Hurricane Agnes – an event shaped by large-scale air-sea systems generated during antecedent months

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SUMMARY

An attempt is made to show that the life history of hurricane Agnes was determined by the antecedent slow evolution of the general circulation on a time scale of months. A self-aggravating complex of mid-tropospheric anomalies is described and quantified – this complex predisposing the eastern seaboard to the aberrant path assumed by Agnes and providing deep moisture-laden air masses from a very warm western Atlantic. The stable configuration of the centres of action is partly attributed to ocean-atmosphere interactions.

1. INTRODUCTION

Hurricane Agnes, June 1972, has been called one of the worst natural disasters and the costliest hurricane in United States history. Estimates of damage run close to $3.5 billion much of which was due to flooding. A preliminary description of the storm and its damage in various states appears in Mariners' Weather Log (1972).

In an earlier brief note (Namias 1973) the author presented some evidence to indicate that the immediate cause of hurricane Agnes may have been the transequatorial movement of a mesoscale cloud system (cloud cluster) from the abnormally warm waters off Peru into a vast area of convection generated by an uncommonly strong polar outbreak into the western Caribbean. These immediate causes are probably linked to antecedent events on the scale of the general circulation. It is the purpose of this paper to show that the general circulation over a large portion of the Northern Hemisphere systematically developed into a highly anomalous pattern during the three or four months preceding June, and that this pattern was to a large extent responsible for Agnes' strange path, her flood-producing rains and perhaps even her inception. Certain coupled large-scale aspects of the Atlantic sea-surface temperatures played an important role both in setting up and stabilizing the anomalous air circulation and in providing a moist source region for air masses entering into Agnes' circulation.

2. MONTHLY MEAN CIRCULATION PATTERNS ASSOCIATED WITH AGNES' LIFE HISTORY

The large-scale features of the global circulation often can be revealed by averaging processes designed to suppress, or average out, the fast-moving systems that characterize the synoptic charts. This is a standard technique in long-range forecasting, and the slow-moving, long-wave troughs found on averaged maps often reveal the pathways that the day-to-day storms follow. It should be emphasized, however, that this is a probabilistic rather than a deterministic approach. The long-term average situation preceding the formation and the unusual path followed by Agnes provides an example of the utility of this technique.

The history of Agnes as a hurricane is generally considered as beginning around 17 June in the area between Yucatan and Cuba. Her slow and erratic path appears on Fig. 1 which gives, in addition, the mean 700 mb contours for June. The highly anomalous features of this chart may be seen by comparing it to the normal June (Fig. 2), based on Junes for the 17 years 1947 – 64. Noteworthy in June 1972 were the large amplitude waves

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from North America eastward resulting in a strong trough over the eastern seaboard, a strong ridge over the central Atlantic and a strong trough over Great Britain. In addition, a remarkably strong zonal flow prevailed in northern latitudes of the North Atlantic. Some of these features have been described by Wagner (1972) and the Long Range Forecast Group of the British Meteorological Office (1972). In addition to visual comparison of Figs. 1 and 2, it is helpful to look at the field of standardized 700 mb height departures (Fig. 3). These were computed by dividing at each point the June 1972 deviations from normal by the appropriate standard deviations for many Junes. From Fig. 3 we see that in June 1972 eastern North America and the North Atlantic were dominated by several uncommonly intense height anomalies. The impact of these anomalies on some of the weather features of the month are described elsewhere (Wagner 1972; British Meteorological Office 1972). Here we will simply say that eastern United States and Great Britain were extremely wet and cool, northern latitudes of the North Atlantic were unusually stormy, but much of the central Atlantic was warm and dry. All these weather abnormalities
may be inferred qualitatively from the configuration and intensity of the height anomalies.

This June height pattern seems to have had its seeds sown much earlier—certainly as early as March and perhaps even February. In fact, the mean standardized anomaly chart constructed for the 30-day period ending 12 June (Fig. 4), before Agnes developed, showed much the same pattern as Fig. 3, seemingly extending an invitation for Agnes to pursue the strange track it did. Some of the major centres can be tracked back to March as indicated in Fig. 3.

The zonal winds at 700 mb over the North Atlantic are shown for both June and May in Fig. 5. Here we see the emergence of an exceptionally strong high latitude jet and the compensating lower latitude zone of weak westerlies in both months, with a slight northward shift (5° latitude) from May to June. Apparently the general circulation of May carried on through June.

To show that the June pattern was established much earlier, I have correlated June's pattern of standardized 700 mb height anomaly with the corresponding patterns for each antecedent month beginning with February. The correlations were computed using data

Figure 2. Normal 700 mb contours for June based on mean of Junes from 1947-63.
Figure 3. Isopleths of standardized values of 700 mb height deviations from normal for June 1972. Intervals are in units of 1 standard deviation; maxima and minima are labelled. Zero isopleth is heavy line. Arrows represent apparent monthly tracks of centres of anomalies with month and intensity indicated alongside heavy circles.

at points 10° longitude and 5° latitude apart in the area from 20° - 70°N and 0° westward to 120°W. Table I lists the correlations.

The lag correlations between March and also May with June are high, but those between February and also April with June, while positive, are not. This circumstance, where one month's pattern is a transitory forerunner of some future pattern is well recognized in long-range forecasting, although it is not well enough understood to be used as a reliable forecasting tool. The phenomenon may imply that some external forcing agent (such as abnormal boundary influence) causes a certain anomalous circulation pattern to emerge during one month, but this pattern may be partially demolished by internal atmospheric adjustments of a hydrodynamic nature during the following month. After such a period of perturbation, external forcing may once again bring the atmospheric circulation back to the original state. In a sense, this type of phenomenon takes place all the time with
synoptic-scale behaviour over periods ranging from days to weeks. In other words, there are often striking recurrences of particular synoptic systems during a month — at times even quasi-periodic (Namias 1966) — with apparently chaotic intervals between. Perhaps a month is too short a time interval to suppress these internal atmospheric adjustments, so that a season may be a more appropriate target for long-range forecasting based on sea and continent influences on the atmosphere (Namias 1964). In the present case there are some indications, as will be shown, that persistent anomalies of sea-surface temperature were the external forcing influences that helped form the March pattern and then reformed and strengthened it in May and June.

The standard deviations of the standardized values, which offer an indication of the overall intensity of the patterns are also revealing (Table 2). These values show a consistently upward trend beginning in February, rising by a factor of 2 by June. This upward trend implies that the anomalous features of the general circulation were reinforced with time — in other words, that an anomalous pattern was being amplified from February to June.
To show the influence of the February through May patterns on the June circulation, I have weighted the antecedent months, May, April, March and February by 4, 3, 2, 1 respectively. This is a ‘filter window’ that places more emphasis on the more recent past activity. Fig. 6 shows the weighted standardized anomalies for this four-month period. Comparing this with the chart for June (Fig. 3), the general agreement in pattern is obvious. The major features of positive and negative areas dominating the Atlantic and eastern North America are well indicated. Especially noteworthy is the suggestive negative channel over south-eastern United States into which Agnes moved, the strong blocking Bermuda High, the anomalously strong North Atlantic jet and the Great Britain negative cell.
The mean contours corresponding to the weighted standardized chart of Fig. 6 are given in Fig. 7. This 'forerunner' captures many of the important features of June 1972—particularly the eastern United States seaboard trough, the strong Atlantic ridge with the westerly jet to its north, and the Great Britain trough. It resembles June 1972 (Fig. 3) much more than the June normal (Fig. 2), a fact already indicated by the correlations of standardized anomalies shown in Table I.

3. Physical Factors Related to the Development and Stabilization of the General Circulation

The preceding discussion was essentially a description of events leading up to the highly anomalous general circulation which played a role in shaping the life history of
Agnes. The description poses a number of questions whose satisfactory answers will require many years of research. Among these are:

(i) What features of the general circulation were germane to the birth, path and precipitation of Agnes?

(ii) Why did the monthly anomalies build up to such extreme levels by June after a few months of development?

Some clues are suggested by considering: (1) large-scale air-sea interactions and (2) atmospheric teleconnections. We shall first discuss item (2) involving the more straightforward indicators of self-reinforcement of the anomalous June circulation pattern.

Maps of teleconnections published by James F. O'Connor (1969) currently offer the best means of determining the probable influence of one anomalous centre of action on others in the general circulation. O'Connor took a 17 year (1947–63) file of 5-day mean 700 mb anomalies, stratified by season and determined the probability of sign of anomaly for points of a 10° lattice when a positive (or negative) centre lay at one point (strictly speaking within one surrounding 10° square). An example of one of these maps is repro-
duced in Fig. 8 where the summertime response to a positive centre at 40°N 40°W is indicated by isopleths of probability. Hence with such a selected centre at 40°N 40°W negative anomalies of 700 mb height are highly likely (up to 86 per cent probable) over the south-eastern United States and over the Davis Strait (84 per cent probable). Stidd (1954) has shown that these isopleths may be interpreted as anomaly isopleths. Furthermore, experience has shown that the space scale of anomalies on 5-day means is much the same as on monthly mean maps (Klein 1962).

From Fig. 8 it is clear that a number of the anomalous features which appear on the observed charts in Figs. 3 and 4 are partially accounted for by the strong mid-Atlantic ridge (Bermuda High). If one inspects similar maps for key points taken at the sites of other centres (maps not reproduced) many of the same features arise, thereby indicating mutually reinforcing anomalies. In view of this fact I have averaged the probabilities for the vigorous centres which appear on the mid-May to mid-June chart shown in Fig. 4, purposely omit-

Figure 8. Isopleths of probability of sign of 700 mb anomalies when positive anomaly centre lies within 10° square centred at 40°N 40°W.
ting the big 4.5σ centre over Florida. The omission was made to see what height anomaly pattern would show up in the Agnes domain as a response to the five remote centres indicated in Fig. 9. The implication is that the entire eastern seaboard would be vulnerable to a tropical storm should it appear in the east Gulf while the major centres were placed as they were in mid-May to mid-June. The interaction of the centres also does not destroy the general pattern of the anomalous features of the general circulation - a pattern quite similar to that observed in June or mid-May to mid-June (Figs. 3 and 4).

From the above information it seems likely that the large-scale systems (the centres of action) of the general circulation during spring and early summer of 1972 were compatibly placed, and that each quasi-permanent centre assisted the development of other described centres. This tells us little about the cause of the most dominant centres - their mode of development and especially their tendency to remain stable and to amplify as June approached. Perhaps this behaviour was associated with some dramatic, large-scale, air-sea interactions over the North Atlantic, a subject now to be discussed.

With atmospheric circulation anomalies as strong as those described for the months February to June, whose cumulative effect is shown by the weighted mean in Fig. 6, one

Figure 9. Isopleths of probability of sign of 700 mb anomalies when the means of teleconnections from the five circled areas are averaged (see text for details).
would expect to find an anomalous distribution of sea surface temperature (SST). Qualitative specification of the SST pattern generated by the anomalous features of Fig. 6 indicates that air-sea heat exchange and oceanic advection led to colder than normal water in northerly latitudes of the North Atlantic, warmer than normal surface waters in mid-Atlantic, and especially warmer than normal water off the eastern seaboard of the United States. The northern latitude cooling was associated with greater than normal transport of Arctic air, higher than normal wind speeds, and cold water (Ekman) transport. The warmer waters were associated with advection of more warm and moist air and with increased Ekman transport from the south. There were, in addition, two other factors operating to produce the same result. These factors were (i) the presence of a great number of icebergs which broke off from the Davis Strait in spring (reportedly more icebergs in North Atlantic waters than any year since 1912, when the Titanic sunk), and (ii) the mild winter of 1971–72, associated with few outbreaks of polar air into eastern United States, which led to anomalously warm water with deviations up to 3–3.5°C off the Atlantic seaboard. By June these factors and the abnormal circulations described developed the SST anomaly pattern shown in Fig. 10 and the average zonal SST anomaly profile shown in Fig. 11. The meridional gradient between latitudes 40°–55°N averaged 2–1°C stronger than normal.

While these SST gradients were largely generated by abnormal atmospheric systems, it is probable that they fed back and influenced atmospheric activity. They may do this by strengthening the meridional baroclinicity of the air and thereby encourage the rapid formation, movement and development of synoptic wave systems, so prominent during spring 1972. This situation led to a cold wet spring in Great Britain (British Meteorological Office 1972, Perry 1972). The net effect would also be to strengthen the high latitude westerlies, ultimately resulting in the pronounced jet shown in Fig. 5. Once such a jet is formed, its strong lateral shear can lead to horizontal (isentropic) mixing, thereby producing transverse supergradient flow to the south of the jet and helping to strengthen the Atlantic anticyclone on its right flank. This concept in which the pressure field adjusts to the wind field was first pointed out by Rossby (1937, 1938). We thus offer the hypothesis that the disturbed thermal character of the upper layer of the sea associated with events from the antecedent winter and spring, conditioned the general circulation in June in such a way as to provide zones disposed to cyclone generation and movement and likewise zones favouring anticyclones. Hurricane Agnes fell into one of the former zones and was steered meridionally rather than zonally by the strong Bermuda High. At the same time the air masses feeding into Agnes arrived after pursuing a trajectory over anomalously warm western Atlantic waters (Fig. 10). By the time these moist air masses in advance of the storm reached Hatteras, the dew points at 1200 GMT on 21 June reached 24°C. The excessive rains with Agnes appear to have been augmented by the steady influx of this very moist air, much like the situation of Connie and Diane in August 1955 (Namias and Dunn 1955). However, some of the ascending air motion was produced by an extratropical depression which merged with Agnes. Furthermore, some of the moisture may have been contributed by the very wet eastern seaboard -- rendered wet by heavy spring rains.

But was the formation of Agnes unrelated to the large-scale and long-term events we have described? The immediate causes of Agnes, as suggested by the author (Namias 1973) were (i) a favourable large-scale environment in the Gulf of Mexico and western Caribbean consisting of a large area of disturbed convective cloud generated by an unusually far-south penetrating cold front and (ii) a 'nucleating' cloud cluster which generated over the warm waters of an El Niño off Peru and then moved northward across the Isthmus of Panama into the large disturbed area. One of these presumably prerequisite phenomena, the strong Arctic front, was set in motion by the amplification of a long wave trough and ridge respectively in the eastern Pacific and Canada. It appears unlikely that this front would drive so far south in June as it did (to Yucatan and Cuba) were it not for the weakness over the south-eastern United States (see Figs. 1 and 3). While our present state of knowledge does not permit an inference as to the probability of the development and
Figure 10. Sea surface temperature departures from normal for 1-26 June 1972 (from Fleet Numerical Weather Central, Monterey, California).

Figure 11. Sea surface temperature anomaly profile for June 1972 for North Atlantic (10°-60°W). Computed from Fig. 10.
northward movement of the cloud cluster from the El Niño area, it seems quite certain that events in the Northern Hemisphere are important in the development of the El Niño—a convective cloud producer (Bjerknes 1966). To sum up we speculate that the birth, path and other aspects of the life history of Agnes were contingent on the large-scale long-term evolution of the general circulation.

4. Conclusions

The general circulation prior to the development of Hurricane Agnes had developed into a highly anomalous pattern from Europe westward to North America—the period of development extending over at least three or four months. The character of the abnormality was strongly reflected in mid-tropospheric height patterns and was highlighted by employing standardized anomalies of 700 mb height. Four or five unusually intense centres of action including the east United States coast trough, the mid-Atlantic ridge, the Davis Strait trough, and the Great Britain trough reinforced one another over a four month period and succeeded in providing a vulnerable area (the eastern seaboard) for hurricane Agnes.

The amplification of the system may have been related to strong large-scale air-sea coupling wherein a strong meridional sea surface temperature gradient in the North Atlantic, first developed by heat exchanges and oceanic advection caused by atmospheric systems, fed back to influence the atmosphere. The result was an extremely fast jet at higher latitudes. Lateral mixing south of the jet may have been influential in strengthening the Atlantic high which, by blocking and long wave responses, may have helped sustain strong troughs over eastern United States and Great Britain. Of course, baroclinic development in these troughs would also strengthen the intervening Atlantic anticyclone.

The exceptionally heavy precipitation was partly attributed to the great supply of moisture fed into the storm and a merged extratropical disturbance. Some of this moisture came from the abnormally warm western Atlantic—rendered warm by the mild antecedent winter and the subsequent air and water circulations.

Finally, the stage for Agnes' birth might have been set by the slow-evolving general circulation and its attendant synoptic-scale features such as the preceding massive Arctic outbreak and the development of the El Niño off Peru.

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