Assessing the Impact of Different Satellite Retrieval Methods on Forecast Available Potential Energy

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ABSTRACT

The isentropic form for available potential energy (APE) is used to analyze the impact of the inclusion of satellite temperature retrieval data on forecasts made with the NASA Goddard Laboratory for Atmospheres (GLA) fourth order model. Two analysis datasets are used for the forecasts, one containing the NESDIS TIROS-N retrievals and the other GLA retrievals using the physical inversion method. A third analysis dataset did not contain satellite data and was used as a control. Two analysis datasets, with and without satellite data, were used for verification.

Northern Hemisphere values for the total APE show an increase throughout the 72 h forecast period for all three sets, mostly due to an increase in the zonal component, in contrast to the verification sets, which showed a steady level of total APE. The three forecast sets start with different values of total APE but by 36 h, the differences begin to diminish. At 72 h the total APE values for the three sets are almost identical. The magnitude of the total APE in the Southern Hemisphere does not increase in time and remains within the range of the verification sets.

The vertically integrated grid point distributions of the eddy APE which provide geographical representations of baroclinic zones show little difference between the 0 h forecast fields and the analysis fields. At the end of the forecast period, however, there are moderate differences in the southern Pacific and Indian oceans. The grid point distributions of eddy APE are quite different among the three forecasts as well as the verification sets. In the Northern Hemisphere there are very pronounced differences in grid point distribution over Asia, the North Pacific Ocean and North America. These differences increase in area and magnitude as the forecast period progresses. They show coherence in their eastward progression with time across the eastern Pacific and North America. Examination of the grid point distributions indicates that the forecasts are slow, for example, in developing a low in the northern Rockies and never correctly capture its position or intensity. The differences noted above are a reflection of incorrect timing, position and/or magnitude. Isentropic cross sections for 50°N show that the time lag exists around the entire parallel. The forecast set using the GLAS retrievals does somewhat better than the other sets in predicting intensity and position of developing lows, but all three forecasts resemble each other rather than the verification sets. This would seem to indicate that model characteristics are overwhelming any differences in the data sets.

1. Introduction

Although a decade has passed since the Global Weather Experiment (GWE), data gathered then continue to be used in a wide range of studies of the atmosphere. They include basic diagnostic studies designed to enhance our understanding of atmospheric processes, the testing and improvement of numerical prediction models, and the impact of the new data sources employed during GWE. The possible contributions of satellite sounding data to improved numerical predictions is of special importance because these data provide a truly global coverage. In this paper we employ the concept of available potential energy to investigate the possible impact of the satellite sounding data on a numerical prediction case study conducted by Baker et al. (1984) using the NASA Goddard Laboratory for Atmospheres (GLA) fourth order model.

Previous studies have used a variety of techniques and parameters to examine the effect of satellite soundings on model analyses and forecasts. Results have been mixed in assessing their impact. Some studies have shown a positive contribution from the addition of satellite data. Halem et al. (1982), using the NASA GLA model, found a positive but weak impact over North America and Europe. The 300 mb 6 h forecast error downstream of data-sparse regions was reduced by more than 50% by using the FGGE dataset which included satellite retrievals versus using the conventional data only (NOSAT) set. The results of Wolfson et al. (1985), who used the Israeli Meteorological Ser-
vice dry, primitive equation model, showed that the impact of satellite data was the greatest in the active areas of low pressure systems. This impact is positive in that the systematic errors in forecasting are reduced. They also indicated that there was no significant impact, either positive or negative, from using satellite data in nonactive regions. Aune et al. (1987) used a mesoscale model similar to the Mesoscale Analysis and Simulation System (MASS) described by Kaplan et al. (1982) to evaluate the impact of incorporating Visible Infrared Spin-Scan Radiometer (VISSR) Atmospheric Sounder (VAS) data in a regional scale model. Their results showed that the inclusion of satellite data increased the temperature gradient along a frontal zone. Other studies have shown a less favorable impact from the assimilation of satellite data. Koehler et al. (1983) found that satellite based analyses and forecasts using the National Meteorological Center (NMC) Limited-area Fine Mesh Model (LFM) located main trough and ridge systems but the thermal gradients were reduced. Salstein et al. (1987) examined the global circulation during part of the first Special Observing Period (SOP-1) (6 January–4 February 1979) for both satellite and nonsatellite datasets from the NASA GLA model. Their results indicated that the zonal mean circulation was somewhat weaker in the analyses with satellite retrievals compared to analyses without retrievals and analyses from a long term model integration. The long term integration showed the GLA model tended to increase the magnitudes of the winds while modifying temperature extremes. The weaker circulation in the satellite retrieval analyses may be a “correction” of the GLA model tendency to increase the magnitude of the winds. The weaker circulation would lead to decreases in the zonally averaged eddy transports of momentum and heat and in some of the energy terms as compared to both nonsatellite and model integration results. An intensive study of two oceanic cyclones in the Northern Hemisphere by Gallimore and Johnson (1986), again using the NASA GLA model, found that the inclusion of satellite data reduced the variability of the temperature and static stability, thus modifying the baroclinic structure of these two cyclones. Within the limited area of their study, they also found less zonal available potential energy in its approximate (isobaric) form in the satellite dataset which indicated less energy available for storm growth. Halem et al. (1982) and Bengtsson et al. (1982) noted, however, that the impact from the inclusion of satellite data depends on the model resolution, the analysis and initialization procedures, and the quantity of data available.

A major goal of any global model and its dataset is to accurately depict the development and movement of extratropical cyclones. An important parameter used to examine cyclone scale activity is the evolution of the eddy component of the available potential energy (APE) in its isentropic form for it can be a major source of the kinetic energy of cyclones. Analyses from NMC (Min and Horn 1982; Koehler and Min 1984), European Centre for Medium Range Weather Forecasting (ECMWF) (Koehler and Whittaker 1985) and NASA GLA (Horn et al. 1988) have been examined, and this parameter has been shown to be closely related to cyclone activity. We will use the eddy component of the APE to analyze three NASA GLA model forecasts to determine the impact of not only satellite versus nonsatellite datasets, but also different satellite retrieval techniques.

2. Data and procedures

This study uses the NASA GLA fourth-order global atmospheric model described by Kalnay-Rivas et al. (1977) and Kalnay-Rivas and Hoitsma (1979). Data assimilation has been described by Halem et al. (1982) and the objective analysis scheme by Baker (1983). The model has a uniform nonstaggered 4° latitude by 5° longitude horizontal grid and nine vertical sigma levels. Vertical interpolations were made to produce pressure analyses on isentropic surfaces at 10 K intervals from the lowest surface potential temperature (210 K) to 400 K, approximately 130 mb.

Analysis datasets were produced as part of a case study by Baker et al. (1984) using the GLA data assimilation procedure referenced in the previous paragraph. From these assimilation datasets, three experiments were selected for this case study. The first dataset (CONTROL, Experiment 1 from Baker et al.) assimilated only nonsatellite (conventional) observations. The initial conditions for this assimilation set were from the NMC global analysis at 0000 UTC 5 January 1979. The same initial conditions were used in the assimilation of another dataset containing all FGEF IIb data available. While this assimilation set was not used directly in this study, the 6 h forecast from 1800 UTC 17 January valid at 0000 UTC 18 January from this dataset provided the initial conditions for the second (NESS) and third (GLAS) datasets in this study. The second dataset (NESS, Experiment 4 from Baker et al.) resulted from the assimilation of conventional plus all available NESDIS TIROS-N operational (statistical) clear and partly cloudy temperature retrievals added globally. The third set of analyses (GLAS, Experiment 10 from Baker et al.) was generated using conventional observations and GLA temperature retrievals added globally in an interactive mode. The GLA retrievals use a physical inversion method which is described by Susskind et al. (1982, 1984). In the interactive mode, the assimilating model 6 h forecast provides the first guess for the retrievals. No initialization was performed at 0000 UTC 21 January for any of these experiments. In addition to the forecast sets, two GLA analysis sets,
NOSAT (conventional data only) and FGGE (conventional plus NESDIS TIROS-N retrievals) were used for verification in our study of the forecasts using CONTROL, NESS, and GLAS data. The NOSAT and FGGE datasets were described by Halem et al. (1982) and examined by Horn et al. (1988). Analyses from CONTROL and NOSAT should be quite similar since Baker et al. (1984) and Halem et al. (1982) used data assimilation procedures that were the same except for the vertical interpolation between model sigma levels and the mandatory pressure analysis levels. Using the approach described in Baker (1983), differences between the model first guess and analyzed fields were interpolated from pressure to sigma in the CONTROL run. The NOSAT set was prepared by interpolating analyzed fields (rather than differences from the model first guess) from pressure to sigma. The NESS and FGGE sets should also be quite similar with differences attributed to the use of cloudy retrievals in the FGGE set and differences in vertical interpolation.

The available potential energy is calculated as the difference between the total potential energy (i.e., the sum of the internal and gravitational potential energy) of the given atmospheric conditions and a horizontal, stably stratified reference state derived from an adiabatic redistribution of the mass. The total potential energy can be expressed as

$$TPE = \frac{c_p}{g \rho_0 (1 + \kappa)} \left[ \int_S \int_{\theta_j}^\Theta \overline{p}^{1+\kappa} d\theta dS \right] + \left[ \int_S \left( \overline{\theta} \overline{p}^{1+\kappa} - \kappa \overline{p}^{1+\kappa} \right) dS \right],$$

where $c_p$ is specific heat at constant pressure, $g$ is gravitational acceleration, $\kappa$ is the ratio of the gas constant.

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**Fig. 1.** Time series of total, zonal and eddy APE for the NESS, GLAS and CONTROL forecast sets and FGGE and NOSAT analysis sets. Units: $10^3$ J m$^{-2}$. 
determination technique is described in Koehler (1986). The importance of this formulation is that it is a vertically integrated quantity that implicitly allows the variation of lapse rate at each grid point. Therefore, it depends not only on thermal gradients but also on static stability. Both ingredients are critical to extratropical cyclone development.

This study will focus on the APE as it evolves throughout the 72 h forecast period (21–24 January 1979). Global and hemispheric reference states will be used to compare the total APE and its zonal and eddy components in the forecast sets to similar quantities in the analysis (verification) sets. The geographical distribution of the vertically integrated grid point contributions of eddy APE will be used to diagnose the initial hour and forecast extratropical cyclone activity in the Northern and Southern hemispheres. Finally, this study will concentrate on North America where the forecasts missed the development of a major cyclone.

3. Results

a. Comparison of hemispheric values

Time series of the total APE, as well as the zonal and eddy components, for the three forecast sets and the two verification sets are presented in Fig. 1. The values are plotted for every 12 hours through the forecast period. In the Northern Hemisphere at 0 h, the

Fig. 2. Southern Hemisphere ECMWF sea level pressure and 500 mb heights analyses. (a) Sea level pressure. Units: mb with leading 9 or 10 not plotted. (b) 500 mb heights. Units: km with leading 5 and trailing 0 not plotted. The 30°S and 60°S parallels are shown.

(R_d) to c_p, \( p_0 \) is 1000 mb, \( p \) is pressure, \( \theta \) is potential temperature, capital \( S \) is hemispheric surface area and 
\[
dS = a^2 \cos \phi d\lambda d\phi,
\]
where \( a \) is the radius of the earth, \( \phi \) is latitude, \( \lambda \) is longitude. The small \( s \) subscript denotes a value at the earth’s surface and the small \( t \) subscript denotes a value at the top of the volume of atmosphere. Complete expressions for the isentropic formulation of APE used in this study are presented in Min and Horn (1982), and the reference pressure

Fig. 3. Southern Hemisphere grid point distribution of eddy APE for 0000 UTC 21 January 1979 with lows (L) and highs (H) superimposed. Units: 10^7 J kg⁻¹. The 30°S and 60°S parallels are shown.
are in the zonal term, especially with respect to the FGGE verification set. The forecast sets tend to converge so that initial differences are lessened as the forecast proceeds.

On the other hand, in the Southern Hemisphere where the satellite data are given more weight, the magnitude of the APE calculated from the forecasts does not increase with time and the APE based on the three datasets remain within the range of the two verification sets. Most of the differences in the datasets appear in the eddy terms with very little difference in the zonal terms. Also note that the magnitudes of the eddy and zonal components in the forecast sets are close to or below the magnitudes of the analysis sets, while in the Northern Hemisphere the magnitudes are generally above those of the analysis sets, especially in the later part of the forecast period. The differences in the analysis sets have been discussed previously (Horn et al. 1988) and are likely related to the weaker thermal gradients found in datasets containing satellite observations. This, however, does not explain the different behavior of the forecast sets in the two hemispheres.

b. Grid point differences

1) SOUTHERN HEMISPHERE

Before examining global differences, it is helpful to look at the vertically integrated grid point distribution of eddy APE for one time period and include the positions of highs and lows. Figures 2a, b show the ECMWF sea level pressure and 500 mb analyses for the Southern Hemisphere for the initial period. The low pressure systems in the Southern Hemisphere tend to move in a circle around Antarctica. Cyclolysis occurs when a low turns toward the continent. Figure 3 displays the vertically integrated grid point distribution of eddy APE for the FGGE set. Some common features of such a distribution are the “pools” of negative eddy APE values (i.e., the pressure on the isentropic surfaces is lower than the reference pressure, indicating relatively cold air) found behind organized low pressure centers. A change from negative to positive values occurs in strong baroclinic zones (i.e., across the frontal systems). [See Horn et al. (1988) for a more detailed discussion.] During this forecast period, most of the lows shown in Fig. 2a will dissipate. With only a few cases of cyclogenesis, the sea level pressure pattern tends toward a ring of low pressure encircling Antarctica with a few moving eddies.

In displaying the differences in the global vertically integrated grid point distribution of eddy APE in Fig. 4, the analysis set is subtracted from the forecast set (i.e., NESS-FGGE, GLAS-FGGE, CONTROL-NO-
Fig. 5. Southern Hemisphere grid point distribution of eddy APE for 0000 UTC 24 January 1979 for the NESS, GLAS and CONTROL forecast sets and the FGGE and NOSAT verification sets. Units: $10^3$ J kg$^{-1}$. The 30°S and 60°S parallels are shown.

Fig. 6. Southern Hemisphere ECMWF sea level pressure analysis for 0000 UTC 24 January 1979. Units: mb with leading 9 or 10 not plotted. The 30°S and 60°S parallels are shown.

SAT). In contrast to the very small 0 h forecast-analysis differences (ignoring Antarctica), the 72 h differences are moderate in the Southern Hemisphere. The largest differences that occur in the southern Pacific and Indian oceans are in regions of moving low pressure systems and intense pressure gradients. It should be noted that larger CONTROL-NOSAT differences would occur primarily over land. The CONTROL forecast and the NOSAT analysis will be quite similar over data-void oceans since NOSAT would have assimilated very little data there and would act like a forecast. This is untrue for the NESS-FGGE and GLAS-FGGE differences. Over the oceans FGGE is a forecast that is updated by satellite soundings so that differences are primarily due to satellite soundings in the FGGE analyses. Figure 5 displays the eddy APE grid point distributions for all three forecast sets and both verification sets for the final forecast period, 0000 UTC 24 January 1979. The corresponding ECMWF sea level pressure analysis is also shown (Fig. 6). The most notable feature of the grid point distributions is their dissimilarity. Even the verification sets are different. The areas between New Zealand and South America and Madagascar and Ant-
2) Northern Hemisphere

Figures 7a, b show the NMC sea level pressure and 500 mb height analyses for 0000 UTC 21 January 1979 for the Northern Hemisphere. Note in particular the major low in the Bering Sea (central pressure of the low was about 948 mb) and also the low over the southern United States. Other lows are located off Newfoundland, off the west coast of Africa and in the Western Siberian Lowland. Figure 8 displays the Northern Hemisphere grid point distribution of the FGGE set for 0000 UTC 21 January 1979, the initial period in the forecast. Note again the relationship between the areas of positive and negative APE and the highs and lows of the synoptic charts. In the Northern Hemisphere, there are pronounced differences in the eddy APE grid point distribution after 72 h (Fig. 4). All three forecast sets show large differences over Asia, the North Pacific Ocean and North America. In particular, the area across North America and into the northern Atlantic Ocean has a series of negative-positive difference couplets positioned in the areas where cyclone development occurred during the forecast period. These couplets reflect a combination of incorrect timing, position and/or magnitude of the cyclogenesis process.

Since the largest differences are over North America, that area and the adjacent oceans will be used for a more detailed study of cyclone development throughout the forecast period. Figure 9 shows a sequence of

Fig. 7. Northern Hemisphere NMC sea level pressure and 500 mb heights analyses. (a) Sea level pressure. Units: mb with leading 9 or 10 not plotted. (b) 500 mb heights. Units: km with leading 5 and trailing 0 not plotted. The 30°N and 60°N parallels are shown.

Fig. 8. Northern Hemisphere grid point distribution of eddy APE for 0000 UTC 21 January 1979 with surface fronts and lows (L) and highs (H) superimposed. Units: 10^3 J kg^-1. The 30°N and 60°N parallels are shown.

Arctica seem to have the greatest disagreement. Overall, when comparing the differences between the forecast sets and FGGE (Fig. 4) and also NOSAT (not shown), the NESS forecast appears to have best captured the features seen in the verification sets.
eddy APE grid point differences every 24 hours starting with 0000 UTC 22 January (the second forecast period) in the same order as Fig. 4 (i.e., NESS-FGGE, GLAS-FGGE, CONTROL-NOSAT). Figure 10 shows the sequence of 500 mb heights from the NMC analysis for this same area. A short-wave trough over the northern Rockies was beginning to amplify and move through the longer wave pattern into the middle of the United States. At the surface (not shown), cyclogenesis was occurring in association with the short wave, and development occurs as the wave amplifies and moves south. In Fig. 9, negligible initial differences have grown so that by the second forecast period (22 January), differences begin to appear over the eastern Pacific and western North America. The differences are coherent, increasing in area and magnitude as the forecasts progress. The sequence details an eastward progression of both positive and negative differences with time across the eastern Pacific and North America. Note that in the area of the eastern Pacific off the west coast of North America from around 30°–40°N, fewer satellite retrievals were produced than in the northern part of the eastern Pacific. Baker et al. (1984), however, found that differences in this region resulted from differing amplification rates and are not just the propagation of differences from data-sparse regions.

In order to assess the quality of the forecasts that include satellite retrievals, comparisons with a different data source such as RAOBs should be performed. The RAOB dense area over North America using the NOSAT analysis was chosen for this comparison. Figure 11 shows the NESS-NOSAT and GLAS-NOSAT grid differences.
point differences over North America. Clearly the GLAS forecast is better than either the NESS or CONTROL in this area.

Figure 12 shows the eddy APE grid point distributions of the 36, 48, 60 and 72 h forecasts and the corresponding NOSAT analyses. The development of a low in the northern Rockies on 1200 UTC 22 January as well as its intensification and movement into the southern United States are clearly depicted in the FGGE analyses by the formation and increase in magnitude of the negative pool behind the low. The resulting increase in the gradient from negative to positive values indicates the formation of an intense baroclinic zone. The forecasts develop this low 12 hours later but never capture its intensity or correct position. The NESS forecast is the poorest of the three, while the GLAS forecast does a slightly better job than CONTROL. These results agree with those reported in Baker et al. (1984). They found that the experiment using the NESS TIROS-N retrievals had a poorer forecast over North America while the GLAS experiment showed an improvement in this area compared to the CONTROL. A more important point is that at 72 h all three forecasts are quite similar, indicating that model characteristics may be overwhelming any differences in the datasets.

d. Isentropic cross sections

The eddy APE is a vertically integrated quantity with implied dependence on both temperature and static stability. To examine the vertical structure of the atmosphere an isentropic cross section (Fig. 13) along the entire 50°N parallel is used. This cross section, which depicts results from the final forecast period, was selected because it appears to lie along the zone of greatest thermal variance. Figure 13 illustrates the warm “troughs,” cold “ridges” and steeply sloping isentropes indicative of frontal zones. Large pressure differences between isentropes indicate weak static stability. In the cold ridge east of the Rocky Mountains, the tighter vertical gradient in the analyses indicates stronger static stability than in the forecasts. Only the GLAS forecast gives a hint of this gradient, indicating that it was somewhat better at developing the vertical structure of static stability in this area than the other forecasts.

Another indication of the forecast accuracy is in the positioning of the troughs and ridges in the cross section. The vertical axes of four of the warm troughs have been marked so that a comparison of their positions can be made. In the FGGE and NOSAT analyses for 24 January, the axes of all the troughs nearly coincide. The axes of the forecasts also nearly coincide with each other except for the warm trough near the West Coast and Rocky Mountains. The forecast trough axes, however, generally lag the analyses trough axes by as much as 10°–15° of longitude. Pressures on the individual isentropic levels vary by as much as 50–100 mb from the analyses even when the lag is taken into account. If the forecast troughs are superimposed on the analysis troughs (i.e., the lag is removed), all the troughs are coincident around the entire parallel except for the NESS and CONTROL forecasts near the Rocky Mountains. This suggests that the forecast development of cyclones is too slow not only over North America but over the whole hemisphere.

4. Summary

In this study, we have examined the impact of satellite data on the forecast results of the NASA GLA fourth-order model. Calculations of the APE (isen-
Fig. 10. Northern Hemisphere NMC 500 mb heights for the same time sequence and area as Fig. 9. Units: km with the leading 5 and trailing 0 not plotted.

tropic formulation) have been used to study the differences in the forecast sets both globally and in the Northern Hemisphere and to analyze the development of a major cyclone over the southern United States during the forecast period. Hemispheric totals of APE show increases throughout the forecast cycle in all three forecast sets. This could imply that the conversion to kinetic energy is too weak or the generation of APE is
too strong in the GLA model, which increases the APE. The calculation of these quantities was beyond the scope of this study. Because the inclusion of satellite data tends to weaken the zonal circulation, the FGGE analyses may be "correcting" the model tendency to increase the zonal circulation and thus show lower values of APE.

Global differences in vertically integrated grid point distributions of the eddy APE provided a geographical representation of where the forecasts were varying from...
the actual analyses. While there were moderate differences in the southern Pacific and Indian oceans, the major differences occurred over the eastern North Pacific Ocean and North America. These differences increased in area and magnitude with time and exhibited an eastward progression throughout the forecast cycle. A series of negative-positive difference couplets occurred around the hemisphere in areas where cyclone development was noted. This indicates that the forecasts of cyclogenesis were incorrect with regard to either

the timing, position or intensity. Examination of isentropic cross sections for the final forecast period showed a lag of 10°–15° of longitude in the positioning of the lows around the 50°N parallel in all the forecast sets.

Comparison of vertically integrated grid point distributions of eddy APE in the forecast sets and the two verification sets for the Southern Hemisphere showed that the patterns were somewhat dissimilar for both forecast sets and verification sets for the final forecast.
period. The NESS forecast came the closest to capturing features of both verification sets.

In the Northern Hemisphere, a comparison of the grid point distributions of eddy APE in the forecast sets and the NOSAT analysis revealed that as the forecast cycle progressed, the three forecast distributions began to resemble each other rather than the NOSAT analysis. The GLAS forecast set did slightly better in capturing the cyclone development both over the southern United States as well as around the hemisphere (as seen in the smaller differences in Fig. 4). It is difficult to determine if this was due to a better retrieval scheme (i.e., the physical inversion method) or the use of an interactive assimilation cycle. Because all three forecasts failed to correctly capture the development, however, the GLA model characteristics are quite possibly more important than the different datasets in this case. This suggests that an assessment of the impact of different datasets should be based on the results of more than one forecast model.

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FIG. 13. Isentropic cross sections along the 50°N parallel. Isentropes are every 10 K and the last zero has been dropped from the label (e.g., 28 = 280 K). The solid vertical lines mark the positions of the four "warm" troughs.