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Status of Experiments with a 6-Hour Analysis/Forecast Cycle

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I. April 1975 6-Hour Cycle Experiment

During the summer of 1975, Data Assimilation Branch conducted a 6-hour cycle experiment. The configuration of the analysis/forecast cycle was identical to that of the NMC final cycle except that the update frequency was doubled; analyses were produced at 6-hour rather than 12-hour intervals. The forecast model used in the NMC final cycle is an 8-layer global prediction model (Stackpole, et al., 1974), and the analysis model used is a three-dimensional spectral objective analysis (Flattery, 1970). The experiment began from the 00 GMT April 10, 1975 NMC final analysis and thereafter was completely independent of the NMC final cycle. After six days the troposphere over Antarctica had exhausted in the forecast model, and the experiment was terminated.

Graphs of surface and tropopause pressures at two individual grid points (70W, 30N; 70W, 30S) showed some disturbing trends. At both points the amplitude of the high-frequency noise components of the surface pressure increased in each cycle, indicating a high and ever-increasing noise level. Also the tropopause at both points showed a relentless trend to higher pressures, indicating a thickening of the model stratosphere and a shrinking of its troposphere. The global RMS surface pressure tendency and mean-square divergence were plotted hourly during each forecast cycle. These are shown in Figure 1. Characteristically, the RMS surface pressure tendency (Figure 1a) shows a marked increase in the first hour ... due to initial imbalances ... followed by a gradual decline to an approximate asymptotic level. This behavior is a normal feature of the NMC final cycle as well. However, in the

6-hour cycle, the asymptotic level becomes progressively higher. At the end of the first cycle the value is about 0.2 mb per time step. By the termination of the experiment, the value has more than doubled. The general increase in noise level is also reflected in the mean-square divergence plots (Figure 1b).

Other symptoms of the failure of the 6-hour cycle can be seen in Figure 2, which shows analyzed and forecast heights at 100 mb and 1000 mb at the edge of the Antarctic continent (77.5S, 162.5E). A prominent feature is the "sawtooth" variation between analysis and forecast at 100 mb. The analyzed height is invariably higher than the forecast height valid at the same time. Each forecast lowered the analyzed height, but the subsequent analysis raised it again. The change during a six-hour forecast is quite large ... of the order of 100-150 m ... but the change from forecast to analysis is larger still. The result is a sharp upward trend such that the analyzed 100 mb height increases by about 600 m over the three-day interval shown in Figure 2a. No such trend is apparent in the 12-hour cycle, although the sawtooth pattern is evident but with less amplitude. At 1000 mb the trend in the heights (Figure 2b) is large and in the opposite direction, but the sawtooth variation is much less pronounced. The 12-hour cycle does not exhibit the downward trend.

Efforts to diagnose the reason for the failure of the 6-hour cycle focused on controlling the noise reflected in the RMS surface pressure tendency and mean-square divergence statistics, and on controlling the misbehavior that occurred over Antarctica. In the forecast model, a special viscosity term was applied to the divergent component of the wind in the stratosphere to control the accumulation of noise. In diagnosing the problem over Antarctica, a list was made of all the ways in which the analysis could cause a change to the forecast heights, and then each item on the list was investigated in turn. The most obvious way for the analysis to produce a change to the forecast is by the introduction of observational data. However, the behavior of the 6-hour cycle over Antarctica is independent of the presence of any observational data; all data in the area near the point shown in Figure 2 were rejected by the analysis because they exceeded toss-out limits. A second way the forecast could be changed is by interpolation errors in going from model coordinates (σ) to pressure coordinates and back again. An improved vertical interpolation procedure was inplemented, but interpolation errors were found to be very small, regardless of which interpolation scheme was used. A third way in which the forecast could be changed is by the spectral analysis of the forecast, which is performed in order to obtain a first guess for the analysis. However, the spectral analysis of the forecast proved to be a faithful reproduction of the forecast. A fourth way that the forecast could be changed is by a vertical coordinate transformation that takes place in each analysis. A new set of empirical vertical functions is computed for each analysis of forecast data and for each analysis of observational data. Hence, the guess coefficients used in the analysis are not compatible with the vertical functions being used. To overcome this problem, the guess coefficients are modified such that they are compatible. This transformation results in an error, but again the error is small compared to the overall change taking place over Antarctica.

Finally, the analysis procedure can make changes to the forecast height field by the way in which the analysis model wind law is enforced. In the analysis two nearly independent analyses of heights and winds are made and then a weighted averaging or blending of height and wind coefficients is performed to produce a strong balance between mass and motion fields. By imposing a stronger balance in the analysis than existed in the forecast, both the heights and winds are altered, even in the absence of observational data. This alteration accounts for nearly all of the difference between analyzed and forecast heights seen in the sawtooth pattern of Figure 2a. Hence, it was decided to discontinue the blending of height and wind coefficients.

A partial rerun was performed for the April period with the above changes. After nine cycles the experiment was postponed because of other higher priority commitments. Results were not conclusive, although it appeared that the 6-hour cycle was still unstable in the Southern Hemispheric stratosphere at high latitudes. Heights in this area continued to rise at 50 mb but less sharply than in the first experiment. At 100 mb and 1000 mb (Figure 3) the heights did not show a strong upward or downward trend. The sawtooth behavior in Figure 2 disappeared in the rerun, and its disappearance was a direct result of discontinuing the blending of height and wind coefficients in the analysis.

II. Purpose and Configuration of the August 1975 Experiment

A number of changes were introduced into the NMC 8-layer global model after the April test. Perhaps the most significant change, with respect to the 6-hour cycle, is the method by which the pole points are treated. In April the model equations were actually solved for the pole points. Because of excessive truncation error, this led to unreasonable solutions. On December 10, 1975 this procedure was replaced by one in which the pole points are obtained as the circumpolar average of the quantities at the adjacent row.

Other changes to the analysis/forecast system include: (1) use of a new tropopause finder; (2) use of increased weights for heights in the wind analysis and winds in the height analysis, resulting in a stronger enforcement of the model wind law but without blending coefficients; (3) use of fixed, predetermined functions for representing the vertical variation of heights and winds; (4) use of looser toss-out limits for data near the South Pole; and (5) use of the Flattery temperature analysis in the lowest four levels (1000, 850, 700, and 500 mbs). Previously temperatures at all levels were obtained hydrostatically from analyzed thicknesses. Currently this method is still used above 500 mb.

Because of the changes that were made to the models, a second 6-hour cycle experiment was recently conducted. The primary purpose of this experiment was to determine whether or not the model changes improved the analysis/forecast system to the point where it is stable with a 6-hour update period. Secondly, if the 6-hour cycle appeared reasonably stable, it would become necessary to ascertain whether or not the 6-hour cycle produced better analyses than a similarly configured 12-hour cycle. The forecast model was run without any special form of noise control. The divergence damping which had been used in the April rerun of the 6-hour cycle was not used. The experiment began with an analysis at 00 GMT August 18, 1975, and was run for a five day period.

The data base for the 6-hour cycle experiment included all of the conventional NMC data, except radiosonde data, plus all experimental data collected for the August Data Systems Test (DST). The data base is the same as that used in the DST System 3 (12-hour cycle) experiment, and the 6-hour cycle covers the same five day time period as System 3. A primary source of experimental data consisted of Nimbus 6 satellite soundings. Errors are known to exist in this data, but these errors are common to both the 6-hour cycle and System 3. Radiosonde data were withheld for verification purposes. The main difference between System 3 and the August 6-hour cycle is the difference in update frequency; however, the 6-hour cycle experiment was conducted with the version of the code used in the January DST, which eliminated all Nimbus 6 soundings taken over high terrain. In the 12-hour cycle all soundings were used; in the 6-hour cycle soundings were ignored if the terrain height at the point of observation was more than 100 m above the 850 mb height. Thus, no upper air data were used over the Himalayas, Antarctica, and portions of the Rocky Mountains.

III. Results and Comparisons

The performance of the August 6-hour cycle was assessed by comparing it to System 3 and the April 6-hour cycle. Statistics like those depicted in Figures 1 and 2 were generated for the August 6-hour cycle and System 3. In addition the August 6-hour cycle and System 3 were verified against radiosonde data withheld from both systems. Finally, an 84-hour forecast using the NMC 6-level PE coarse mesh model (Shuman and Hovermale, 1968) was attempted for the August 6-hour cycle and System 3, beginning with the last analysis of the five day experiment (00 GMT August 23, 1975).

The RMS surface pressure tendency and mean-square divergence for the August 6-hour cycle are depicted in Figure 4. These statistics are similar to those plotted in Figure 1 for April. Whereas the asymptotic level of the RMS surface pressure tendency for the April 6-hour cycle more than doubles in five days, the August 6-hour cycle does not show an increase in asymptotic level over the five day period. The behavior of the surface pressure tendency is very similar to that of System 3 for the same period (Figure 5). Both systems exhibit a peak around the first hour of the forecast of slightly less than 0.5 mb per time step. By the end of each 12-hour forecast, System 3 has reached a slightly lower level because the model has had twice as much time to reach its asymptotic value. The mean-square divergence during the first several 6-hour cycles rises steeply early in each forecast, much like the April case. But near the end of each 6-hour period, the divergence levels off, which the divergence from the April case did not do. Furthermore, the divergence value at the end of each 6-hour forecast is roughly 35% lower in the August case than in the April case.

The first and seventh 6-hour cycles are exceptions to this behavior. The larger values of mean-square divergence in the first cycle can probably be attributed to initial imbalances at the start of the experiment. The first guess for the first cycle came from the NMC final cycle which uses a much different observational data base than the 6-hour cycle. Also a vertical coordinate transformation had to be performed on the first cycle to make the guess coefficients compatible with the vertical functions chosen for the experiment. This transformation was avoided on all subsequent cycles since the same set of functions was used throughout the 6-hour cycle experiment. In System 3 a different set of vertical functions was used for each analysis, and hence a vertical coordinate transformation was performed for each analysis. The large values of mean-square divergence on the seventh cycle, which began on 12 GMT August 19, 1975, are probably caused by stratospheric exhaustions which occurred in the forecast model over Antarctica. The depletion first occurred at a point where the analyzed tropopause was 68 mb, which means the model stratosphere was initially only 18 mb thick.

Beginning around 12 GMT August 20 the mean-square divergence began to increase steadily. Over the last seven cycles the divergence at the end of the forecast increased from 1.03×10^{-9} $\sec^{-2}$ to 1.43×10^{-9} $\sec^{-2}$, an increase of about 40%. This increase in divergence with time did not occur in System 3 (Figure 5). At least part of this noise accumulation is believed due to analysis problems over high terrain where sea level observations are not available. For example, over the Himalayan Mountains and Plateau of Tibet (around 30N, 90E), the 1000 mb analyzed height dropped from -77 m to -2456 m in the 6-hour cycle over the five day period in August. The same trend is in evidence in System 3 but is less severe. At the same point the 1000 mb height dropped from -82 m to -364 m in System 3. Both the 6 and 12-hour cycles end up with unreasonable 1000 mb height patterns in this area. However, the 6-hour cycle is much worse and would certainly lead to eventual failure of the 6-hour cycle. Furthermore, the unreasonable behavior over the Himalayas did not confine itself to the low levels. Eventually a strong anticyclone developed at both

500 mb and 100 mb, and large convective adjustments were made by the 8-layer forecast model at both low and high levels.

The unreasonable analyses occur because in this area no data, either forecast or observational, enter the system at 1000 mb. In this particular region no surface or radiosonde data are available, and forecast data are not used if they are more than 500 m below ground. Consequently, 1000 mb heights over high terrain are obtained by extrapolation of the vertical functions used in the analysis. Obviously these vertical functions make poor extrapolators.

The August 6-hour cycle was also monitored very closely in the area around the South Pole, since it is here that failure first occurred during the April 6-hour cycle. Plots similar to Figure 2 are shown in Figure 6. Figure 6 depicts forecast heights for 100 and 1000 mb at the South Pole for the August 6-hour cycle and System 3. Recall that Figure 2 was for the April 6-hour cycle and was several degrees away from the pole point. Analyzed values are not shown in Figure 6 because many of them were very close to the forecast values. In other words the sawtooth character of Figure 2 disappeared because height and wind coefficients were no longer being blended. An important feature of the August 6-hour cycle is that the heights are not rising strongly at 100 mb and falling rapidly at 1000 mb as was the case in April. This improvement in behavior is mainly a result of the new way that the forecast is made at the pole point. The differences between 6 and 12-hour cycle in Figure 6 are due primarily to the differences in treatment of satellite data. In the 6-hour cycle the satellite soundings were not used over high terrain, whereas they were in the 12-hour cycle. The important point to be made about the area around the South Pole is that the pathological behavior evident in the April 6-hour cycle has disappeared in the August 6-hour cycle.

Even though the August 6-hour cycle is obviously becoming unstable, it had improved considerably since the April experiment, and therefore it was decided to verify the 6-hour forecasts against radiosonde data. These verifications were then compared to verifications of 12-hour forecasts from System 3. The results are shown in Tables 1 - 4. Only half the 6-hour forecasts, those valid at 00 and 12 GMT, were verified, since these are the only times that 12-hour forecasts are available for comparison. Verification scores are in the form of RMS differences between observations and forecasts interpolated to the observation points. The number of verification points ranged from 58 to 70, and all are located in the Northern Hemisphere. Heights, temperatures, and winds were verified at four different levels. None of the verification data was used in either the 6 or 12-hour cycle.

On the average the 6-hour cycle verified better than the 12-hour cycle at all levels and for all variables verified. The largest improvements occurred at the lowest and highest levels (850 mb and 100 mb). Furthermore, in the 12-hour cycle the errors tended to get larger with time. This trend does not appear in the 6-hour cycle except in the high-level wind errors.

Finally, an 84-hour forecast using the NMC 6-level PE coarse mesh model was attempted for both the 6 and 12-hour cycles beginning from the last analysis produced by each system. The forecast made from the 12-hour cycle analysis ran to 84 hours, but the forecast made from the 6-hour cycle analysis failed at hour 57. Failure occurred due to stratospheric depletion over the Himalayan Mountain region. This failure is undoubtably related to the analysis problem in areas of high terrain. Since the forecast from the 6-hour cycle analysis failed, no verification of either forecast is presented here.

IV. Conclusion

It is clear that the 6-hour cycle, as configured for the August experiment, cannot run indefinitely without failure. It is also clear that the 6-hour cycle has been greatly improved since the April 1975 experiment. This fact is evident in the RMS surface pressure tendency and mean-square divergence statistics, as well as in the behavior around the South Pole. At least two problems must be corrected in order to make the 6-hour cycle stable. First of all, the tropopause finder must be modified such that unrealistically low values of tropopause pressure are not allowed to occur. Such a change is necessary to keep the forecast model stratosphere from depleting near the South Pole. Secondly, the underground height analysis in areas of high terrain must be controlled to prevent contamination of the analysis above ground. One way to improve the underground analysis is by allowing underground forecast data to be used in the spectral analysis of the forecast, which serves as a first guess for the analysis of observational data. These underground heights are obtained by Shuell reduction (Technical Procedures Bulletin, No. 57, 1970). A test during the April 6-hour cycle experiment indicated that using Shuell reduced heights in the analysis of the forecast resulted in a deeper vortex over the Himalayan Mountains than if underground heights were not used at all. Therefore, it appears necessary to devise a different reduction scheme for producing underground heights to be used in the analysis of the forecast.

If the 6-hour cycle still proves unstable after successful correction of the above two problems, it may be necessary to employ additional forms of noise control. One such form might be some kind of divergence damping like that used in the April 6-hour cycle rerun. Another way to reduce noise might be to use less resolution in the spectral analysis of the forecast as a means of filtering the forecast.

Finally, the comparative verification scores between the August 6-hour cycle and System 3 (Tables 1 - 4) indicate the advantage in reducing the update period from 12 to 6 hours. If a primary source of observational data continues to be asynoptic in nature as is the case with satellite derived soundings and winds, it seems important and logical to use a shorter update interval than 12 hours. The verification scores support this premise.

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2. Shuman, F., and J. Hovermale, 1968: An operational six-layer primitive equation model. J. Appl. Meteor., 7, 525-547.

3. Stackpole, J., L. Vanderman, and F. Shuman, 1974: The NMC 8-layer global primitive-equation model on a latitude-longitude grid. GARP Publication Series, No. 14, WMO, Geneva, 79-93.

4. Technical Procedures Bulletin No. 57, 1970: Revised Method of 1000 mb Height computation in the PE Model. NWS Technical Procedures Bulletin Series.

Table 1. RMS errors at 850 mb for August 1975, 6 and 12-hour forecasts.

Date/Time	Height (m)		Temp (°C)		Vector Wind (kts)	
	6Hr	12Hr	6Hr	12Hr	6Hr	12Hr
18/12Z	19.2	18.2	3.1	3.0	9.8	10.5
19/00Z	20.4	25.3	2.9	3.2	11.6	12.2
19/12Z	19.9	24.6	2.1	2.4	11.3	13.3
20/00Z	16.0	21.5	3.1	3.1	9.7	11.3
20/12Z	21.6	33.1	2.7	3.2	11.0	13.5
21/00Z	21.3	26.1	2.5	3.0	10.6	11.8
21/12Z	23.8	38.2	2.4	3.6	10.3	13.2
22/00Z	22.9	20.2	2.8	3.3	12.4	14.3
22/12Z	21.8	33.6	2.9	4.3	10.6	13.6
23/00Z	18.9	27.1	2.9	4.1	10.0	12.6
Average	20.6	26.8	2.7	3.3	10.7	12.6

Table 2. RMS errors at 500 mb for August 1975, 6 and 12-hour forecasts.

Date/Time	Height (m)		Temp (°C)		Vector Wind (kts)	
	6Hr	12Hr	6Hr	12Hr	6Hr	12Hr
18/12Z	33.7	26.5	1.9	1.6	12.8	12.4
19/00Z	22.4	38.0	1.5	1.9	10.9	13.8
19/12Z	38.3	28.8	2.2	2.2	15.1	13.9
20/00Z	33.5	34.7	1.5	1.9	12.5	14.4
20/12Z	42.9	44.3	2.0	1.8	14.0	14.4
21/00Z	32.4	33.0	1.8	1.8	12.4	15.9
21/12Z	40.3	45.5	2.0	2.0	13.6	16.5
22/00Z	38.2	31.8	2.5	2.1	16.8	19.3
22/12Z	36.6	41.6	2.1	2.0	15.5	18.1
23/00Z	32.0	48.4	1.9	2.3	12.8	15.8
Average	35.1	37.3	1.9	2.0	13.6	15.5

Table 3. RMS errors at 300 mb for August 1975, 6 and 12-hour forecasts.

Date/Time	Height (m)		Temp (°C)		Vector Wind (kts)	
	6Hr	12Hr	6Hr	12Hr	6Hr	12Hr
18/12Z	46.1	34.2	2.7	2.8	19.0	19.2
19/00Z	31.2	51.9	2.5	2.6	20.4	21.9
19/12Z	55.6	51.3	3.1	3.0	21.7	21.6
20/00Z	48.7	59.4	2.5	2.4	19.7	20.9
20/12Z	67.6	74.7	2.5	3.4	21.5	19.9
21/00Z	48.1	55.1	2.6	2.8	22.3	26.0
21/12Z	69.1	75.8	3.3	3.7	23.4	28.1
22/00Z	71.8	70.3	3.6	3.6	28.9	30.4
22/12Z	56.0	71.0	3.1	3.8	26.1	32.1
23/00Z	44.7	76.0	2.6	2.9	24.0	26.6
Average	53.9	62.0	2.9	3.1	22.7	24.7

Table 4. RMS errors at 100 mb for August 1975, 6 and 12-hour forecasts.

Date/Time	Height (m)		Temp (°C)		Vector Wind (kts)	
	6Hr	12Hr	6Hr	12Hr	6Hr	12Hr
18/12Z	54.8	60.1	2.3	2.4	13.3	16.5
19/00Z	84.6	90.6	3.6	3.1	15.6	17.9
19/12Z	99.3	91.9	4.5	4.0	17.2	22.1
20/00Z	81.2	83.4	4.1	4.1	18.3	21.4
20/12Z	78.5	81.3	5.1	4.9	18.5	22.7
21/00Z	88.7	107.6	4.6	5.9	22.7	27.3
21/12Z	91.9	87.7	4.4	4.7	20.5	27.8
22/00Z	76.3	104.2	4.1	5.8	22.1	36.1
22/12Z	91.4	97.4	4.7	5.5	22.0	30.6
23/00Z	88.9	108.2	4.2	5.5	21.6	28.6
Average	83.6	91.2	4.2	4.6	19.2	25.1

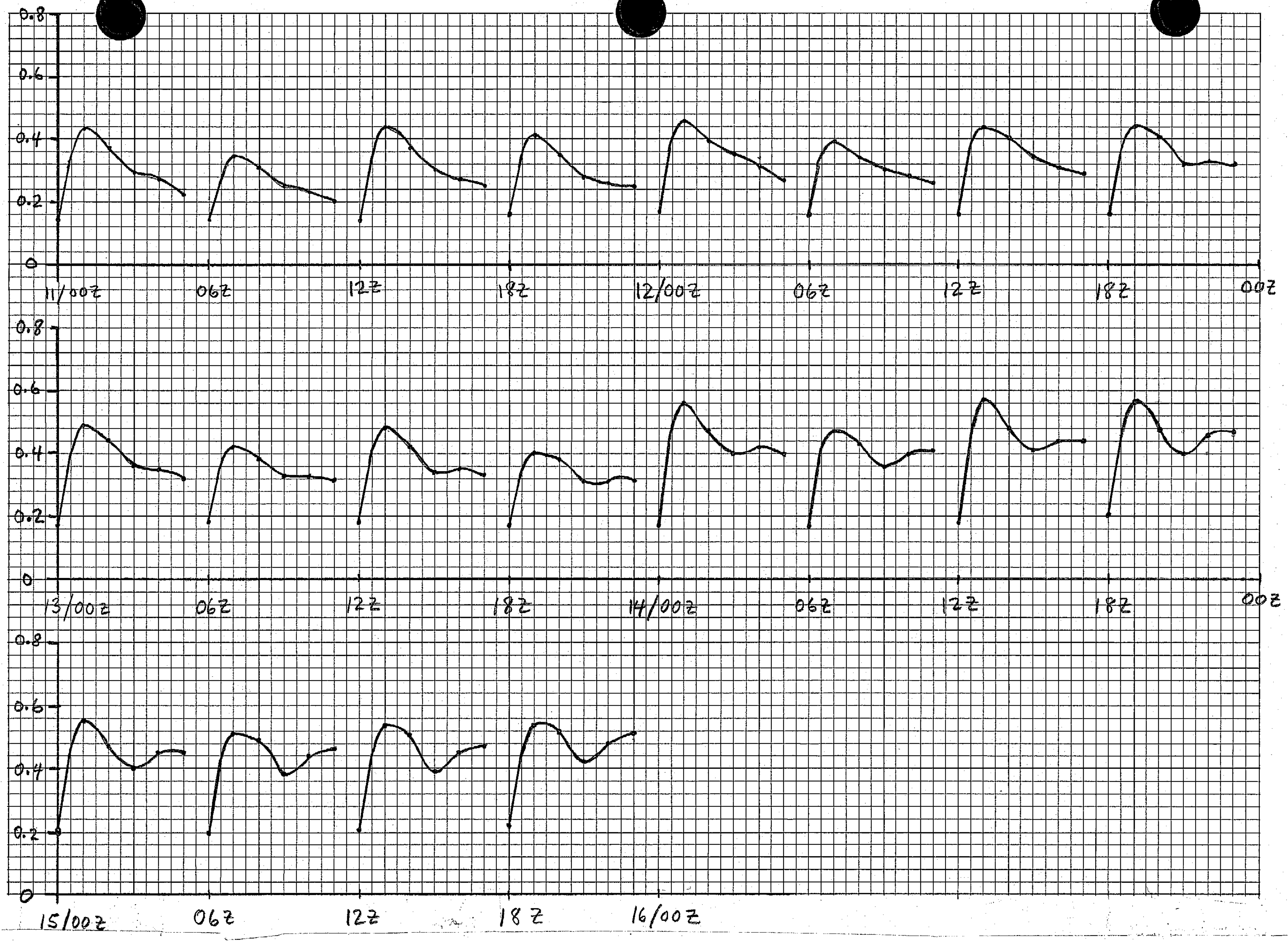

Figure 1a. RMS surface pressure tendency (mb/Δt), April 1975, 6-hour cycle.

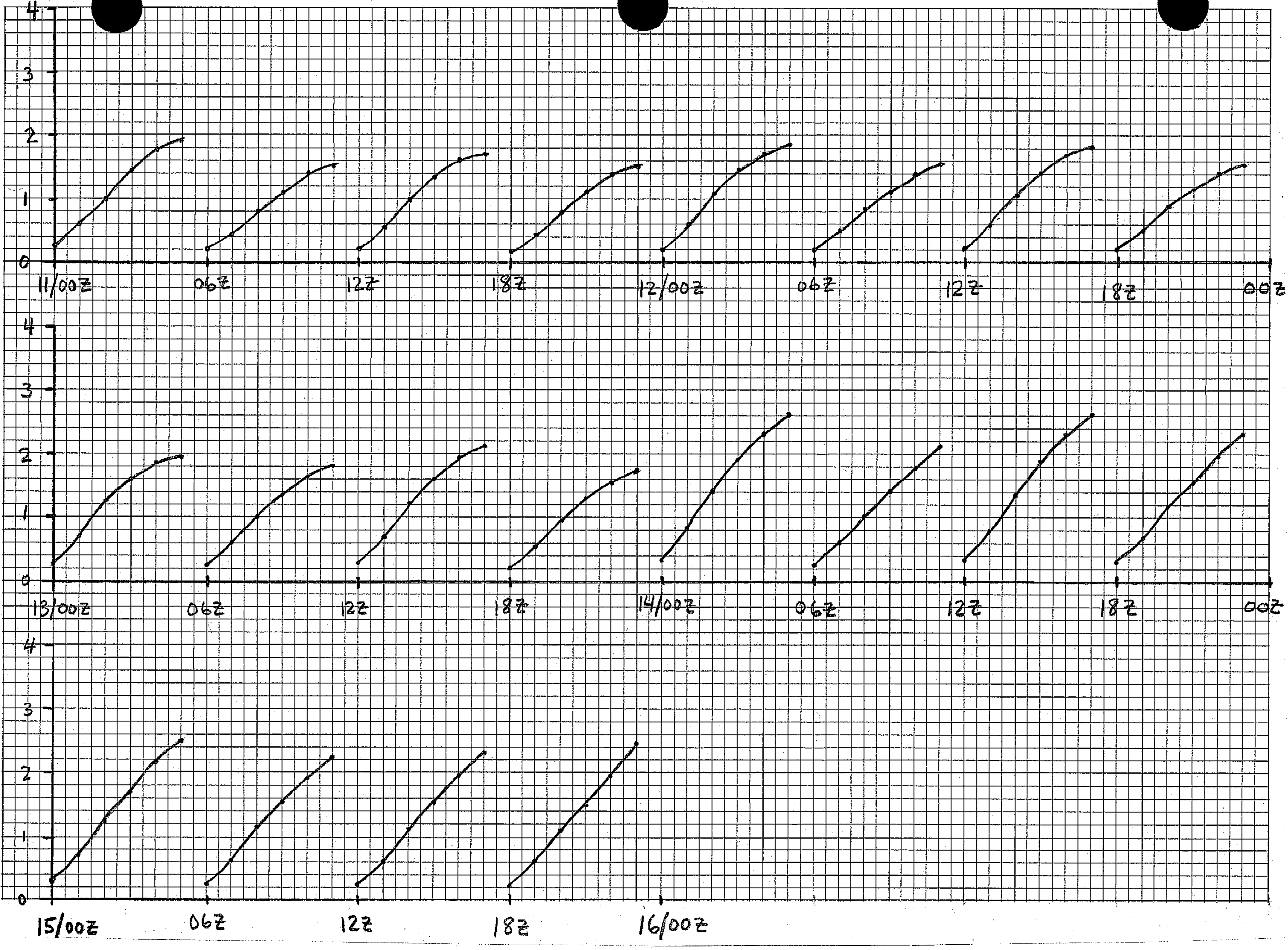

Figure 1b. Mean-square divergence (x10^{-9} sec^{-2}), April 1975, 6-hour cycle.

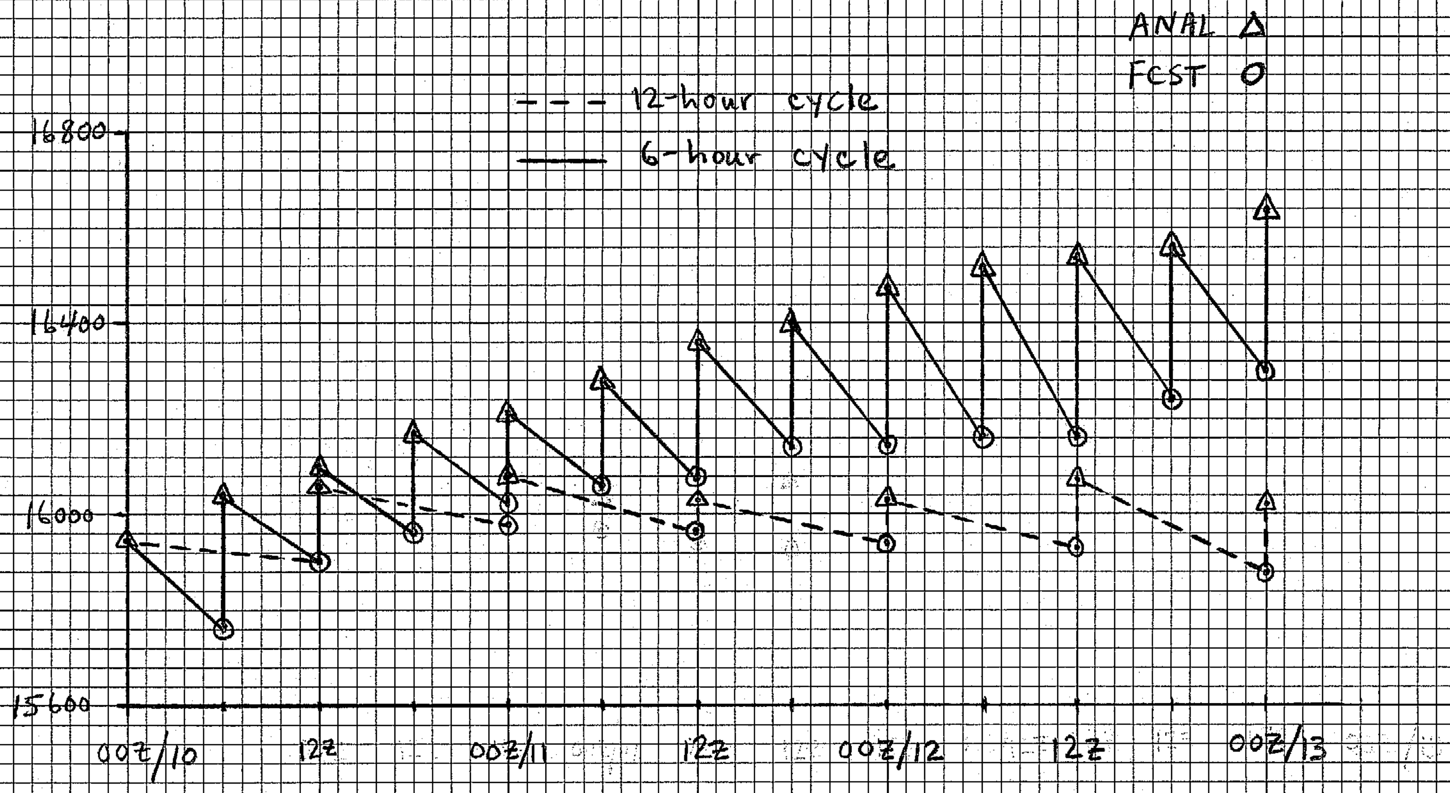

Figure 2a. 100 mb height (m) at 77.5S, 162.5E, April 1975.

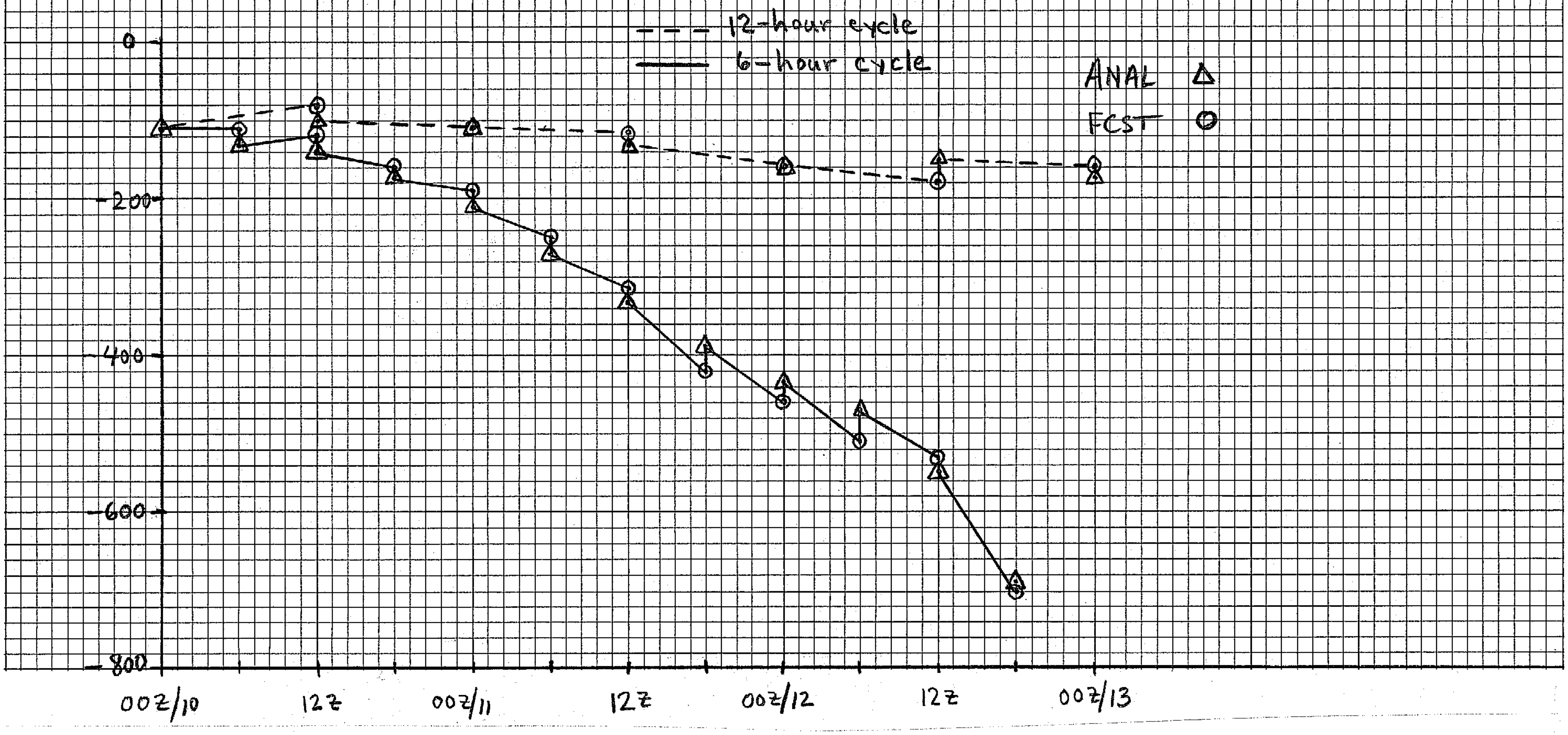

Figure 2b. 1000 mb height (m) at 77.5S, 162.5E, April 1975.

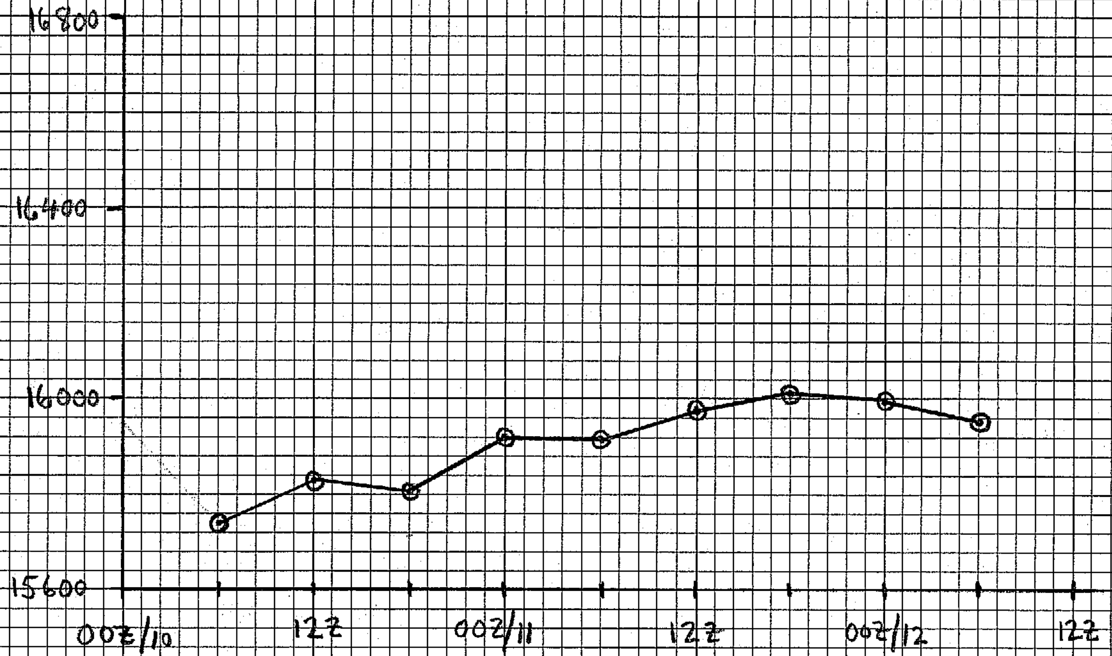

Figure 3a. 100 mb forecast height (m) at 77.5S, 162.5E, April 1975, 6-hour cycle rerun.

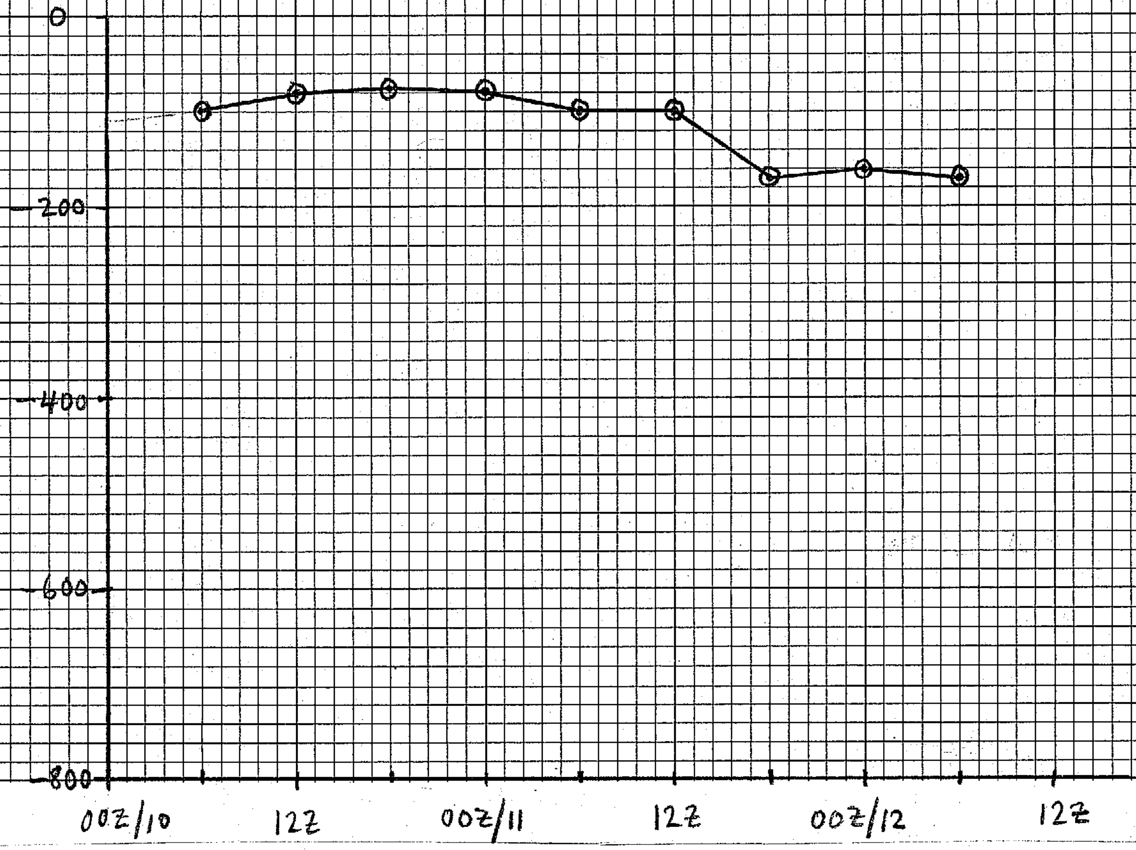

Figure 3b. 1000 mb forecast height (m) at 77.5S, 162.5E, April 1975, 6-hour cycle rerun.

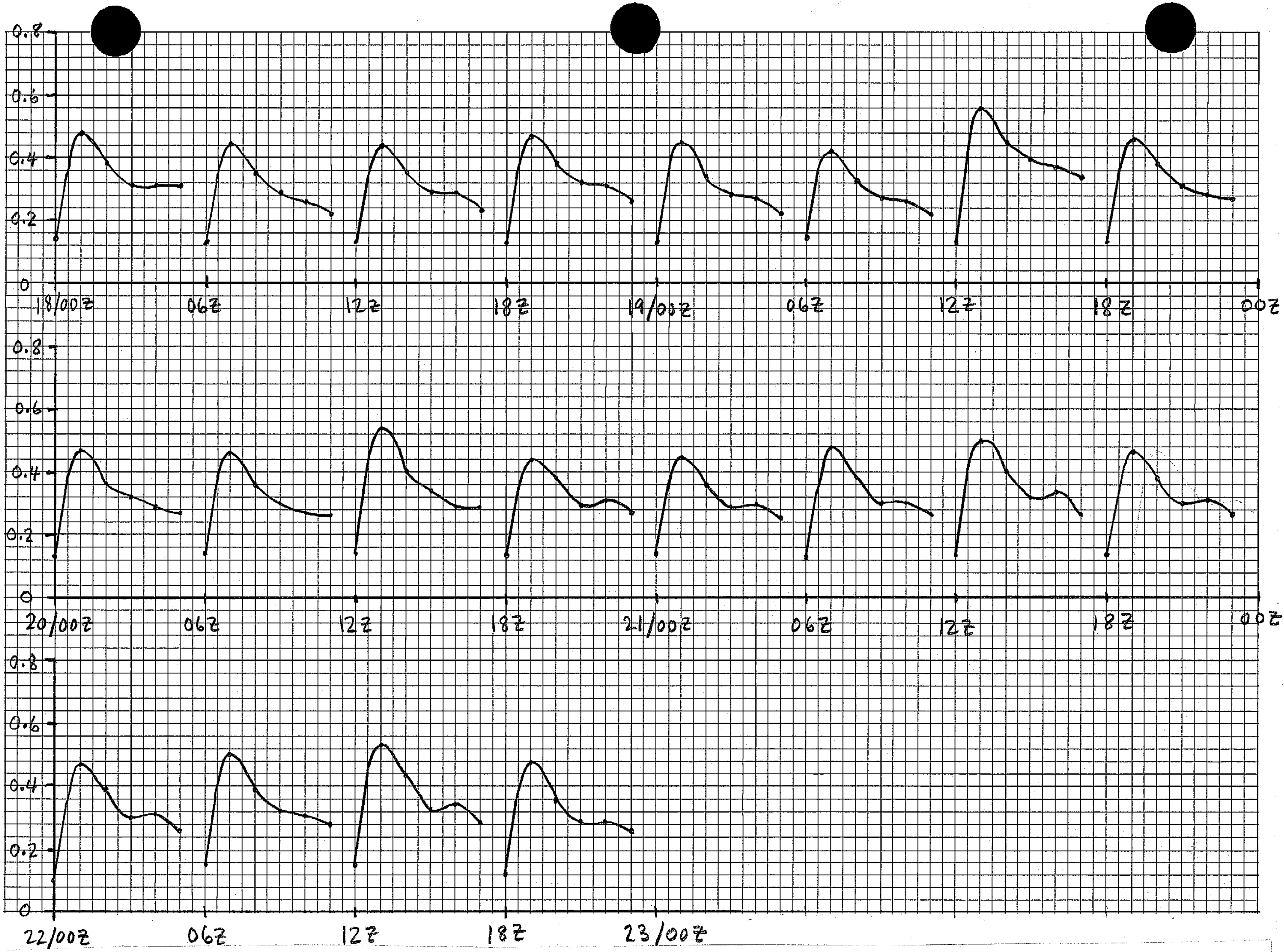

Figure 4a. RMS surface pressure tendency (mb/Δt), August 1975, 6-hour cycle.

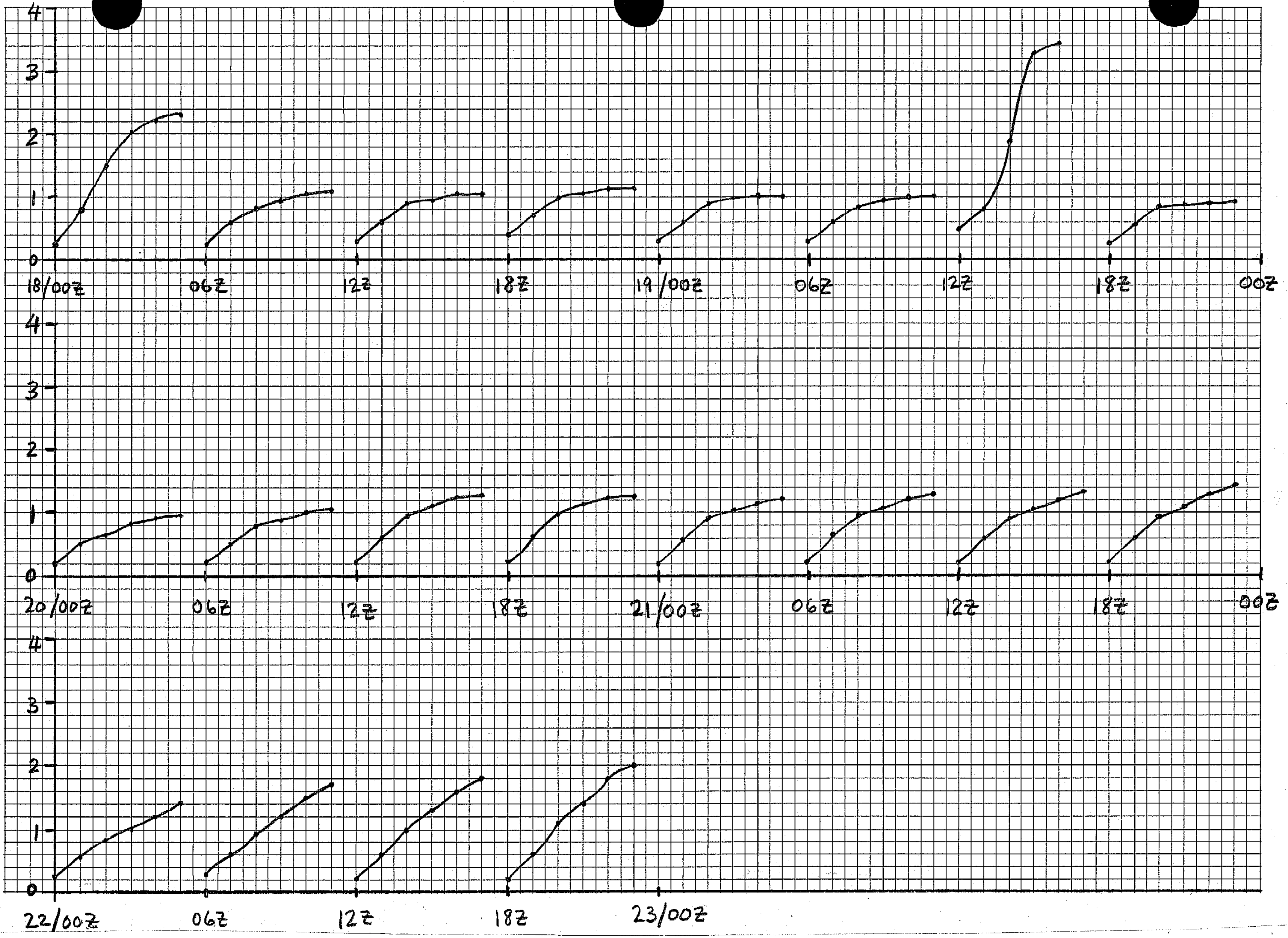

Figure 4b. Mean-square divergence (x10^{-9} $\sec^{-2}$), August 1975, 6-hour cycle.

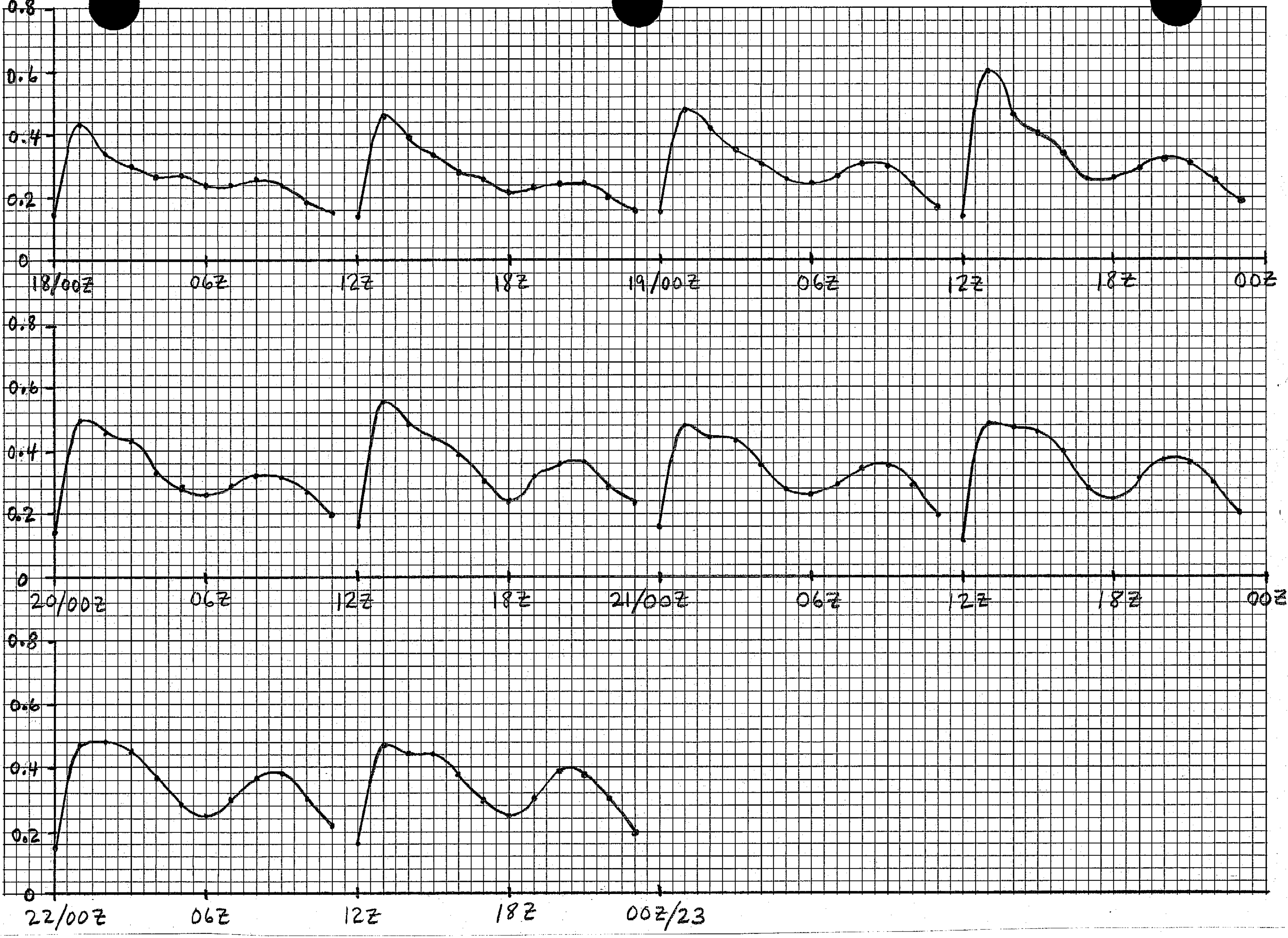

Figure 5a. RMS surface pressure tendency (mb/Δt), August 1975, 12-hour cycle.

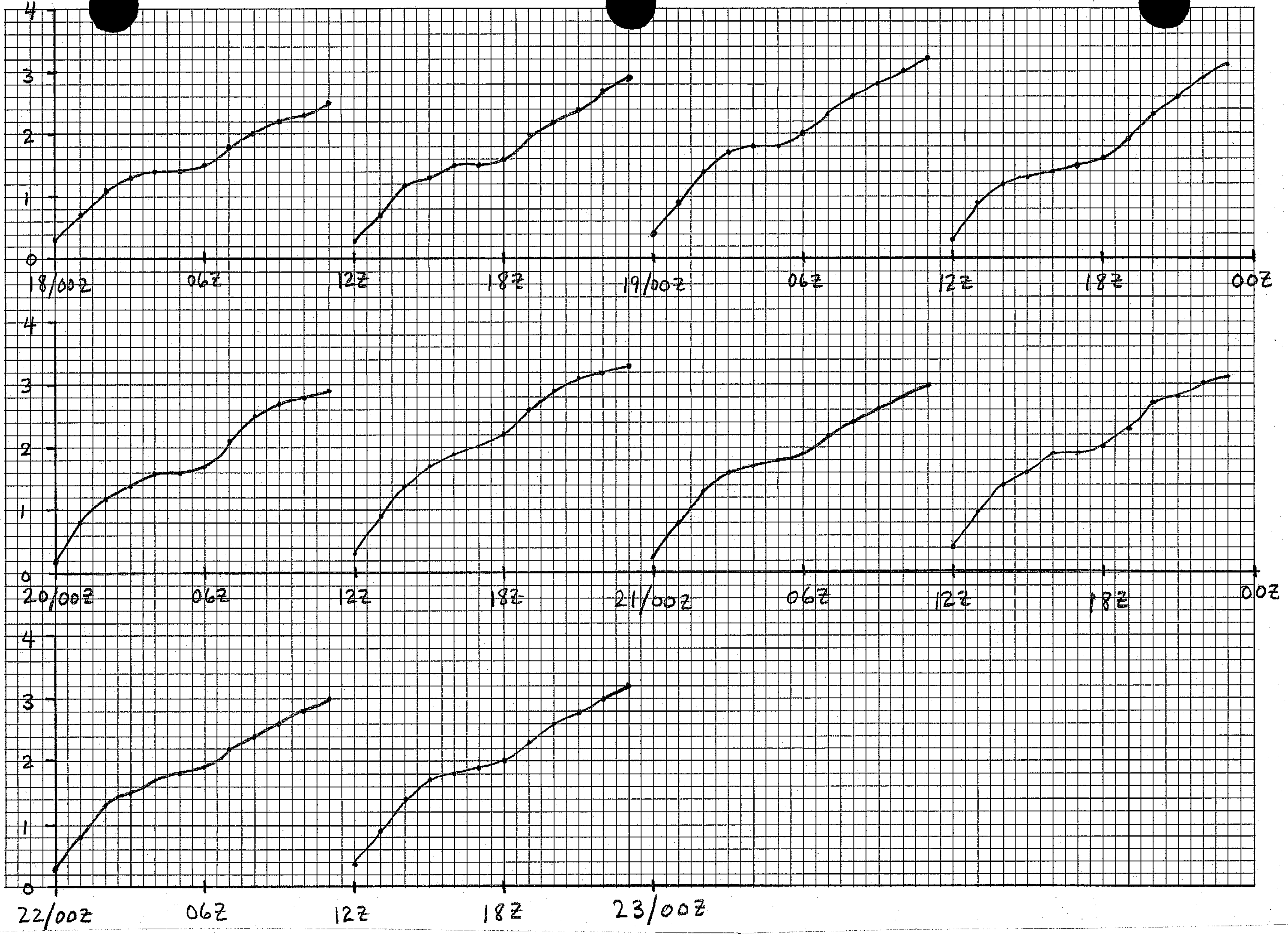

Figure 5b. Mean-square divergence ($\times 10^{-9}$ sec^{-2}), August 1975, 12-hour cycle.

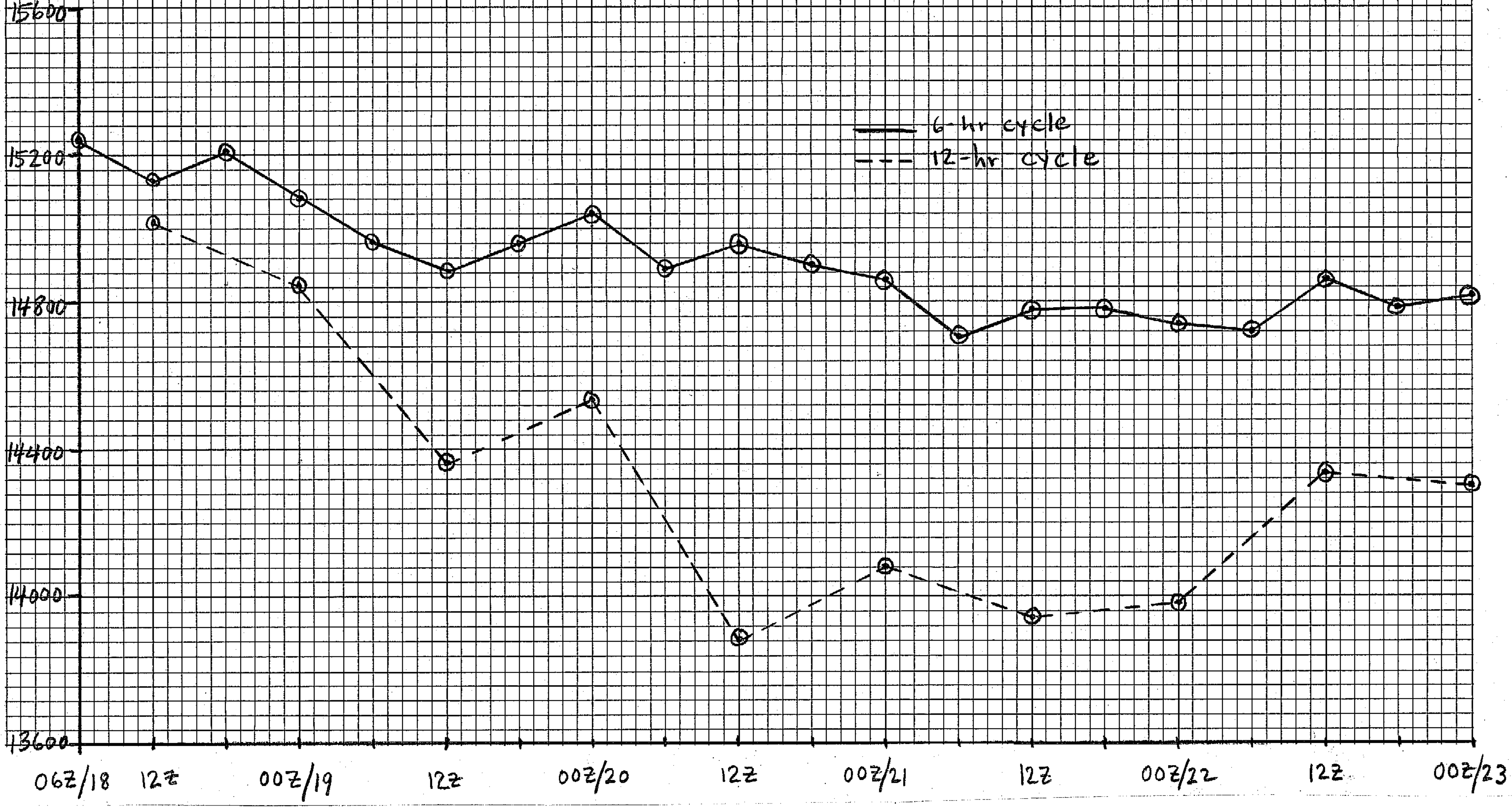

Figure 6a. 100 mb forecast heights (m) at south pole, August 1975.

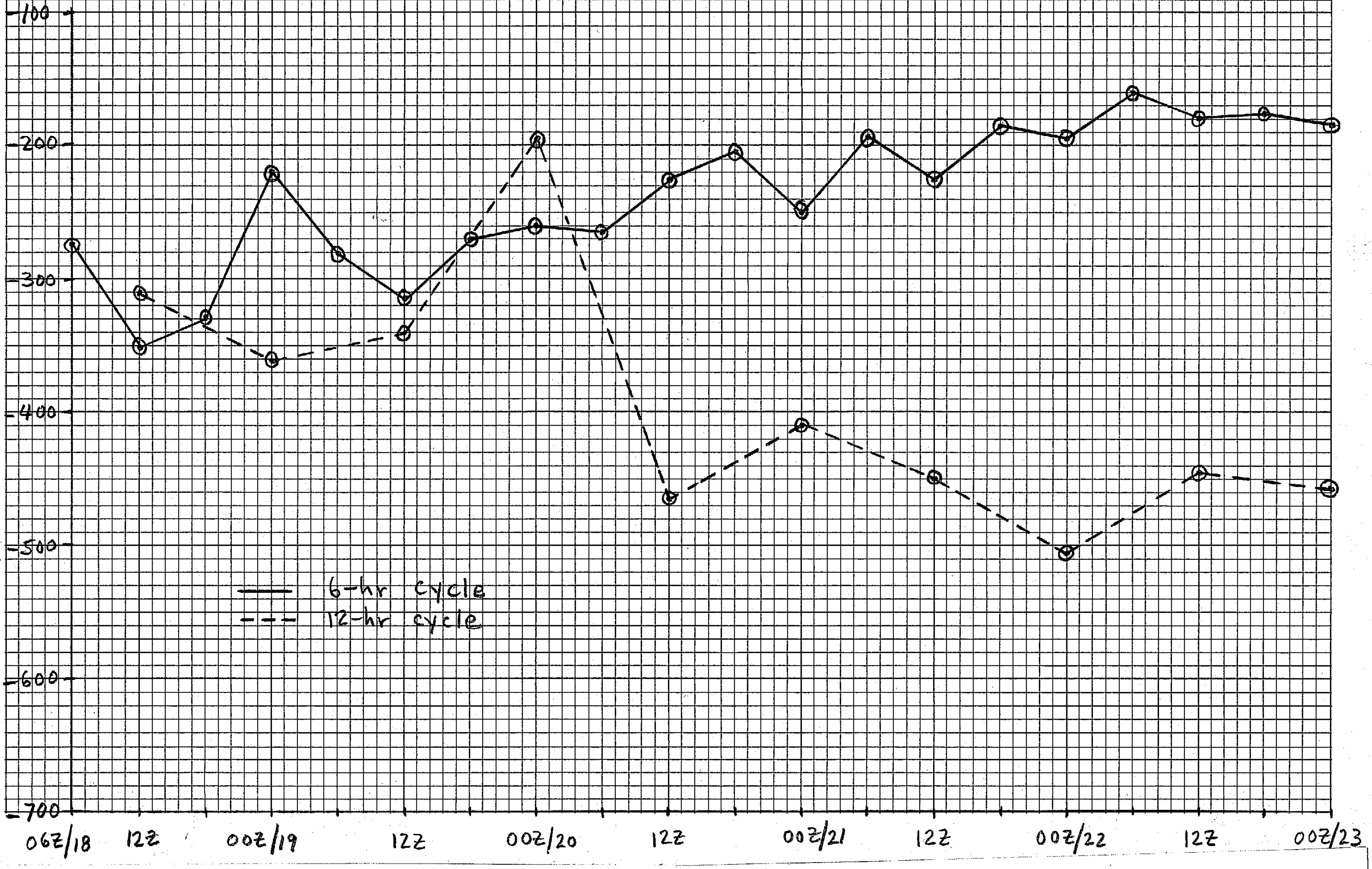

Figure 6b. 1000 mb forecast heights (m) at south pole, August 1975.