>
<tr>
<td>$\geq 45$</td>
<td>$\geq 81$</td>
<td>2895</td>
<td>39</td>
<td>0.013</td>
</tr>
<tr>
<td>$\geq 40$</td>
<td>$\geq 100$</td>
<td>5117</td>
<td>44</td>
<td>0.009</td>
</tr>
<tr>
<td>$\geq 45$</td>
<td>$\geq 100$</td>
<td>2326</td>
<td>39</td>
<td>0.017</td>
</tr>
<tr>
<td>$\geq 45$</td>
<td>$\geq 90$</td>
<td>2599</td>
<td>39</td>
<td>0.015</td>
</tr>
<tr>
<td>$\geq 50$</td>
<td>$\geq 64$</td>
<td>1060</td>
<td>32</td>
<td>0.030</td>
</tr>
</tbody>
</table>

In order to create the predictor-predictand dataset needed in our algorithm development, it was necessary to keep the sampling procedure statistically reliable. Storm cells taking place over the sea area were excluded in the dataset because no corresponding convective events were observed.

As we could see from above, the event detection ratio from cell identification process is such low that it is impossible to nowcast convective weathers only by the identified cells. Severe thunderstorms are strong convective systems that develop in specific atmospheric environment. Some convective parameters which reflect the dynamic or thermodynamic effects of atmospheric environment on thunderstorm development could be of great help to diagnose the initiation, growth and dissipation of the storm cells and predict the types of convective weathers(Li Yaodong, 2004). So these environment variables must be considered in the convective weather nowcast problem.

The numbers of identified cells in the EFS months over PRD region in 2004 are shown in the second column in Table.2. The numbers of convective weather events are shown in the third column. The fourth column shows the numbers of cell-relevant events, i.e., the convective weather events produced apparently by the cells. The fifth column shows the numbers of events that are irrelevant to
the identified thunderstorm cells. This could be due to restriction of cell threshold definition which excluded those weak and small cells with reflectivity less than 50 dBz and area less than 64 km², while still could produced severe weather events. This threshold restriction could cause the event exclusion ratio, the ratio of the number of cell-irrelevant events to the number of total events, as large as 19 %, as is shown in the last column. This means that 80% of events were cell related, namely, produced by thunderstorm cells. Only less than 20% of events had been found cell irrelevant and were excluded from the dataset.

<table>
<thead>
<tr>
<th>Month</th>
<th>No. of Identified cells</th>
<th>No. of events</th>
<th>No. of cell-relevant events</th>
<th>No. of cell-irrelevant events</th>
<th>Event exclusion ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>April</td>
<td>1064</td>
<td>36</td>
<td>32</td>
<td>4</td>
<td>0.11</td>
</tr>
<tr>
<td>May</td>
<td>918</td>
<td>197</td>
<td>160</td>
<td>37</td>
<td>0.19</td>
</tr>
<tr>
<td>June</td>
<td>726</td>
<td>125</td>
<td>101</td>
<td>24</td>
<td>0.19</td>
</tr>
</tbody>
</table>

Table 2 Statistics on cell identification and cell-event relationship

Fig. 1a shows the ratios of the numbers of convective weather events to the numbers of identified cells for the EFS months. These ratios are 3%, 17.4%, and 13.9% from April to June 2004 respectively. Therefore, we could not get much more information about the severe weather occurrence from cell identification. A great portion of the identified cells account for precipitation, only very few of the cells account for convective weathers. Directly using these cells to nowcast severe weathers could only lead to unbearably high false alarm ratio. Fig. 1b shows the proportion of convective events that were found to be cell-relevant. More than 80% of convective weathers could be detected through radar thunderstorm cell identification. Only a small portion of cells had been missed owing to the limitation of cell identification approach.

4 CONVECTIVE WEATHER POTENTIAL ALGORITHM

It is obvious that most of the thunderstorm cells on the radar imageries produced precipitation. Only a small portion of them could produce severe convective weathers. The purpose of CWP algorithm was to distinguish such severe weather echoes from precipitation ones.

The statistical dataset was subdivided into two subsets: dependent or development dataset and independent or verification dataset. The dependent dataset comprised two thirds of samples derived from the original dataset through a random-selection procedure. This subset was used to develop CWP algorithm through a multiple linear regression process. The independent dataset
comprised the other one third of data samples. This subset were used to evaluate the algorithm performance. 30 candidate predictors were applied to a multiple linear regression process to obtain a linear expression of convective weather probabilities. These candidate predictors and their units are listed in Tab.3, including 26 environment-based predictors and 4 cell-based predictors.

There were originally 2708 storm cells obtained from radar reflectivity imageries during April-June 2004. Due to lack of achieved NWP model data and no convective weather records available over the sea, only a set of 1513 samples were available, in which two thirds of cases (1010) were used for development dataset. The other one third of cases (503) were used for verification dataset. The predictand represents the probability of event occurrences for an individual cell. The value of predictand was normalized according to the cell-event correspondence. If a correspondence existed, unity was assigned to the statistical predictand. Otherwise, 0 was assigned.

The selection procedure of predictors through the multiple linear regression yielded the following algebraic relationships between the available predictors and event probability:

\[
\text{CWP} = 8.53 + 0.0593 \times \text{REFLTY} - 0.0022 \times \text{CAREA55} - 1273.07 \times \text{DIV850} + 1158.06 \times \text{VOR500} - 0.017T^2_{200-500} - 0.011 v_{500-850} - 0.030 V_{850} - 0.033 V_{500} + 0.018 \times u_{700} + 0.024 \times u_{500} + 0.0034 \times RH_{850-700-500} + 0.022 \times Ki - 0.0085 \times \text{LCL}
\]

(1)

The above equation produces convective weather potential which represents the probability of a storm cell to generate convective weathers in a very short period of time (1 hour) within an area not exceeding 64 km in range from a echo centroid. As indicated in Eq. (1), 13 predictors were introduced into the potential equation. These predictors include variables that describe storm characteristics and storm’s environment conditions. They are cell maximum reflectivity (REFLTY), cell area with reflectivity ≥ 55 dBZ (CAREA55), 850-hPa divergence (DIV850), 500-hPa vorticity (VOR500), temperature difference between 200 and 500 hPa (T500-200), v-component wind shear between 500 and 850 hPa (v500-850), 850-hPa wind velocity (V_{850}), 700-hPa u-component of wind (u_{700}), relative humidity at lower layer (RH_{500+700+850}), K index (Ki) and lifting condensation level (LCL). The predictors in Eq.(1) indicate that storm cells are more likely to produced convective weather in situations with strong reflectivity, high upper-layer thermal instability, relatively high lower layer humidity, strong mid-tropospheric winds, strong mid-tropospheric vorticity, strong lower layer convergence and generally strong vertical meridional wind shear, etc.

### Table 3. Candidate predictors for the convective weather potential

<table>
<thead>
<tr>
<th>Environment-based predictors from model:</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>V850</strong></td>
</tr>
<tr>
<td><strong>V700</strong></td>
</tr>
<tr>
<td><strong>V500</strong></td>
</tr>
<tr>
<td><strong>u850</strong></td>
</tr>
<tr>
<td><strong>u700</strong></td>
</tr>
<tr>
<td><strong>u500</strong></td>
</tr>
<tr>
<td><strong>u200</strong></td>
</tr>
<tr>
<td><strong>v850</strong></td>
</tr>
<tr>
<td><strong>v700</strong></td>
</tr>
<tr>
<td><strong>v500</strong></td>
</tr>
<tr>
<td><strong>v200</strong></td>
</tr>
<tr>
<td><strong>u500-850</strong></td>
</tr>
<tr>
<td><strong>u200-500</strong></td>
</tr>
<tr>
<td><strong>v500-850</strong></td>
</tr>
</tbody>
</table>
v200-850   V-component wind shear between 200 and 500 hPa, m s⁻¹
DIV850    Divergence at 850 hPa, s⁻¹
DIV200    Divergence at 850 hPa, s⁻¹
VOR500    Vorticity at 850 hPa, s⁻¹
T850-500    Temperature departure between 850 hPa and 500 hPa, ° C
T500-200    Temperature departure between 500 hPa and 200 hPa, ° C
RH850+700+500    Mean relative humidity of 850, 700 and 500 hPa
TOTALS    Total totals index (T850 + TD850 - 2T500), ° C
KI          K index, ° C
CAPE      Convective available potential energy, J m⁻²
SI         Showalter index, ° C
LCL       Lifting condensation level, m

Cell-based predictors:
REFLTY    Intensity of radar echo cell, dBZ
CAREA50   Area of echo cell with reflectivity ≥ 50dBZ, km²
CAREA55   Area of echo cell with reflectivity ≥ 55dBZ, km²
CAREA60   Area of echo cell with reflectivity ≥ 60dBZ, km²

5 ALGORITHM PERFORMANCE

The output of CWP algorithm is probability or potential of severe convective weather occurrence for an individual cell. To test the statistical reliability of the algorithm, evaluation was made on dependent dataset. The observations of severe convective weather were verified over each 10% probability interval to see how closely the average forecasted probability approximated the actual event relative frequency (RF). In Fig. 2, the observed RF is plotted as a function of the mean forecasted probability. The solid line represents perfect reliability. CWP varies closely to the perfect reliability criterion for most probability ranges. Overall, in the lower probability range 0-35%, the RF of convective weather occurrence tends to be lower than CWP values. While in the upper probability range >35%, the RF of convective weathers tends to be higher than CWP values.

![Figure 2 Observed relative frequency of convective weather as a function of probability forecasts.](image)

Though CWP algorithms provide probabilistic forecast, their performance is most easily evaluated by
examining the yes/no forecasts (convective/precipitating) based on the probabilities. The yes/no forecasts are generally derived by setting a fixed threshold probability value, and forecasting all storm cells with probabilities at or above the threshold to be convective.

The performance of the yes/no forecasts may be described by three commonly-used measures, the probability of detection (POD), false alarm ratio (FAR), and critical success index (CSI) (Donaldson et al., 1975; Schaefer, 1990). Let x be the number of convective cells correctly forecasted to be convective, y the number of convective cells incorrectly forecasted to be non-convective, and z the number of non-convective cell incorrectly forecasted to be convective. Then the scores are defined by:

\[ POD = \frac{x}{x+y} \] (2)

\[ FAR = \frac{z}{x+z} \] (3)

\[ CSI = \frac{x+y+z}{x+y} \] (4)

The performance of the CWP algorithm in terms of POD, FAR and CSI is shown in Fig. 3. These scores were from a sample of cases for the development dataset (a) and verification dataset (b).

For dependent dataset, CWP varies between the range 0.0-0.5. As has been shown, the yes/no forecast skill is highly dependent on CWP threshold. If the threshold CWP value is set very high, not enough convective weathers would be forecasted and the POD would be rather low. While if the threshold is set too low, too many false alarms would be issued. The optimum choice may be setting the threshold at a point where the CSI maintains high while achieving an acceptable high POD and relatively low FAR. The point is found at the place where the CSI is as close as possible to the peak CSI value. For example, when using 0.195 as CWP threshold probability, about 75% of the severe cells were detected (POD = 0.75); 67% of the "yes" forecasts were false alarms (FAR = 0.67). The CSI at the threshold 0.195 was 0.294.

For independent dataset, results are similar. If threshold value 0.195 is applied, the CSI reaches 0.28. The POD obtains a value of 0.71. The FAR is 0.68. These results indicate that the CWP algorithm is rather robust statistically.

![Figure 3](image)

**Figure 3** The variations of POD, FAR and CSI with respect to CWP probability threshold.

(a) for dependent dataset; (b) for independent dataset.

For comparison, skill scores from other nowcast algorithms of similar kind are listed in Tab. 4. The CWP skill scores are quite well. CSI is higher than the other algorithms. And POD has even a much higher score.
While FAR remains almost the same level as others. These comparisons indicate that the CWP has rather good capability for the nowcast of convective weather events over the PRD region.

Table 4  Comparisons among several nowcast algorithms

<table>
<thead>
<tr>
<th>Skill scores</th>
<th>CWP</th>
<th>TITAN</th>
<th>FSLEXTN</th>
<th>NN-SWP</th>
<th>ANC</th>
</tr>
</thead>
<tbody>
<tr>
<td>POD</td>
<td>0.71</td>
<td>0.37</td>
<td>0.35</td>
<td>0.50</td>
<td>0.414</td>
</tr>
<tr>
<td>FAR</td>
<td>0.68</td>
<td>0.66</td>
<td>0.63</td>
<td>0.70</td>
<td>0.698</td>
</tr>
<tr>
<td>CSI</td>
<td>0.28</td>
<td>0.22</td>
<td>0.22</td>
<td>0.23</td>
<td>0.212</td>
</tr>
</tbody>
</table>

Notes: TITAN is the nowcasting system of NCAR (Wilson et al., 1998; Dixon et al., 1993). FSLEXTN is the extrapolation nowcasting system developed by U.S. National Oceanic and Atmospheric Administration (NOAA) Forecast Systems Laboratory (FSL) (Wilson et al., 1998; Brown et al., 1997; Jackson et al., 1993; Jackson et al., 1995). ANC is the nowcasting system of NCAR (Dixon et al., 1993). NN-SWP is the experimental severe weather nowcast algorithm based on neural network (Feng Yerong, David H. Kitzmiller, 2004).

A example of severe weather nowcast using the CWP algorithm is shown in Fig. 4. On the radar reflectivity image at 16:20 on May 16, 2004, there were four thunderstorm cells detected by the cell identification process. The CWP algorithm yielded 0.35, 0.31, 0.225, and 0.19 respectively for these four cells. Three cells were forecasted to produce convective weather within 1 h because of their CWP value exceeding the probability threshold 0.19. The other one was forecasted not to produce convective weather because of their CWP value not exceeding the probability threshold. Two convective weather events were correctly forecasted, both convective events were thunderstorm wind gusts happening at Sanshui city and Heyuan city. One false alarm had been issued. And the other cell with CWP less than the threshold also successfully forecasted to be a non-convective cell. The CWP algorithm made successful nowcasts for four thunderstorm cells.

![Figure 4](image)

6 SUMMARY

A convective weather potential algorithm was developed in this study. The algorithm underwent cell identification and the development of nowcast algorithm for cell-generated convective weather probability. The cell identification process had been carried out through a pre-determined threshold combination of storm cell intensity and coverage.

The threshold combination is that the echo intensity should be greater than or equal to 50 dBz and echo area should be greater than or equal to 64 square kilometers. These threshold criteria identified thousands of thunderstorm cells during the EFS in 2004 over southern China’s PRD Region. Most of the storm cells were associated with precipitation. Only very small portion, say, less than 18%, were related to convective weathers. Though the convective-relevant cells was such
a low number, more than 80% of such cells were captured by the cell identification process in the dependent dataset.

The probabilistic forecast algorithm of thunderstorm cells to generate convective weathers was developed using both radar-based and NWP-based predictors through a multiple linear regression approach. This CWP was used to make probabilistic forecast of the storm cell-produced convective weather events over the PRD of China within 1-h valid time. Verification of the yes/no forecast of CWP algorithm were conducted for both dependent and independent datasets by setting certain probabilistic threshold. CWP algorithm categorical forecasts yielded much higher scores compared to other nowcast algorithms alike. For independent dataset, when using threshold 0.195, the CWP yielded a CSI of 0.28 and a POD of 0.71, while keeping a tolerant FAR of 0.68.

Though the verification of the CWP algorithm's performance for both dependent and independent samples and an example of nowcast showed that the algorithm was of skill in nowcasting convective weathers, it still need further improvement. Due to more or less subjective definition of thunderstorm cell, a few convective weather cases were excluded from the statistical sample because their relevant cells were too small or too weak to be detected automatically through the pre-determined threshold criteria. The proportion of this excluded convective weather events is about 18%. A more powerful cell identification approach is expected in order to keep as many convective weather samples as possible in the development dataset.

With the development and deployment of other unconventional facilities such geostationary satellites, wind profilers, lightning locators and GPS moisture monitoring instruments, the CWP algorithm is expected to be improved by incorporating such data as much as possible. Other radar products such as Vertically Integrated Liquid (VIL), radar radial wind can be incorporated into the algorithm, too.

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