Numerical Prediction of the Onset of Blocking: A Case Study with Forecast Ensembles

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(Manuscript received 21 January 1997, in final form 20 June 1997)

ABSTRACT

The forecastability of a blocking episode during January 1985 over Europe and the eastern Atlantic Ocean is studied with forecast ensembles. Ten-member ensembles from version CCM2 (at T42 resolution) of the Community Climate Model of the National Center for Atmospheric Research are initialized at various lead times prior to the analyzed block onset and run out to 14 days. Particular attention is focused on the ensemble initialized five days prior to block onset since, of all the ensembles, this one was characterized by the greatest variability concerning the block-onset prediction. Two of the 10 members of this particular ensemble predicted a transition from unblocked to blocked flow over the Atlantic–Europe half of the Northern Hemisphere during the 14-day forecast range, but not without error; details regarding the timing and/or location of the block were misforecast. A comparison of these ensemble members, plus one other that did not predict a transition to blocking, with the corresponding analyses revealed that the block forecast errors could be traced to a model failure to predict the anomalously weakened midtropospheric planetary-scale geostrophic westerlies analyzed upstream of and prior to the block onset. The forecast error appeared to be attributable to a model bias toward an erroneously southward displacement of the midtropospheric zonal jet over Europe and the eastern Atlantic Ocean. On the other hand, the interaction between the planetary-scale flow and synoptic-scale activity, as measured by the midtropospheric advection of synoptic-scale quasigeostrophic potential vorticity by the planetary-scale geostrophic wind, was well predicted by the ensemble members, but perhaps fortuitously. The results demonstrate that the forecast ensemble was able to overcome the influence of the systematic error by indicating the possibility of a transition to blocked flow over the domain and within the forecast range.

1. Introduction

Extending the range at which the transition to blocking flow regimes in the atmosphere can be accurately forecast remains a challenging problem in numerical weather prediction. For example, while Tibaldi et al. (1995) note a recent improvement with which blocks are predicted at medium range (3–10 days in advance) by the operational model of the European Centre for Medium-Range Weather Forecasts, the model still underpredicts the frequency of blocking. This in turn contributes to the medium-range forecasts' systematic error which may limit the accuracy of extended-range forecasts (beyond 10 days in advance).

The relative importance of initial data uncertainty versus model error in determining the accuracy of a forecast initialized within range of a block onset is unclear. Numerical prediction experiments have shown that this accuracy is sensitive to model systematic error (Miyakoda and Sirutis 1990; Anderson 1993) and resolution (Tracton 1990), while Brankovic et al. (1990) have noted that a forecast ensemble member can predict the transition to blocking even if the ensemble mean forecast is poor due to model systematic error. It appears likely, therefore, that both initial data uncertainty (as assessed by the dispersion of an ensemble about a control forecast) and model systematic error (as measured by the difference between the control or ensemble mean forecast and the verifying analysis, averaged over many forecasts) may be contributing to a model's failure to predict the onset of blocking.

Tracton (1990) has noted that planetary-scale features were more accurately predicted at short range than were subplanetary-scale features prior to the onset of a blocking case studied. Furthermore, Colucci and Alberta (1996) have identified potential planetary-scale precursors to block onset. Specifically, most of the blocking cases they studied were preceded upstream by anomalously weak westerlies and anomalously strong southerlies in the planetary-scale 500-mb geostrophic wind field. It is possible, therefore, that these antecedent planetary-scale signatures may be accurately predicted even if the subsequent transition to blocking is not.

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It is well known that intense synoptic-scale activity often locally precedes block onset; indeed, Colucci and Alberta (1996) find evidence for such activity no earlier than five days prior to each of the blocking cases studied. One would not necessarily expect this activity to be well predicted by numerical forecast models, although Mullen and Baumhefner (1994) have shown that ensembles in even a low-resolution model are capable of simulating explosive, synoptic-scale cyclone events. We therefore hypothesize that at least one member of a low-resolution forecast ensemble initialized prior to (e.g., five days before) block onset should be able to predict the coincidence of synoptic- and planetary-scale antecedent conditions for, and the subsequent transition to, blocking. This hypothesis motivates the current study.

In the work reported here, we have initialized forecast ensembles at different lead times preceding the onset of an analyzed blocking episode in January 1985, using the CCM2 version of the Community Climate Model (CCM) of the National Center for Atmospheric Research (NCAR). Particular attention was focused upon the ensemble initialized five days prior to block onset, since this ensemble was characterized by the greatest variability concerning the block prediction. The behavior of each ensemble member was investigated, with emphasis on the manner in which planetary- and synoptic-scale features were predicted prior to block onset. Thus, in Branstator's (1986) terminology, we are studying the forecastability of these features by the ensemble members.

The conclusions that we reach are only valid, of course, for the case chosen and the model employed in this study and should therefore be interpreted with caution. Nevertheless our findings encourage us by suggesting that potentially useful information about the possibility of transitions to blocked flow may be obtained from forecast ensembles despite model error and relatively low model resolution.

2. The blocking case study

The case selected for the numerical forecast experiments occurred during January 1985 and is Atlantic case 8 in the Colucci and Alberta (1996) catalog of blocking episodes during the 1980–81 through 1986–87 winter seasons. Synoptic details and a quasigeostrophic diagnosis of this event have been presented by Alberta et al. (1991); a brief overview will be given here.

The evolution of this blocking episode in 500-mb height analyses is illustrated in Fig. 1. These analyses were constructed from 500-mb heights on an approximately 2.8° × 2.8° latitude–longitude Gaussian grid (T42 resolution) accessed from the World Meteorological Organization archive of the European Centre for Medium-Range Weather Forecasts (ECMWF). The analyses show that a ridge over the eastern Atlantic Ocean on 1 January (Fig. 1a) evolved into a blockinglike system by 7 January (Fig. 1b), with a 500-mb anticyclone near Iceland. However, this system did not persist in the analyses and disappeared by 10 January (Fig. 1c). The blocklike system was reestablished on 12 January (Fig. 1d) and reached peak intensity on 14 January (Fig. 1e); note in Fig. 1e the 500-mb anticyclone over Scandinavia and 500-mb cyclone over France.

Colucci and Alberta (1996) objectively defined blocking by the persistence, for at least five consecutive days, of negative zonal index spanning at least 20 consecutive degrees of longitude. The zonal index along a longitude is the 500-mb height at 40°N minus that at 60°N such that a negative zonal index corresponds to higher 500-mb heights at 60°N than at 40°N, or geostrophic easterlies at 500 mb between 40°N and 60°N. A sector of the Northern Hemisphere, either Atlantic (90°W eastward through 90°E) or Pacific (elsewhere), is said to be blocked when the blocking definition is satisfied somewhere in that sector; otherwise, the flow over that sector is said to be unblocked. The block onset date is identified as the first day that the objective definition of blocking is satisfied over a sector. By this definition, the Atlantic sector was found to be blocked from 0000 UTC 12 January through 0000 UTC 18 January 1985. Henceforth, 12 January 1985 will be regarded as the onset date for this blocking episode. The westernmost longitude (approximately 11°W) of the negative zonal index region associated with the blocking system on the block onset date will be referred to as the block location, following Colucci and Alberta (1996). Both Atlantic and Pacific sectors were otherwise unblocked during January 1985.

3. The ensemble forecast experiments

The numerical model used in the ensemble forecast experiments was the CCM2 version of the NCAR CCM. The CCM2 is a global spectral model with 18 vertical levels, T42 horizontal resolution, and sea surface temperatures interpolated from observed montly means. For a complete description of the model the reader is referred to Hack et al. (1993) and references therein.

The forecast ensembles each consisted of a control run, initialized with analyses from the National Centers for Environmental Prediction (NCEP), and nine perturbation runs constructed following the method of Mullen and Baumhefner (1994). The perturbations are designed to simulate the amplitude and spectral characteristics of differences between NCEP and ECMWF analyses. The model's nonlinear normal-mode initialization procedure, required because the perturbations are unbalanced, reduces the magnitude of the perturbations. Furthermore, the perturbation fields are not spatially correlated, nor is one ensemble member's perturbation field correlated with that of another ensemble member for the same initial time. This ''Monte Carlo'' procedure differs from the application of ''dynamically constrained'' perturbations such as in the breeding technique of Toth and Kalnay (1993). However, work in progress (not shown) indicates that the two techniques for constructing perturbations (Monte Carlo and breeding) yield similar dispersions of the ensemble members about the ensemble mean as a function of lead time. Our study of the forecastability of blocking with ensembles constructed with the Monte Carlo technique is therefore justified.

The initial dates for the 10-member forecast ensembles were 1, 4, 7, and 11 January 1985, or 11, 8, 5, and 1 day(s), respectively, prior to the onset of the blocking event being studied. The forecasts were each run out to 14 days in advance. The forecasts, initialized with NCEP analyses, are verified with ECMWF analyses. While this may seem inconsistent, the NCEP–ECMWF analysis differences are random and do not affect the verification of the large-scale phenomenon (blocking) studied here.

4. Verification of the forecast ensembles

The 500-mb height forecasts produced by each ensemble member at each initial time were searched for evidence that the flow over either the Atlantic or Pacific sectors was forecast to be blocked according to the objective definition described in section 2. Since the forecasts were at 14-day ranges, then it would be impossible for a perfectly accurate forecast initialized on 1 January to satisfy the objective defintion of blocking; the forecast range would have included only the first four days of the analyzed blocking episode. The blocking definition was therefore relaxed so as to require persistence of the negative zonal index for at least four days in the forecasts initialized on 1 January; this permits an evaluation of the ability of these forecasts to predict blocked flow at the end of their forecast range.

The verification of the forecasts of blocking by each ensemble member at each initial time is presented in Table 1. Most ensemble members initialized on 1 January did not predict a transition to blocking during the 14-day forecast range, even with the relaxed persistence criterion for blocking. One ensemble member (number 6) initialized on 1 January incorrectly persisted the Atlantic blocklike system analyzed around 7 January (see Fig. 1b); this predicted block coincided on two days with the analyzed block, such that this particular ensemble member correctly predicted that there would be blocked flow over the Atlantic sector on 12 and 13 January.

Most ensemble members initialized on 4 January incorrectly persisted the blocklike system analyzed over the Atlantic at the initial time (not shown). None of these predicted blocks, however, coincided with the analyzed block.

Two of the 10 ensemble members initialized on 7 January predicted a transition to blocking over the Atlantic sector during the 14-day forecast range. One of these (number 1) correctly predicted the block onset date, while the other (number 10) delayed the block onset by two days relative to the analysis. Inspection of the 500-mb height fields (Fig. 2) predicted by these ensemble members on the day of each respective forecast block onset reveals that each forecast a blocklike system considerably east of the analyzed block position; compare Fig. 2a to Fig. 1d and Fig. 2b to Fig. 1e. The forecast block locations, as defined previously, were at 39° and 36°E for ensemble members 1 and 10, respectively, as opposed to the analyzed location at 11°W. Objectively, these two forecast ensemble members correctly predicted that the Atlantic sector would become blocked during the forecast range, although one member erred in the timing of block onset. From a synoptic perspective, however, both ensemble members mislocated the blocking feature, appearing to develop a ridge into a block over Asia while weakening the Atlantic ridge which evolved into the analyzed block.

Finally, each member of the ensemble initialized on 11 January correctly predicted the onset of blocking one day later. Half of these correctly predicted the block termination date (18 January) with the remainder either dissipating the block one day prematurely (17 January) or one day late (19 January). Each forecast ensemble member also predicted the location of the block within 10 longitude degrees of that analyzed (not shown).

It is clear from Table 1 that as the lead time decreased the accuracy of the ensemble forecasts of the 12–18 January blocking event increased. Specifically, the number of ensemble members predicting that the flow over the Atlantic–Europe region would be blocked on 14 January (the peak of this episode) increased from 0 from the 1 and 4 January initial dates to 2 from 7 January and all ten from 11 January. Attention will be henceforth focused upon the ensemble initialized on 7 January since this one was characterized by the greatest variability concerning the block onset prediction.

Forecast and analyzed circulation features prior to the forecast and analyzed block onsets were inspected for insight into the behaviors of the forecast ensembles. One day prior to the analyzed block onset, the region west of the incipient block (i.e., over the central Atlantic Ocean) was characterized, in the analyzed 500-mb planetary-scale geostrophic wind anomalies (Fig. 3), by weaker than normal westerlies ($u' < 0$) and greater than normal southerlies ($v' > 0$). These anomalies have been calculated from subtraction of the 1979–88 January mean planetary-scale 500-mb height field from the planetary-scale analyses. The climatological and analyzed planetary-scale fields in turn have been constructed through spectral filtering of these fields so as to retain total and zonal wavenumbers 0–7, following Colucci and Alberta (1996).

As mentioned earlier, each of the blocking cases studied by Colucci and Alberta (1996) was preceded by locally intense or explosively developing sea level cyclones. Sanders (1986) has shown that explosive sea level cyclones are typically characterized by large values of midtropospheric cyclonic absolute vorticity advection. This suggests that 500-mb cyclonic absolute

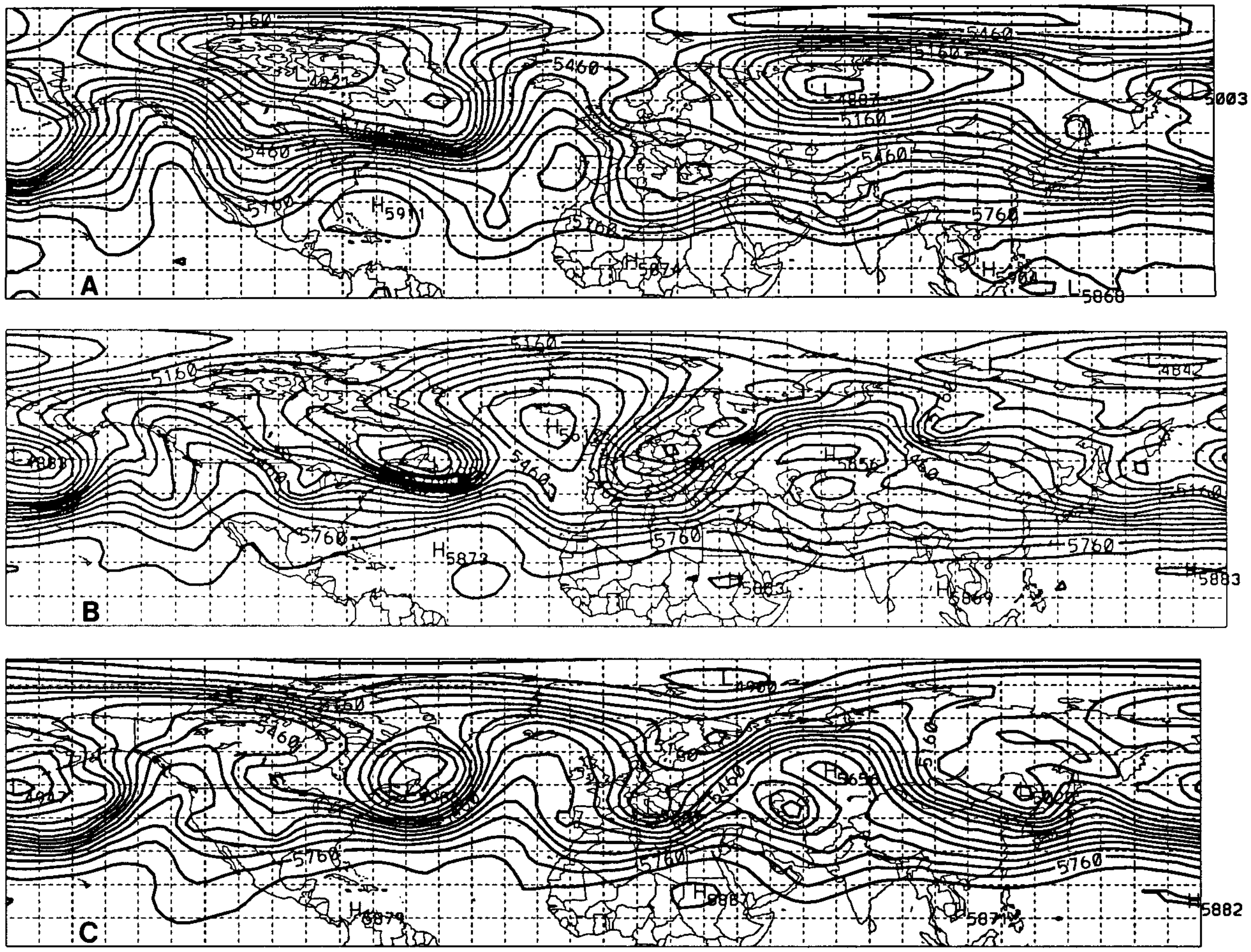

FIG. 1. Analyzed 500-mb heights (contour interval: 60 m) at 0000 UTC (a) 1, (b) 7, (c) 10, (d) 12, and (e) 14 January 1985. Dashed lines are latitude and longitude at 10° intervals beginning with 180° longitude on the west and 0° latitude on the south.

vorticity advection exceeding a suitably chosen threshold may be a signature of an intense or explosive sea level cyclone. Furthermore, the advection of absolute vorticity is dynamically linked to the evolution of the geopotential height fields through the quasigeostrophic height tendency equation (Holton 1992).

More completely linked to geopotential height field evolution than the absolute vorticity advection is the advection of potential vorticity, which includes the fluid mechanical effect of vorticity advection as well as the thermal influence of temperature advection. Qualitatively approximating the 500-mb potential vorticity advection while providing a measure of the interaction between the planetary-scale flow and synoptic-scale processes is the advection of synoptic-scale quasigeostrophic potential vorticity (SQPV) by the planetary-scale 500-mb geostrophic wind. We therefore chose to calculate this quantity as a means of representing the synoptic-to-planetary-scale interaction that might be associated with intense sea level cyclogenesis.

Calculation of SQPV follows the procedure of Colucci and Baumhefner (1992) except that here the static stability is not constant but a function of pressure, and synoptic-scale fields are the total minus planetary-scale fields or waves 8–42. This potential vorticity is calculated from either ECMWF analyses or CCM2 predictions of geopotential height and temperature fields at the 1000-, 850-, 700-, 500-, 300-, 200-, and 100-mb pressure levels.

The analyzed advection of SQPV by the planetary-scale 500-mb geostrophic wind one day prior to the analyzed block onset is presented in Fig. 4. A maximum in the cyclonic potential vorticity advection is located between Greenland and Iceland, or near the center (972 mb) of an intense cyclone in the sea level pressure analyses and west of the incipient block location. The incipient block-onset region is in turn characterized by anticyclonic potential vorticity advection, which would quasigeostrophically favor geopotential height rises in the anticyclonic portion of the developing block.

To facilitate the interpretation of the antecedent planetary- and synoptic-scale fields, it is convenient to present them as area-averaged quantities between 40° and 60°N (the latitudes over which the zonal index is cal-

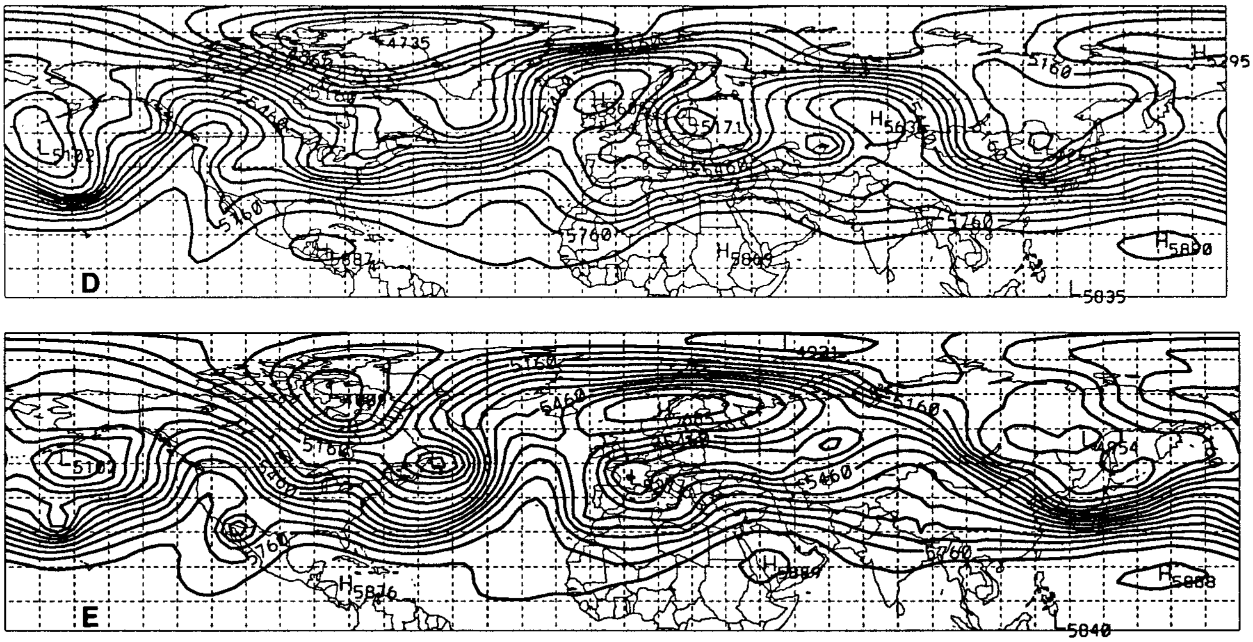

FIG. 1. *(Continued)*

culated). When viewed this way (Fig. 5), it is seen that the region west of the incipient block one day prior to block onset is the only location in the Northern Hemisphere between 40° and 60°N distinguished in the 500-mb analyses by a coincidence of area-averaged $u' < 0$, $v' > 0$ and cyclonic potential vorticity advection exceeding 10^{-9} s^{-2}. There are three other regions where both area-averaged $u' < 0$ and $v' > 0$ coincide, as suggested by Fig. 3, but only one region with large values of area-averaged cyclonic potential vorticity advection (i.e., exceeding 10^{-9} s^{-2}). We may therefore regard the coincidence of these three area-averaged features as the antecedent, upstream condition for block onset in this case. Interpreting large, cyclonic potential vorticity advection at 500 mb as a signature of intense sea level cyclone activity, this antecedent condition is consistent with the necessary conditions for block onset in many of Colucci and Alberta's (1996) cases.

By comparison, a similar display (Fig. 6) constructed for the day 4 forecast from ensemble member 1 initialized on 7 January 1985 and verifying one day prior to the analyzed block onset reveals that a coincidence among the three abovementioned features is predicted well east of the analyzed block onset region and near the location of the forecast block. This forecast ensemble member is missing the coinciding area-averaged $u' < 0$, $v' > 0$ region found in the verifying analysis over the central Atlantic, although the other three analyzed regions of coincident area-averaged $u' < 0$ and $v' > 0$ are well predicted (compare Figs. 5a and 6a). On the other hand, this ensemble member predicts two regions of large area-averaged cyclonic potential vorticity ad-

TABLE 1. Verification of the ensemble forecasts, at four different initial times, for the analyzed block on 12–18 January 1985. A ''yes'' entry for an ensemble member and initial date indicates that this member of the ensemble initialized on that date predicted blocking during the 14-day forecast range over the Atlantic–Europe half of the Northern Hemisphere; the dates that follow are the duration of the predicted block. A ''no'' entry indicates that blocking was not predicted.

Ensemble member	1 January 1985	4 January 1985	7 January 1985	11 January 1985
1	No	No	Yes: 12–16 Jan	Yes: 12–18 Jan
2	No	Yes: 4–8 Jan	No	Yes: 12–17 Jan
3	No	Yes: 4–8 Jan	No	Yes: 12–19 Jan
4	No	Yes: 4–8 Jan	No	Yes: 12–18 Jan
5	No	Yes: 4–8 Jan	No	Yes: 12–19 Jan
6	Yes: 6–13 Jan	Yes: 4–8 Jan	No	Yes: 12–18 Jan
7	No	No	No	Yes: 12–18 Jan
8	No	No	No	Yes: 12–18 Jan
9	No	Yes: 4–8 Jan	No	Yes: 12–17 Jan
10	No	Yes: 4–8 Jan	Yes: 14–18 Jan	Yes: 12–17 Jan

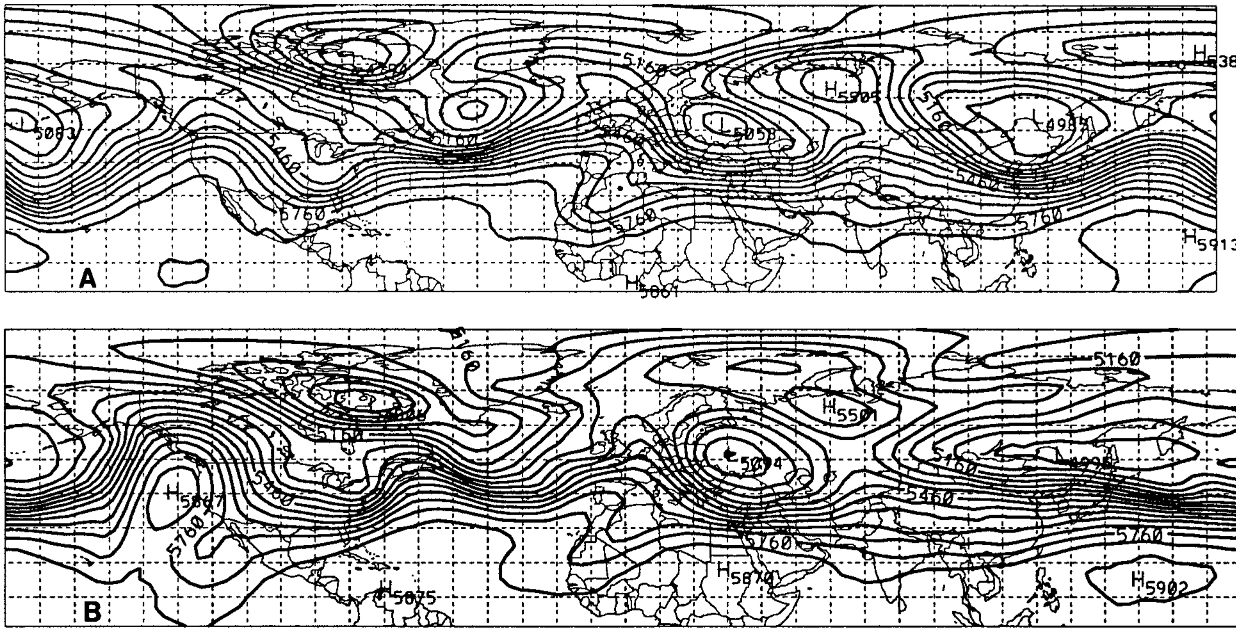

FIG. 2. Forecast 500-mb heights (contour interval: 60 m) at (a) 0000 UTC 12 January 1985 from ensemble member 1 and (b) 0000 UTC 14 January 1985 from ensemble member 10, both intialized at 0000 UTC 7 January 1985. Latitude and longitude are as in Fig. 1.

vection: one over the eastern Atlantic, near its corresponding analyzed position, and another near the forecast block onset region and with no counterpart in the verifying analysis. This ensemble member had no difficulty, therefore, predicting the synoptic-to-planetary-scale interaction (as measured by cyclonic potential vorticity advection) and, in fact, overpredicted the number of locations with large, area-averaged values of this advection. However, it missed a key region of analyzed, area-averaged $u' < 0$ and $v' > 0$. This error was due to its prediction of greater, rather than weaker, than normal planetary-scale 500-mb geostrophic westerlies over the Atlantic Ocean (not shown).

Similarly, the day 4 prediction (Fig. 7) by ensemble member 10, initialized on 7 January and verifying 11 January, is missing the coincident $u' < 0$, $v' > 0$ region over the eastern Atlantic where a region of large, area-averaged cyclonic potential vorticity advection is predicted; a coincidence of these three features is found instead farther east where block onset is predicted by this ensemble member on day 7. An ensemble member (number 6) that did not predict the transition to blocking fails to overlap the three antecedent conditions anywhere (Fig. 8) and is missing the coincident $u' < 0$, $v' > 0$ regions over both the eastern Atlantic and central Asia. Large, area-averaged cyclonic potential vorticity advection is predicted over both these regions, however.

The apparently successful prediction, by a few of the ensemble members, of the interaction between the synoptic- and planetary-scale fields prior to blocking seems inconsistent with the inaccurate prediction of the planetary-scale wind fields. Closer inspection of the forecasts from ensemble member 10 reveals that the west-to-east gradient of SQPV at 500 mb was underpredicted in magnitude upstream of and one day prior to the analyzed block onset (not shown). This, coupled with an overpredicted westerly planetary-scale geostrophic wind, fortuitously yielded an accurate prediction of the planetary-scale advection of SQPV. This ensemble member correctly predicted the location and magnitude of a SQPV maximum at 500 mb near the analyzed sea level cyclone center, but underforecast the SQPV minimum analyzed east of the cyclone (not shown).

5. Initial data uncertainty versus model error

The results presented in the preceding section have indicated that the failure by ensemble members to predict the correct timing and location of block onset was associated with the absence from each of these forecasts of an apparently necessary region of anomalously weak midtropospheric, planetary-scale westerlies upstream of the incipient block location. We turn our attention now to the issue of whether the planetary westerly wind error was random in nature (i.e., reflecting variability within the ensemble) or due to a model bias toward erroneously strong midtropospheric, planetary-scale westerlies over the region in question (eastern Atlantic Ocean). As an illustration, we will focus upon day 4 of the ensemble forecast initialized on 7 January 1985 and verifying one day prior to the analyzed block onset.

Following Brankovic et al. (1990), we partition the ensemble-mean squared forecast error into the squared bias of the ensemble-mean forecast (henceforth mean

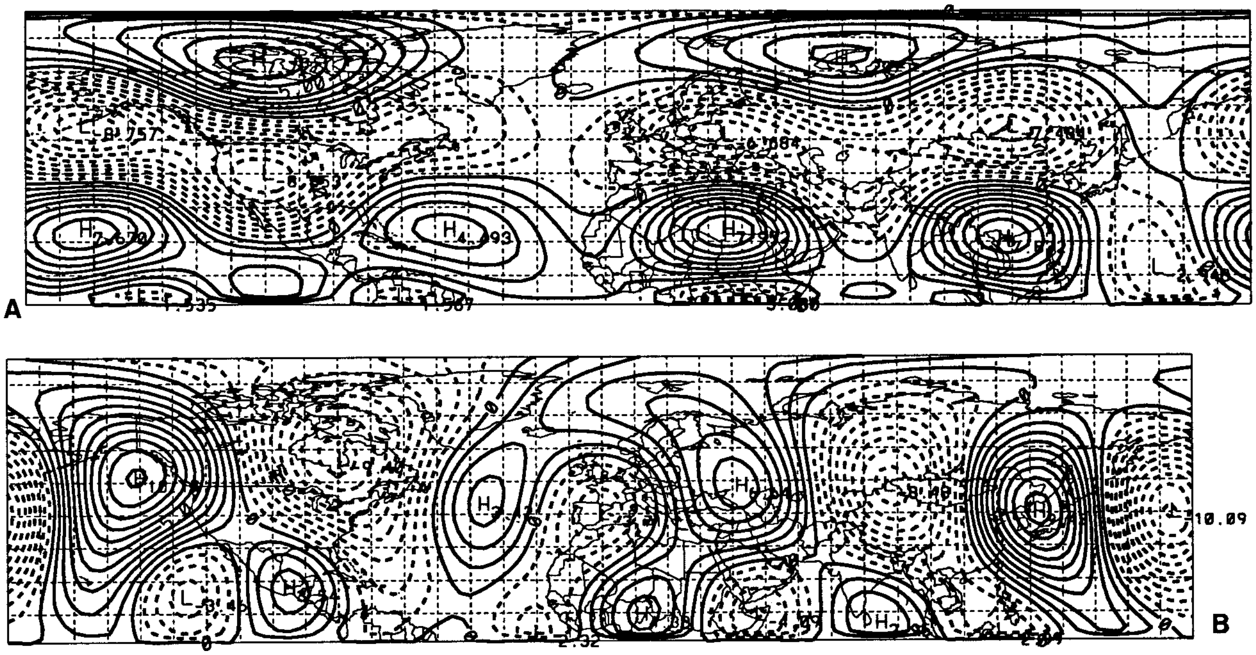

FIG. 3. Planetary-scale, 500-mb geostrophic (a) u and (b) v anomalies (analysis minus climatology; contour interval: 1 m s^{-1}) at 0000 UTC 11 January 1985. Solid contours are positive; dashed contours are negative. Latitude and longitude are as in Figs. 1 and 2.

squared bias) and the ensemble-mean squared dispersion of the ensemble members about the ensemble-mean forecast (henceforth mean squared random error). The mean squared bias of the 4-day forecast u component of the 500-mb planetary-scale geostrophic wind, initialized on 7 January 1985, is presented in Fig. 9a. Near the area of interest, maxima are noted over southeastern Europe and north of Scandinavia. The corresponding mean squared random error (Fig. 9b) is a maximum very near the block onset location over the eastern Atlantic Ocean, although it is almost an order of magnitude smaller than the mean squared bias over the same region.

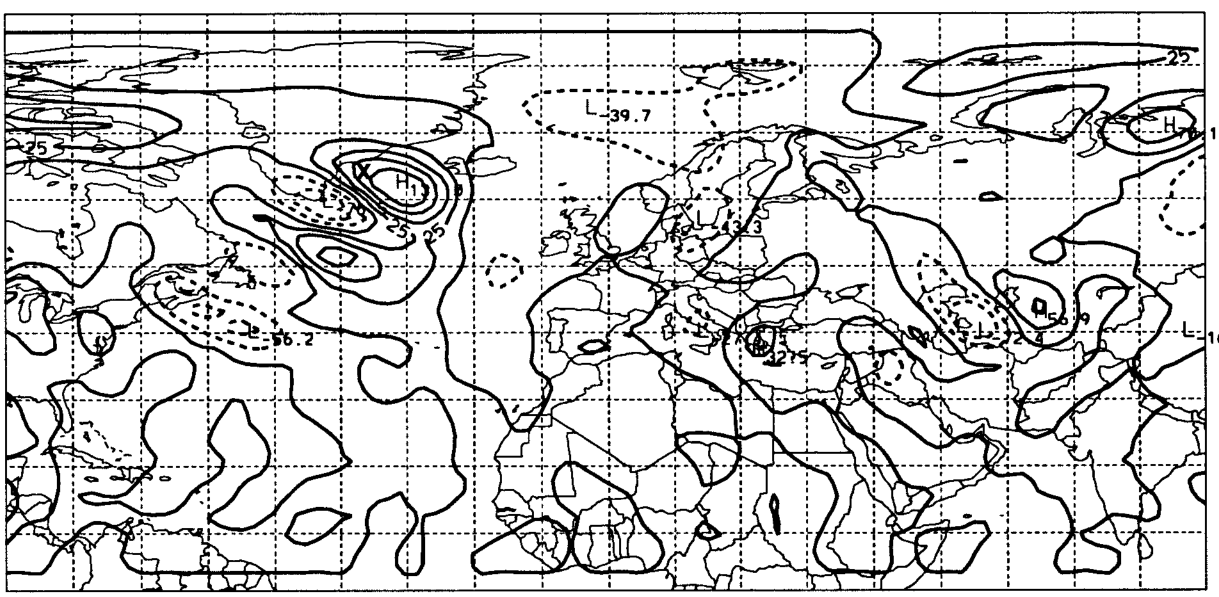

FIG. 4. Analyzed advection of synoptic-scale quasigeostrophic potential vorticity by the planetary-scale, 500-mb geostrophic wind (contour interval: 25×10^{-10} s^{-2}) at 0000 UTC 11 January 1985. The ''X'' denotes the concurrent location of a sea level cyclone with lowest sea level pressure of 972 mb. Solid contours are positive (cyclonic); dashed contours are negative (anticyclonic). Latitude and longitude are as in Figs. 1–3 except that longitude begins with 90°W on the west.

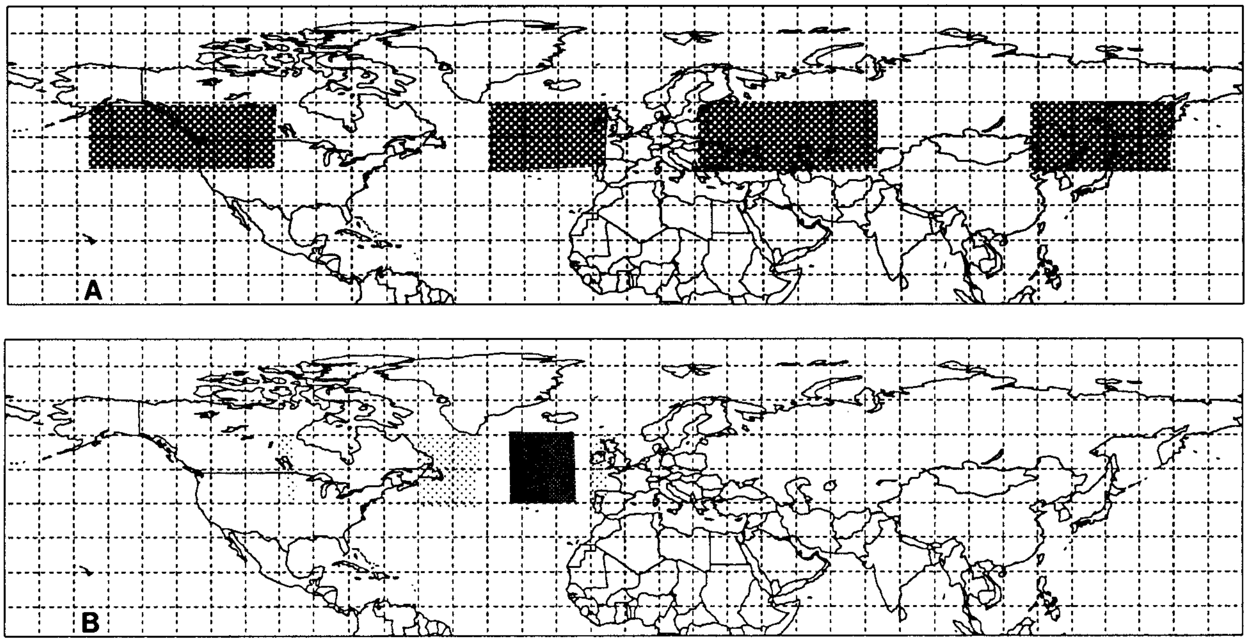

FIG. 5. (a) Stippling denotes the longitudes west of which there was an analyzed coincidence of 20° longitude by 20° latitude area-averaged $u' < 0$ and $v' > 0$ (see text for definitions) between 40° and 60°N at 0000 UTC 11 January 1985. (b) Dark (light) stippling denotes the longitudes west of which there was an analyzed 20° longitude by 20° latitude area-averaged advection of cyclonic (anticyclonic) synoptic-scale potential vorticity by the 500-mb planetary-scale geostrophic wind exceeding 10^{-9} s^{-2} in magnitude between 40° and 60°N at 0000 UTC 11 January 1985. Latitude and longitude are as in Figs. 1–3.

This suggests that the misforecast zonal wind component over the eastern Atlantic Ocean by the ensemble members was due more to model bias than to initial data uncertainty.

The ensemble-mean 500-mb planetary-scale geostrophic zonal wind component at day 4 in the forecast initialized on 7 January 1985 (Fig. 10a) is characterized by maxima over the western Atlantic, eastern Mediterannean, and western Pacific, as found in the corresponding analysis (Fig. 10b), but places the eastward exten-

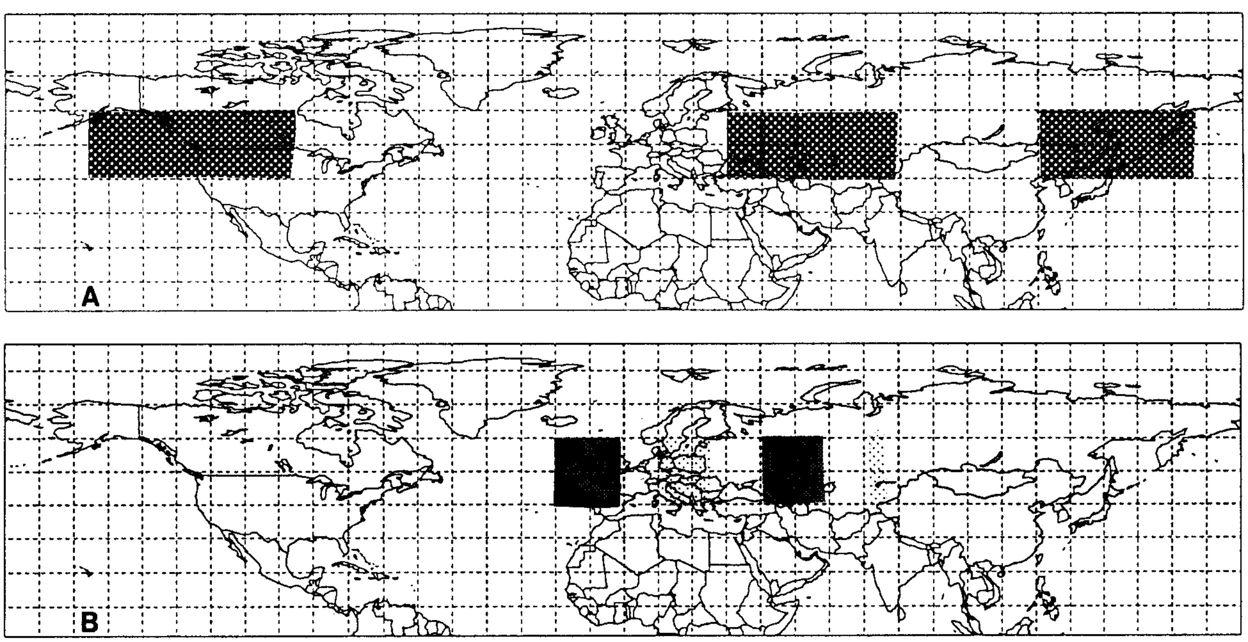

FIG. 6. As in Fig. 5 but as forecast for 0000 UTC 11 January 1985 by ensemble member 1 initialized at 0000 UTC 7 January 1985.

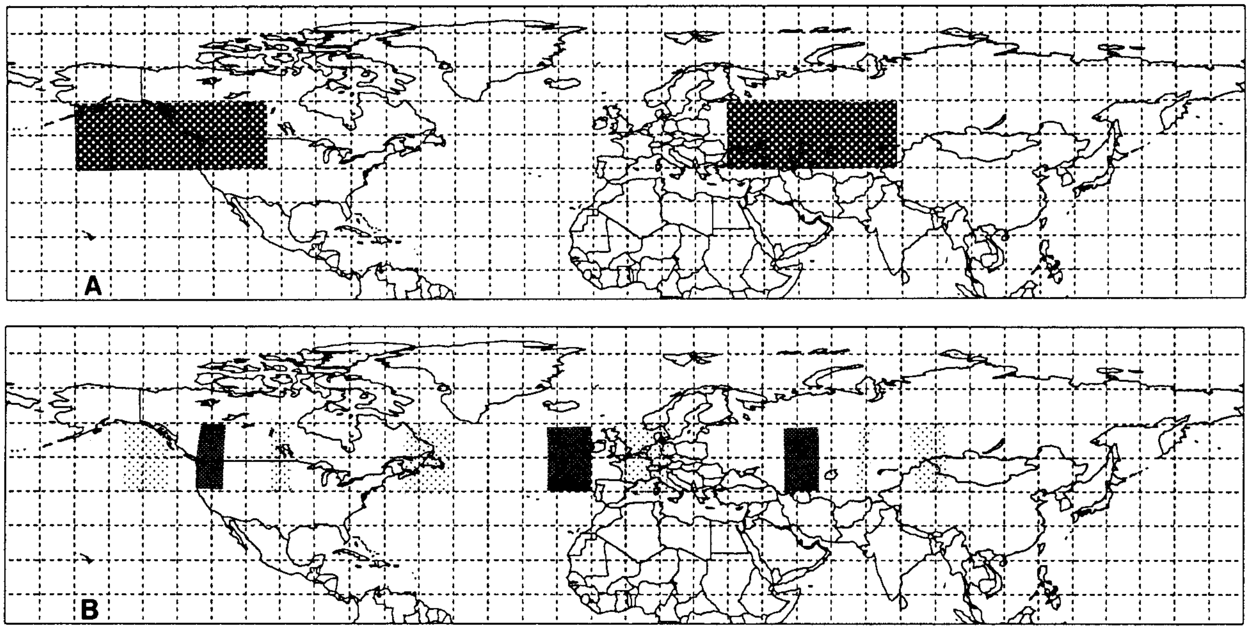

FIG. 7. As in Fig. 5 but as forecast for 0000 UTC 11 January 1985 by ensemble member 10 initialized at 0000 UTC 7 January 1985.

sion of the Atlantic maximum too far south over the eastern Atlantic and western Europe. Consequently, this forecast zonal wind component is too strong over the eastern Atlantic and western Europe, but too weak north of Scandinavia, likely contributing to the bias pattern in Fig. (9a). This erroneously southward displacement of the zonal jet near Europe is consistent with the CCM2's systematic bias toward 500-mb heights that are too low over much of Europe, with a maximum negative bias near the British Isles (not shown). The reasons for this systematic bias are under investigation. Still, despite the systematic error, a few of the ensemble members from the forecast initialized on 7 January were able to predict a transition to blocked flow. Such ''contradictory successes'' have been previously noted by Brankovic et al. (1990).

6. Concluding remarks

We have investigated the forecastability of an atmospheric blocking pattern with forecast ensembles produced by the NCAR CCM2 at T42 resolution and 14-day range, with attention to the onset (rather than maintenance and breakdown) of the block. In particular, we have investigated the manner in which certain circulation features prior to the onset of blocking were predicted by the forecast ensemble initialized five days before block onset.

The block under investigation, analyzed during 12–18 January 1985 over the eastern Atlantic Ocean and Europe, was preceded upstream by anomalously weak westerlies and strong southerlies in the analyzed 500-mb planetary-scale geostrophic wind field. Coincident with these features was evidence in the analyses for synoptic–planetary-scale interaction as measured by large, area-averaged advection of cyclonic SQPV by the 500-mb planetary-scale geostrophic wind.

Two of the 10 members of the forecast ensemble initialized five days prior to the block onset predicted a transition to blocking during the forecast range over the Atlantic–Europe region; both of these misforecast the location of the block while one misforecast the timing of block onset. Detailed inspection of these ensemble members plus one other that did not predict blocking revealed that errors in the prediction of the timing and location of block onset were due to model failure to predict the anomalously weak midtropospheric westerlies upstream of and prior to the onset of blocking. Further scrutiny disclosed that this forecast error was linked with an ensemble-mean forecast bias toward placing the midtropospheric zonal wind maximum too far south upstream of and prior to blocking. This bias is consistent with the model's systematic error.

On the other hand, the location and timing of area-averaged advection of SQPV by the planetary-scale geostrophic wind at 500 mb was well predicted by the ensemble members. In at least one case, however, this could have been a fortuitous consequence of excessively forecast westerlies interacting with an inadequately forecast gradient of SQPV. Nevertheless, these results demonstrate that despite the systematic error there was sufficient variability within the ensemble that a few of the ensemble members were able to correctly suggest that there would be a transition to blocked flow within the forecast range over the region of interest, even if the precise location of the block was misforecast. Furthermore, it is noteworthy that the proportion of ensem-

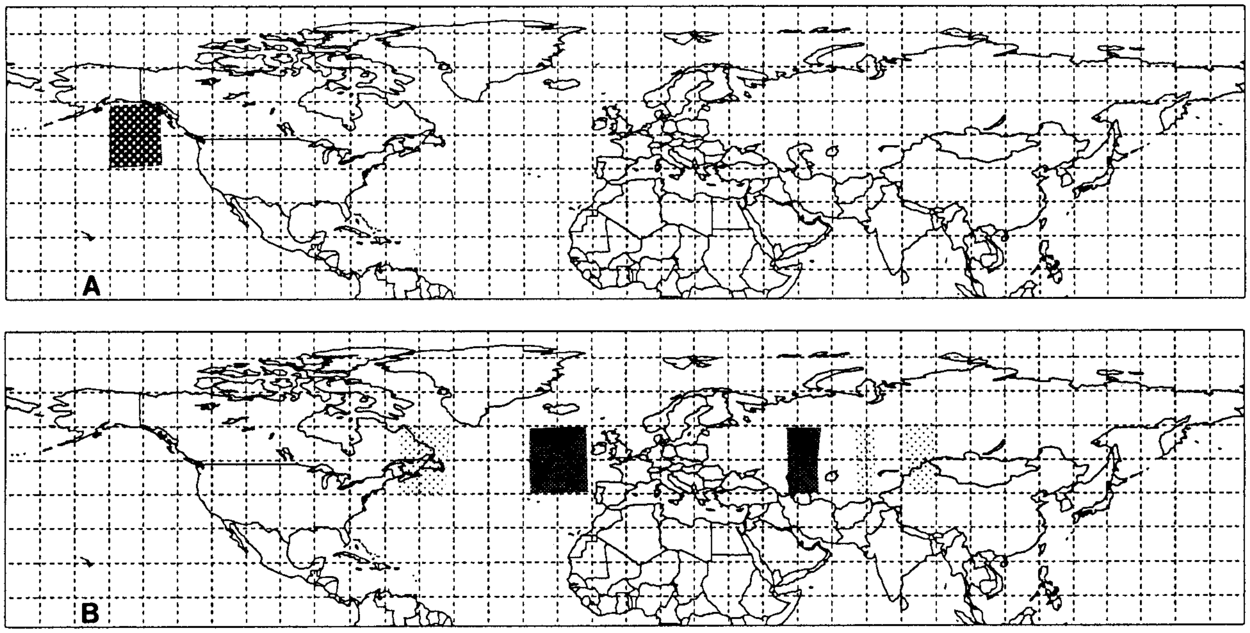

FIG. 8. As in Fig. 5 but as forecast for 0000 UTC 11 January 1985 by ensemble member 6 initialized at 0000 UTC 7 January 1985.

ble members predicting blocked flow on the peak date of the episode increased as the lead time decreased, indicating an increasing likelihood of the event as the event approached.

It would be worthwhile in future research efforts to identify the source of the systematic error. As noted by Klinker (1990), the source may be quite remote from region of maximum bias. Even if the source is identified, it may not be possible or straightforward for the bias to be eliminated. There is mounting evidence (e.g., Buizza and Molteni 1996) that it is essential for models to predict a preconditioned planetary wave state (i.e., one with diffluence, or relatively weakened westerly flow) prior to and upstream of the incipient block in

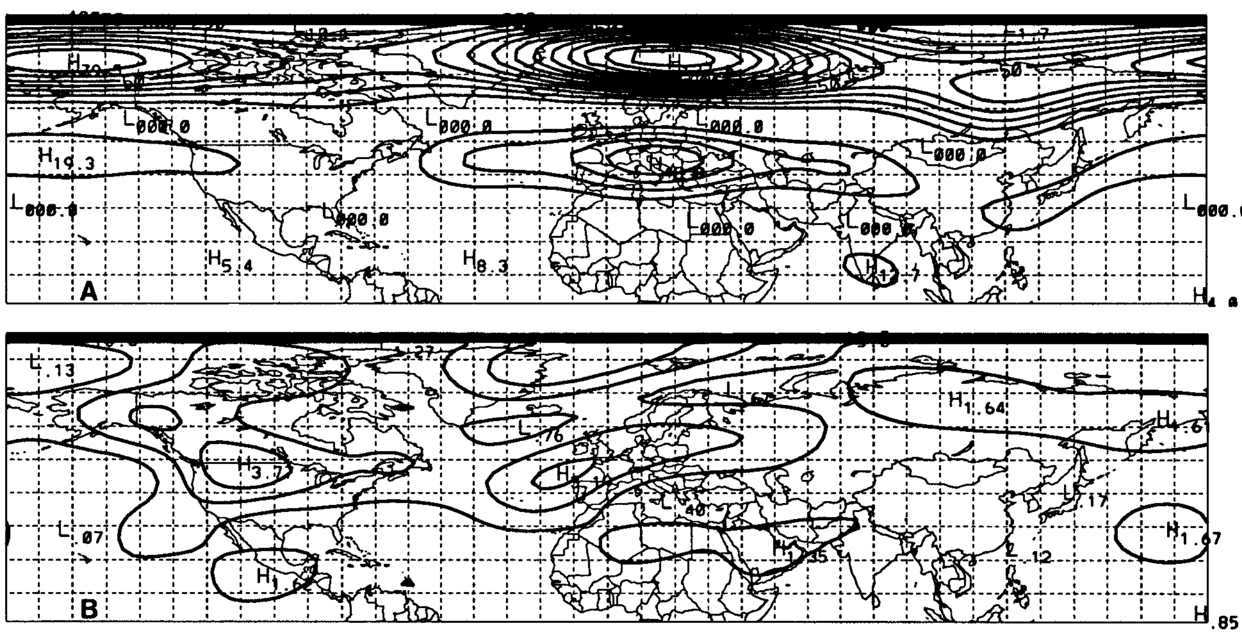

FIG. 9. Mean squared (a) bias (contour interval: 10 m^{-2} s^{-2}) and (b) random error (contour interval: 1 m^{-2} s^{-2}) for the ensemble forecast, initialized 0000 UTC 7 January 1985, of the planetary-scale 500-mb u component of the geostrophic wind at 0000 UTC 11 January 1985. Latitude and longitude are as in Figs. 1–3 and 5–8.

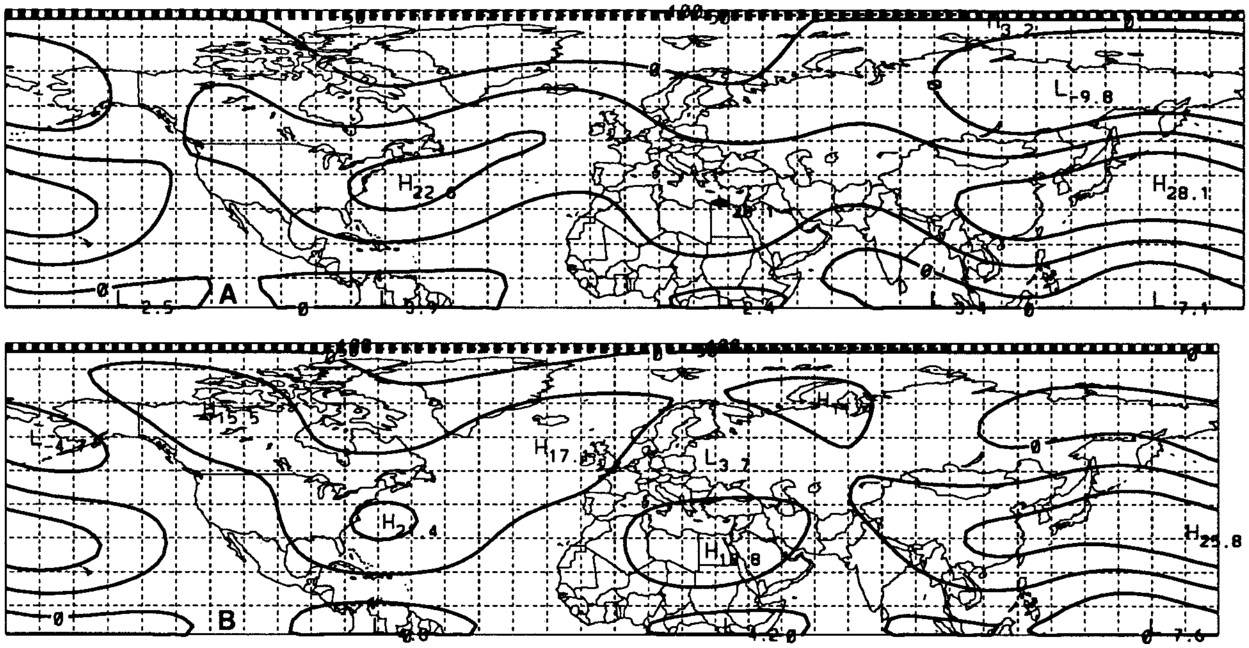

FIG. 10. Planetary-scale *u* component of the 500-mb geostrophic wind (contour interval: 10 m s^{-1}) at 0000 UTC 11 January 1985 as (a) predicted by the mean of the ensemble initialized 0000 UTC 7 January 1985 and (b) analyzed. Latitude and longitude are as in Figs. 1–3 and 5–9.

order for the block to be predicted. A model with a systematic bias toward excessive westerlies over a region may therefore be systematically incapable of predicting sufficient blocking activity immediately downstream of that region.

An important issue in weather prediction by ensemble methods is the development of probabilistic forecasts for the likelihood of an event given the information from the ensemble. That 20% of the CCM2 ensemble members initialized on 7 January 1985 predicted a transition to blocking over the Atlantic–Europe region during the forecast range does not necessarily mean that a 20% probability of analyzed block onset is implied by this forecast; information about the reliability of the ensemble predictions must also bear upon the probabilistic forecast [e.g., Anderson (1996)]. The block onset forecast problem is further complicated by issues of timing and location of the block. In subsequent work we will attempt to construct probabilistic forecasts of block onsets from ensemble output.

The results reported herein may be germane only to the case and model studied. We are currently investigating the forecastability of blocking in ensembles from the NCEP Global Spectral Model (GSM). Preliminary findings from our study of blocks during the 1995–96 winter season indicate that most members of a GSM ensemble, when initialized five days prior to a block onset, correctly predicted a transition to blocking. The percentage of correct transition-to-blocking forecasts per GSM ensemble is larger than that reported here for the lower-resolution CCM at comparable lead times, although the GSM has similar problems with the location and timing of predicted blocks. We will be examining these forecasts, as well as ensemble predictions of blocking during the 1995–96 winter with the NCAR CCM3, in more detail.

Finally, the coincidence of anomalously weak (strong) planetary-scale geostrophic westerlies (southerlies) with large planetary-scale advection of SQPV at 500 mb has been suggested here as a necessary antecedent upstream condition for blocking; this suggestion has guided our study of the forecastability of block onsets. Further research is required in order to establish that this condition is sufficient for blocking. In current research, we are investigating the dynamical connection between this condition and subsequent block onsets. Early results suggest that this condition can be interpreted as anomalous planetary-scale deformation interacting with the synoptic-scale potential vorticity gradient so as to favor the structure of persistent, large-scale geopotential height tendencies analyzed during block onsets. We will report on these efforts in a future contribution.

Acknowledgments. This work was supported in part by Grant ATM-9112922 from the National Science Foundation (NSF) and the National Oceanic and Atmospheric Administration. Some of the calculations were performed on the computer systems of the NSF-sponsored NCAR with resources provided by NCAR's Scientific Computing Division. We thank the anonymous reviewers for suggesting revisions that helped us clarify portions of the text.

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