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TECHNICAL NOTE

EFFECTS OF SCATTEROMETER WINDS ON THE NCEP GLOBAL MODEL ANALYSES AND FORECASTS: TWO CASE STUDIES

CHRISTOPHER A. PETERS *

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* General Sciences Corporation, Laurel, Maryland

OPC CONTRIBUTIONS

No. 1. Burroughs, L. D., 1987: Development of Forecast Guidance for Santa Ana Conditions. National Weather Digest, Vol. 12 No. 1, 7pp.

No. 2. Richardson, W. S., D. J. Schwab, Y. Y. Chao, and D. M. Wright, 1986: Lake Erie Wave Height Forecasts Generated by Empirical and Dynamical Methods -- Comparison and Verification. Technical Note, 23pp.

No. 3. Auer, S. J., 1986: Determination of Errors in LFM Forecasts Surface Lows Over the Northwest Atlantic Ocean. Technical Note/NMC Office Note No. 313, 17pp.

No. 4. Rao, D. B., S. D. Steenrod, and B. V. Sanchez, 1987: A Method of Calculating the Total Flow from A Given Sea Surface Topography. NASA Technical Memorandum 87799., 19pp.

No. 5. Feit, D. M., 1986: Compendium of Marine Meteorological and Oceanographic Products of the Ocean Products Center. NOAA Technical Memorandum NWS NMC 68, 93pp.

No. 6. Auer, S. J., 1986: A Comparison of the LFM, Spectral, and ECMWF Numerical Model Forecasts of Deepening Oceanic Cyclones During One Cool Season. Technical Note/NMC Office Note No. 312, 20pp.

No. 7. Burroughs, L. D., 1987: Development of Open Fog Forecasting Regions. Technical Note/NMC Office Note. No. 323., 36pp.

No. 8. Yu, T. W., 1987: A Technique of Deducing Wind Direction from Satellite Measurements of Wind Speed. Monthly Weather Review, 115, 1929-1939.

No. 9. Auer, S. J., 1987: Five-Year Climatological Survey of the Gulf Stream System and Its Associated Rings. Journal of Geophysical Research, 92, 11,709-11,726.

No. 10. Chao, Y. Y., 1987: Forecasting Wave Conditions Affected by Currents and Bottom Topography. Technical Note, 11pp.

No. 11. Esteva, D. C., 1987: The Editing and Averaging of Altimeter Wave and Wind Data. Technical Note, 4pp.

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No. 19. Esteva, D. C., 1988: Evaluation of Priliminary Experiments Assimilating Seasat Significant Wave Height into a Spectral Wave Model. Journal of Geophysical Research. 93, 14,099-14,105.

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I. Introduction

Satellite ocean surface wind data play an important role in obtaining accurate knowledge of meteorological conditions over data sparse areas. The European Remote-Sensing (ERS-1) scatterometer, an active instrument on board the European Space Agency (ESA) polar orbiting satellite, measures the ocean surface roughness with three antennae. An empirically based transfer function converts these measurements of ocean roughness ("backscatter") to wind speeds and directions, over a 500 km wide swath at a resolution of about 50 km. The conversion from backscatter to wind vectors results in multiple solutions at most locations; hence the wind directions are ambiguous. These directional ambiguities must be objectively removed in order for the data to be useful for numerical weather prediction. In collaboration with NASA-JPL, wind vectors are being processed at NCEP using backscatter-to-wind and vector ambiguity removal algorithms adopted from the United Kingdom Meteorological Office, along with quality control procedures developed specifically for the scatterometer (Offiler, 1992; Woiceshyn et al, 1993). Additionally, a background wind field obtained from either a six hour forecast or an analysis from NCEP's Global Data Assimilation System is used to assist in the removal of directional ambiguities. These scatterometer wind retrieval procedures were implemented operationally at NCEP in September of 1994 (Peters et al, 1994). This data set is now used to provide valuable surface wind information over data sparse ocean regions for marine forecasters and for assimilation into numerical weather prediction models.

Four years of experience with ERS-1 provided NCEP with ample time to examine the data and begin experiments aimed at assimilating the data into numerical weather prediction models. However, to this date the impact of routine assimilation of scatterometer data into the NCEP global model has been found to be only marginally positive. Previous studies examining the impact of scatterometer wind data on numerical models have yielded mixed results. In a study using Seasat winds obtained with objective ambiguity removal, *Baker et al.* [1984] found negligible effects of Seasat data on the objective analysis system of a 4 ^{0} by 5 ^{0} global general circulation model in the northern hemisphere. In the southern hemisphere, the Seasat winds had a positive impact on analyses and forecasts, but this impact was reduced when remotely sensed temperature soundings were also included in the analysis. *Duffy and Atlas* [1986] found a large positive impact including Seasat winds in a limited area NWP model for the case of the *Queen Elizabeth II* (QE II) storm, when a vertical correlation function was used to allow the Seasat winds to influence higher levels of the model. The Seasat winds were processed using subjective ambiguity removal, however, which is not practical in an operational forecasting environment. More recently, *Hoffman* [1993] found essentially neutral impact in a study of ERS-1 winds assimilated into the European Center for Medium-Range Weather Forecasting (ECMWF) system, with "no consistent improvement or degradation" in either hemisphere. These winds were processed objectively using a version of the CMOD2 transfer function (Long, 1985), along with a reference model forecast from the ECMWF for ambiguity removal.

The purpose of this report is to examine the impact of scatterometer winds on the current NCEP global model under specific synoptic conditions. For this purpose, several cases have been identified where the scatterometer data might significantly improve the model's surface analysis, as done by Duffy and Atlas [1986] . These cases typically involve errors in the model's analyzed position of a cyclone, verified by the surface wind field from the scatterometer as well as an independent manual analysis or visible satellite imagery. When the scatterometer winds indicate a substantially large error in the model's position of a cyclone, one would hope that the inclusion of the scatterometer winds into the model's data assimilation would improve the analysis and subsequent forecast. This study attempts to answer the question of what kind of impact (if any) the data are having in improving the model's depiction of the real atmosphere.

II. Methodology

In general, when a change is proposed to an operational NCEP model or new data are introduced to the assimilation system, the change is tested in "parallel" (change vs. control) and globally averaged statistics are calculated, usually looking at the results in terms of height anomaly correlations or precipitation skill scores. While these types of measures are quite useful in gauging the effect of the proposed change on the model's overall skill in predicting large scale flow patterns or in forecasting specific quantities such as precipitation, they may be less useful in determining the impact of the change on a specific variable over data poor regions. Beneficial effects over the oceans may very well be hidden in these gross types of statistics. For example, while the addition of ocean satellite winds to a model's analysis might not yield significant impact in terms of 500 mb anomaly correlation scores, which reflect the quality of the large scale flow forecast at 500 mb (and tend to measure better the skill of the model over data rich areas), they may in fact greatly improve the quality of the model's ocean surface wind field, and indirectly the surface pressure field. Techniques which use the model's own analysis for validation also are suspect over the oceans, where large errors often exist even in the analysis. Thus the benefits of the case study are twofold: 1. by focusing on the aspect of the model being modified they allow a direct, local assessment of impact that may be masked by global statistics, and 2. they may yield some deeper insight into the model's behavior, by revealing its' response to the modification.

The model used for the case studies was NCEP's operational medium range global forecasting model (MRF), with a triangular truncation at wave number 126 (equivalent to a horizontal resolution of about 100 km at the equator) and 28 vertical levels. In order to include the scatterometer winds in the model, the Global Data Assimilation System (GDAS), which uses a Spectral Statistical-Interpolation method (SSI) to incorporate observational data into the analysis, was also run. The current version of the GDAS at NCEP uses observations of temperature, wind, pressure and moisture to modify the model's guess field of spectral coefficients directly, and uses all variables at once to perform the analysis globally (Parrish and Derber, 1992). Data currently being assimilated include those from conventional sources, satellite soundings, and wind speeds from the SSM/I sensors on board the U.S. Defense Meteorological Satellite Program satellites.

In order to assess the impact of the scatterometer winds on the model and its' analysis system, the approach taken was to run the model's data assimilation system with and without scatterometer winds, and examine a 72 hour forecast. For the purposes of this study, only one assimilation cycle was run. A longer period of assimilation might allow more time for the data to "spin up", but the relatively small coverage of ERS-1 data makes it unlikely that much additional benefit would be gained. Experience with ERS-1 has demonstrated that consecutive passes directly over a storm center are extremely rare. Thus the scope of this study is limited to how the model responds to the ingest of scatterometer data at one synoptic time, carefully chosen in the hope of gaining maximum benefit from information showing the model guess to be wrong. Within the synoptic window of six hours, up to approximately 50,000 measurements of scatterometer winds are available for assimilation. Because of the ambiguity problem, different sets of "dealiased" wind vectors are available. For these studies, the following were used: 1. The ESA "Fast-Delivery" winds; 2. The wind vectors processed at NCEP using procedures adopted from the UKMET Office, henceforth referred to as the NCEP-JPL system; and 3. "Subjectively enhanced" winds, where some wind vectors are changed by hand to improve the NCEP-JPL winds (see table 1). The second set (NCEP-JPL) has been found to produce more consistent and meteorologically useful wind directions than the ESA fast delivery winds (Gemmill, 1994). The third option is not feasible operationally, of course, but it provides a further test of the sensitivity of the model to the wind ambiguity removal system. Also, objective systems which use the model's background wind field to select directions, while useful in the majority of instances, may fail during critical cases when the model itself has large errors.

Two cases where the scatterometer winds indicate substantial errors in the GDAS surface analysis were identified for the purpose of this study: 00Z May 2, 1994, and 00Z May 11 1994.

Table 1: Wind vector retrieval systems used in case studies

NAME	*SOURCE AND DESCRIPTION*
ESA-FD	European Space Agency "fast delivery" winds, with ECMWF model forecast winds used for ambiguity removal when autonomous dealiasing procedures fail
NCEP-JPL	NCEP-JPL procedures, with GDAS or 6-hr forecast AVN winds always used in ambiguity removal procedures
SUBJECT	Same as NCEP-JPL, with subjective selection of wind directions in areas where NCEP-JPL system still fails

III. Case 1

The first case examined was on 00Z May 11, 1994. Figures 1 and 2 give an overview of the synoptic situation. Figure 1 shows the NCEP/JPL retrieved scatterometer wind vectors, plotted with the GDAS mean sea level pressure field as the background. Two storms are evident, each near a swath of scatterometer winds. The primary storm is located south of the Aleutian Islands near 170W, 45N in the model analysis. The scatterometer data, however, places the center nearly five degrees to the west, closer to 175W, 45N. The final NCEP surface subjective analysis (Figure 2) confirms the scatterometer's position of the low. A second storm is located further to the west, near the Kamchatka peninsula. Here, the position of the storm in the scatterometer data agrees much more closely with the model analysis. In this case, attention will mainly be focused on the primary storm, labelled "A" in figure 2. This storm exhibits the largest

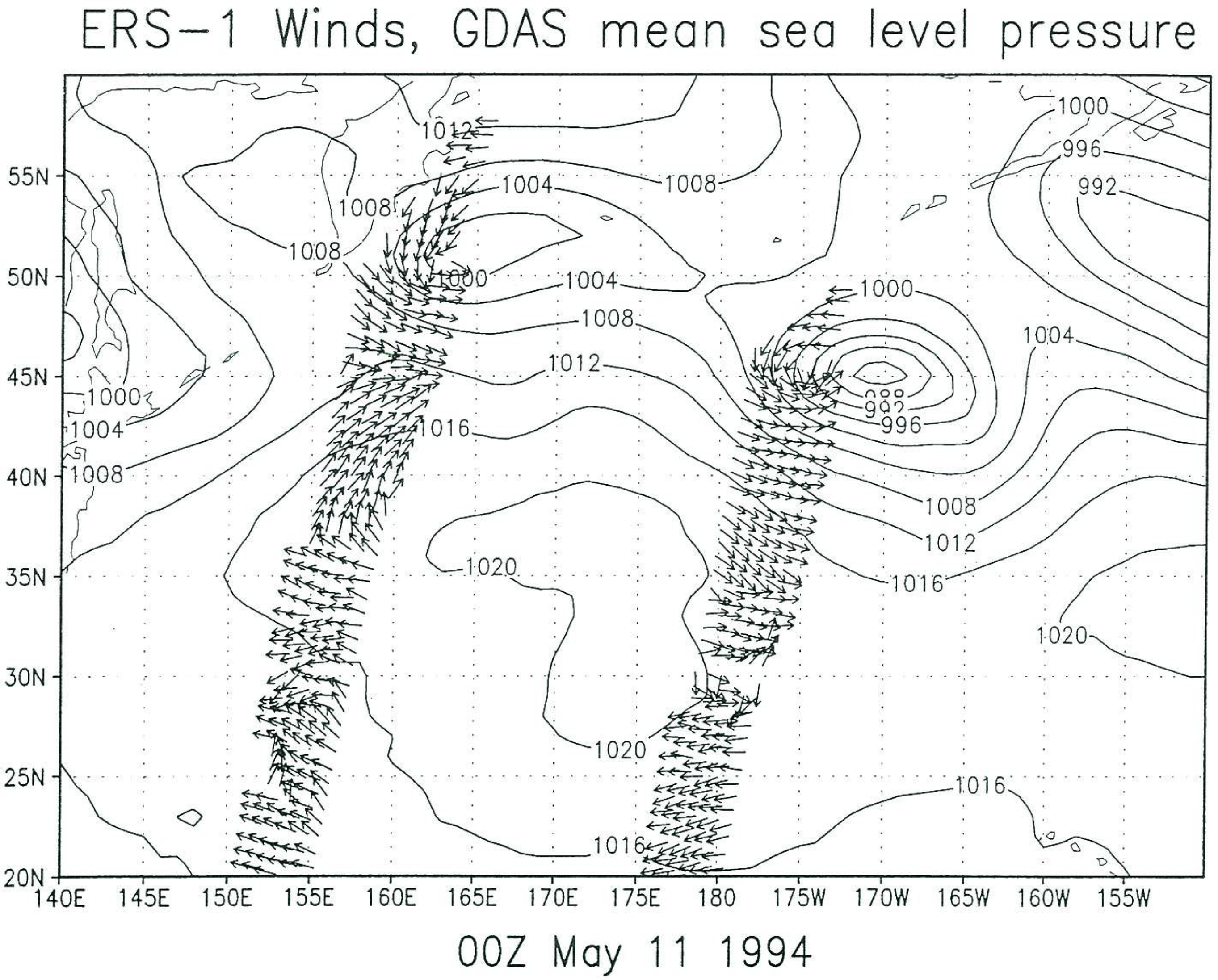


Figure 1: ERS-1 scatterometer winds (NCEP/JPL processing), background mean sea level pressure field from GDAS (mb). Valid 00Z 11 May 1994.

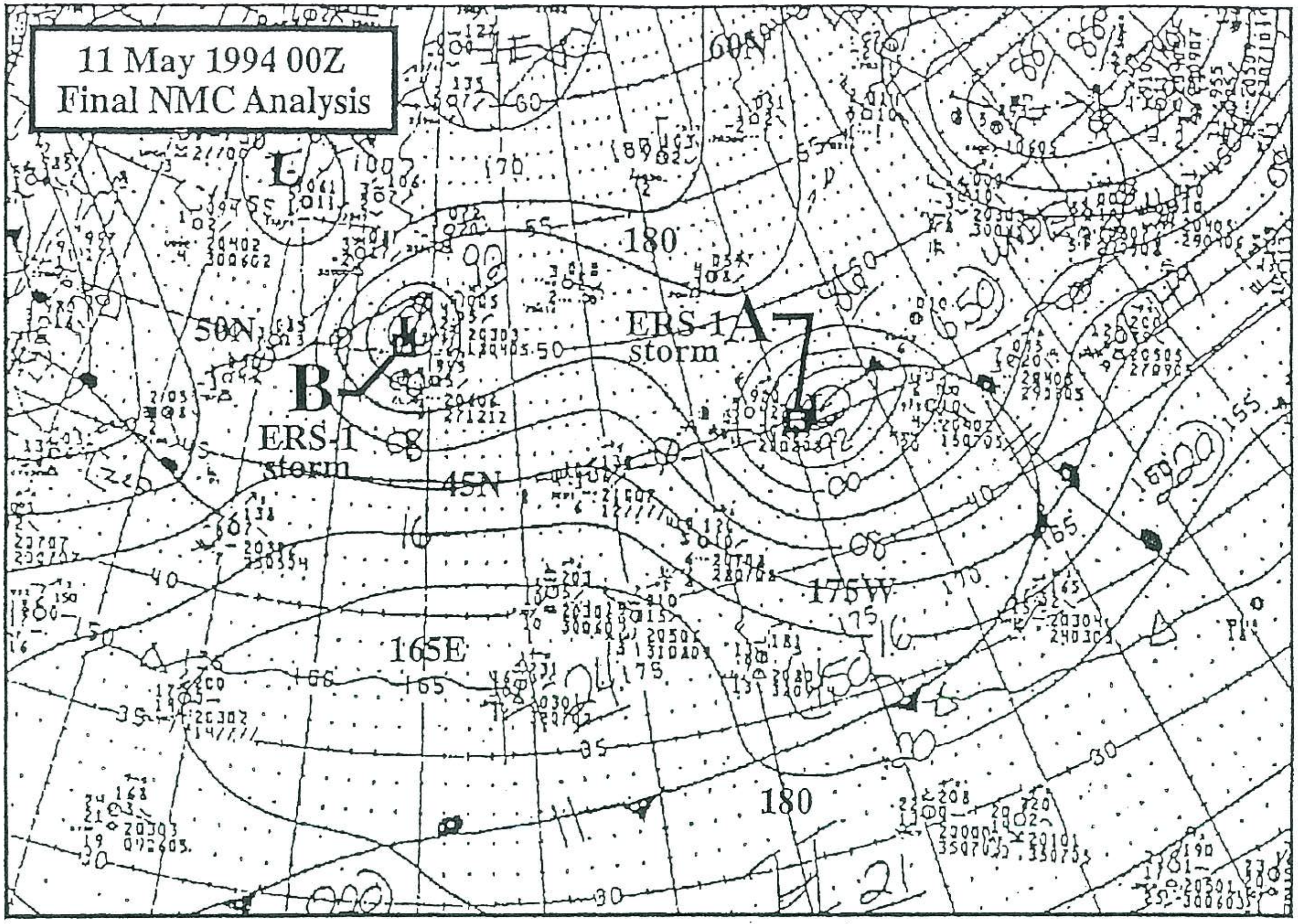


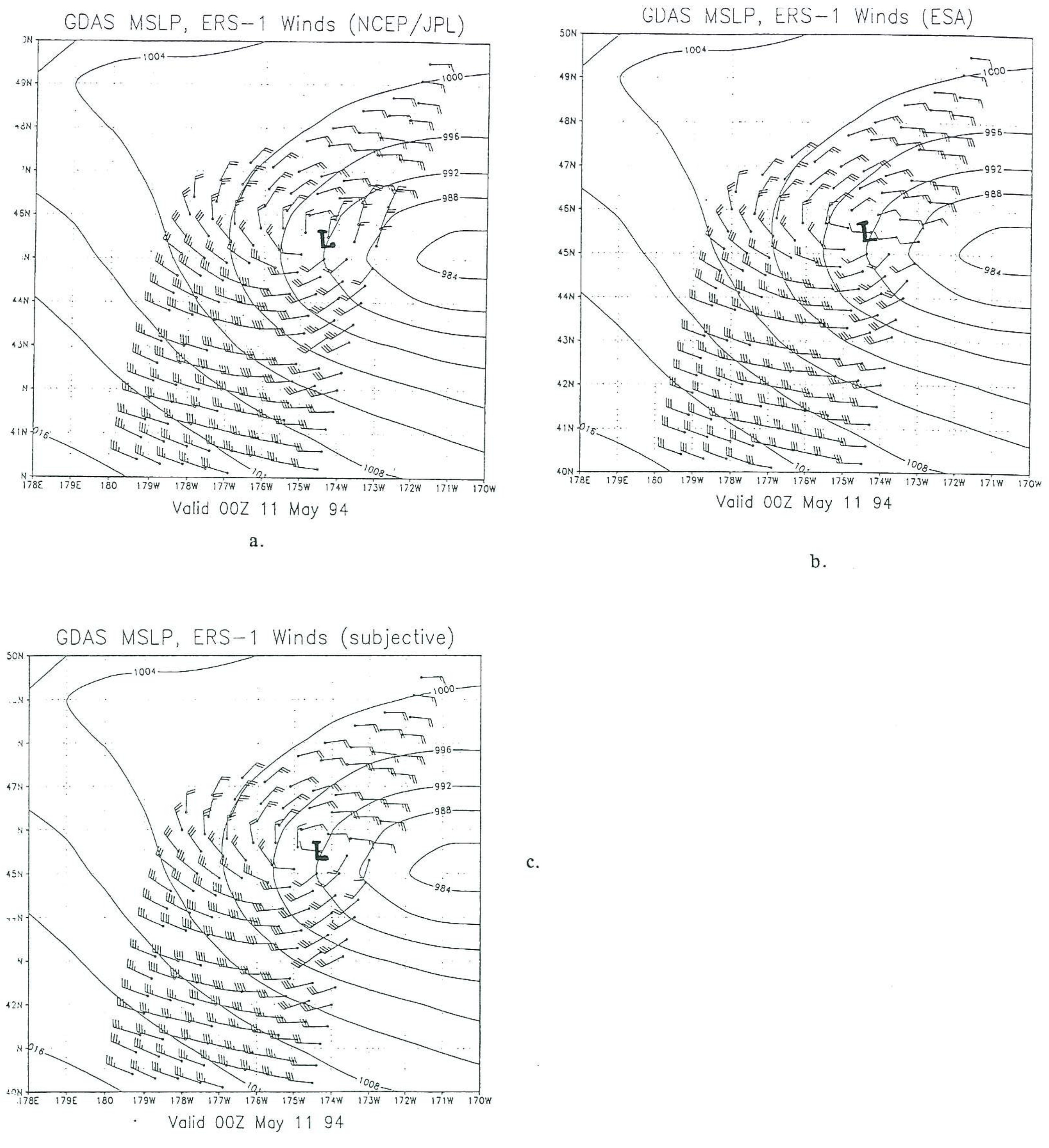
Figure 2: Final NMC hand analysis of Mean Sea Level Pressure, frontal positions. Valid 00Z May 11 1994.

probable error in the GDAS surface mass field.

A closer inspection of the scatterometer data near storm A (figure 3a) reveals some problems with the NCEP/JPL method of wind retrieval. These winds are produced using the CMOD4 transfer function and the global model's analysis (GDAS) for background winds to modify the retrieval probabilities (Peters et al, 1994). In general, they show a circulation center clearly near 174.5 W, 45.5 N (marked with a "L"), except for an area of winds in the northeastern quadrant of the storm. The winds in this area are given as northerly or northeasterly, despite the fact that they are to the east of the center. This is probably a result of the influence of the background wind field, which causes an incorrect solution to be chosen in the directional ambiguity removal. The ESA "fast delivery" wind vectors, shown in figure 3b, show a similar pattern, with some questionable winds to the east of the storm center. One can also attempt to manually select the wind directions in areas where the NCEP-JPL objective method fails. By looking at each node and making a subjective decision on the likely wind direction, using neighboring nodes and theoretical models of cyclone development, one can construct a "subjectively enhanced" wind field. This wind field is likely to be superior to either the ESA winds or the NCEP/JPL winds, and may be useful in testing the sensitivity of the model's analysis to the wind direction retrieval scheme. In this case, about 40 wind directions were identified as incorrectly chosen, and one of the alternative solutions was flagged as correct. An example of this type of manual enhancement is shown in Figure 3c (note that for display purposes, not every node is shown). Differences occur primarily to the east of the center, where a careful look at each node along with the knowledge that the storm was occluded at this point (see fig. 2) led to the decision to select the winds as more southerly.

The first approach taken to investigate the question of impact on the numerical model was to run the GDAS without (control) and with (parallel) scatterometer winds, and look for changes in position and intensity of the storm. In other words, could the additional information from the scatterometer winds improve the position and strength of the low pressure system? To answer this question, various sets of wind vectors were input to the data assimilation system. The first set attempted were the winds obtained objectively with the NCEP/JPL retrieval procedures. Compared with the control (figure 4a-b), they show a considerable lowering of pressures to the west of the erroneous center, and a lowering of the central pressure of the storm, but no movement of the closed center. The most likely location of the low at 00Z May 11 , based on the scatterometer winds and independent hand analysis, is denoted by a small "L", to the left of the model's center in figures 4a-b. The subjectively enhanced winds were next used as input to the assimilation system, showing more substantial impact on the cyclone position (Figure 4c). Here, the impact on the analysis is more substantial and positive. The storm is weakened and placed more to the west when the manual wind vectors are assimilated, closer to the true position. Surprisingly, assimilation of the ESA FD vectors (Figure 4d) yielded a similar result, weakening the storm and trying to move it westward, much as the subjectively enhanced NCEP-JPL winds did. In all cases, however, the addition of scatterometer data to the model's analysis could only elongate and stretch the low towards it's proper position, and could not eradicate the erroneous low pressure center further to the east. This is certainly due to the fact that the scatterometer swaths are narrow (500 km), and in this case only hit the storm itself, not the adjacent area to the east where large errors in the analysis also exist.

Another way to visualize the impact of the scatterometer winds on the analysis is to look at difference plots. By subtracting the control from the ERS-1 runs, one gets a better understanding of where the impact is occurring. Figure 5 shows three difference plots of mean

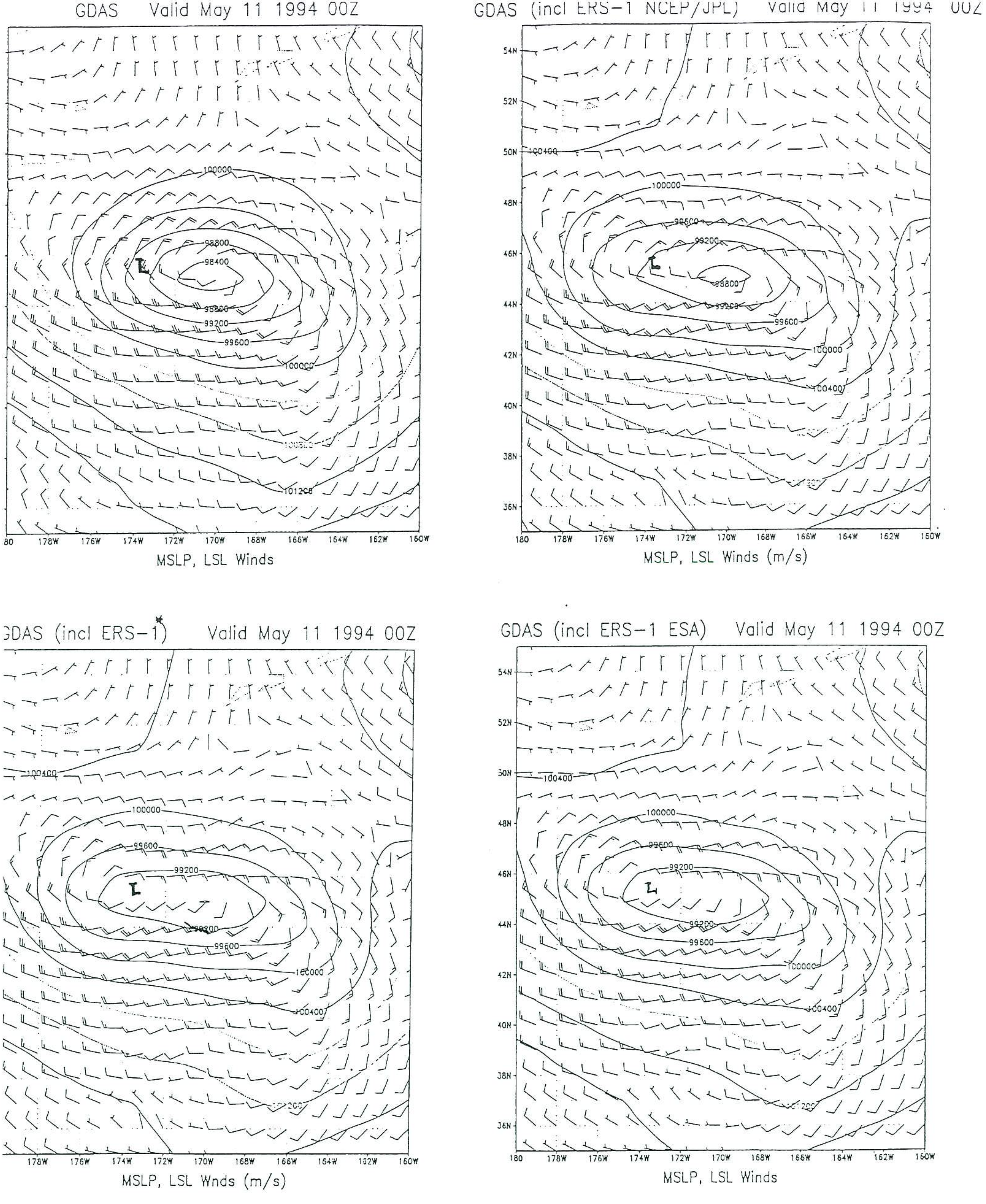


a.

b.

c.

Figure 3: ERS-1 winds in vicinity of storm A; mean sea level pressure from GDAS valid 00Z May 11 1994 (mb). (a) NCEP/JPL processed winds, (b) ESA fast delivery winds, (c) subjectively enhanced NCEP/JPL winds.



GDAS Valid May 11 1994 00Z

GDAS (incl ERS-1 NCEP/JPL) Valid May 11 1994 00Z

DAS (incl ERS-1*) Valid May 11 1994 00Z

GDAS (incl ERS-1 ESA) Valid May 11 1994 00Z

Figure 4: a. MSLP (Pa), lowest sigma layer winds from GDAS analysis valid 00Z May 11 1994 with no ERS-1 data, b. Same but including ERS-1 winds processed with NCEP/JPL method, c. Same but with subjectively enhanced winds included in analysis, d. Same but with ESA FD winds.

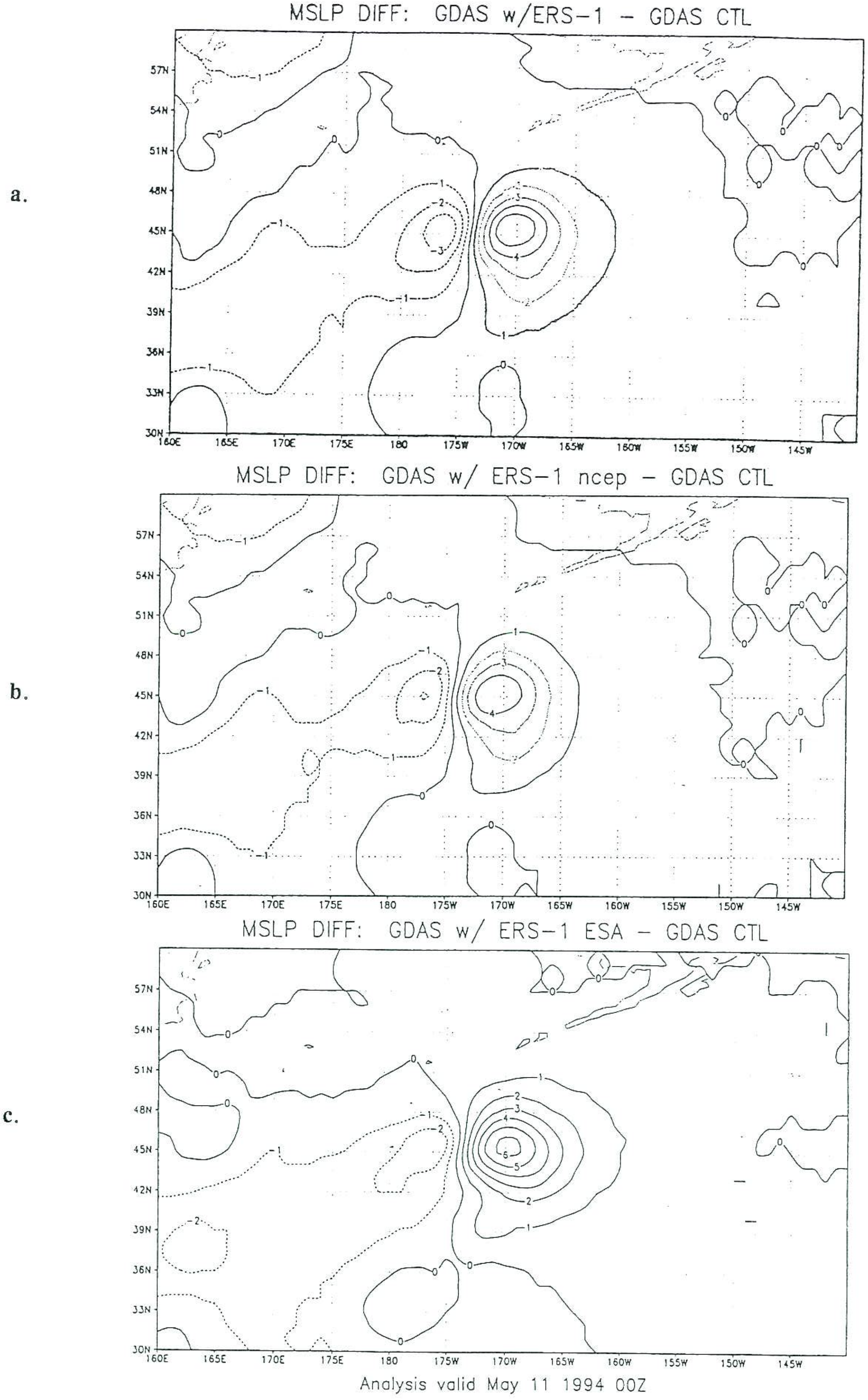


Figure 5: Difference plots of MSLP, in millibars, for GDAS analysis valid 00Z May 11 1994. **a.** GDAS w/ ERS-1 subject - GDAS control; **b.** GDAS including ERS-1 NCEP/JPL - GDAS control (no ERS-1); **c.** GDAS w/ ERS-1 ESA - GDAS control.

sea level pressure (mb): the GDAS runs with scatterometer data - the GDAS "control" (no scatterometer winds), for the three different sets of winds: NCEP/JPL, ESA FD, and subjectively enhanced. The plots reveal a dipole type of structure in the vicinity of the storm, indicating the tendency for the scatterometer data to place the low more westward. Figure 6 shows a cross section along 45 N, through the center of storm A. This figure reveals the differences in wind components between the analysis with scatterometer data and the control (no scatterometer winds). Notice that there are two dipoles evident in the zonal wind component cross section, demonstrating the vertical influence of the scatterometer winds on the analysis. The differences extend upwards only to about 800 mb, whereas in the meridional wind component cross section, there is a larger area of differences which extend all the way up to 200 mb. This represents a change to more southerly winds in the analysis with scatterometer winds, in the region between 175W and 170W. Evidently, the largest correction to the analysis made by the addition of scatterometer winds was to introduce more southerly flow west of the initial erroneous low in the model's first guess.

The modest improvements to the analysis described above lead to the following question: would the changes in the model's mass and wind fields persist and perhaps even amplify throughout the forecast? Would the changes lead to an improved forecast? In order to obtain answers, a 72 hour MRF forecast was generated from the each of the GDAS initial conditions: those generated with no ERS-1 winds (control), and those generated with the three methods of ERS-1 wind retrieval: NCEP/JPL, subjectively enhanced, and ESA FD.

Figure 7a shows the verification for the twenty four hour forecast valid 00Z May 12, 1994. This NCEP hand drawn surface map places "storm A" at about 47 N, 150W in the Gulf of Alaska. "Storm B" is centered near 50N, 180W. Both storms are in the occluded stage and have weakened somewhat in 24 hours with regard to central pressure (refer to Figure 2). The corresponding forecast from the MRF control (no scatterometer winds) is shown below in Figure 7b. There is one fairly large error present in this forecast: storm B appears to be too weak compared with the verification. Also, there is a spurious low to the south of storm B that doesn't exist in the verification. Surprisingly, storm A seems to be correctly forecast, despite the large error in the initial conditions. Figures 7c and 7d show the 24 hour MRF forecasts generated from initial conditions including scatterometer winds, for both the subjectively enhanced (c) and the ESA FD vectors (d). The twenty four hour forecast generated from the NCEP/JPL retrieved vectors was nearly identical to that from the manually enhanced (b), and is omitted for brevity. Both sets of ERS-1 vectors improve the 24 hour forecast very slightly, in terms of the surface pressure field. In the case of storm A, they forecast the same position as the control (no scatterometer winds), but close off the low slightly and reduce the area covered by the 996 mb contour, which agrees better with the verification. Both runs with scatterometer winds also tend to raise pressures south of storm B. In general, inclusion of the scatterometer winds improves the 24 hour forecast mainly by weakening the spurious low seen in Figure 7a south of storm B, and also by slightly improving the sea level pressure forecast of storm A.

When looking for small changes in the forecast, difference plots often reveal more information and also allow a look at the evolution of the impact throughout the forecast. Figure 8 shows the difference plots of mean sea level pressure (a) and 500 mb height (b) between the control run and the run with ERS-1 winds (subjectively enhanced) for the 12 hour forecast. Note the strong dipole in figure 8a, demonstrating that the run including scatterometer winds tends to place the low more westward even after 12 hours. At 12 hours (figure 8b), the control minus the ERS-1 run (subjective) shows impact extending up to the 500 mb level, with a small dipole.

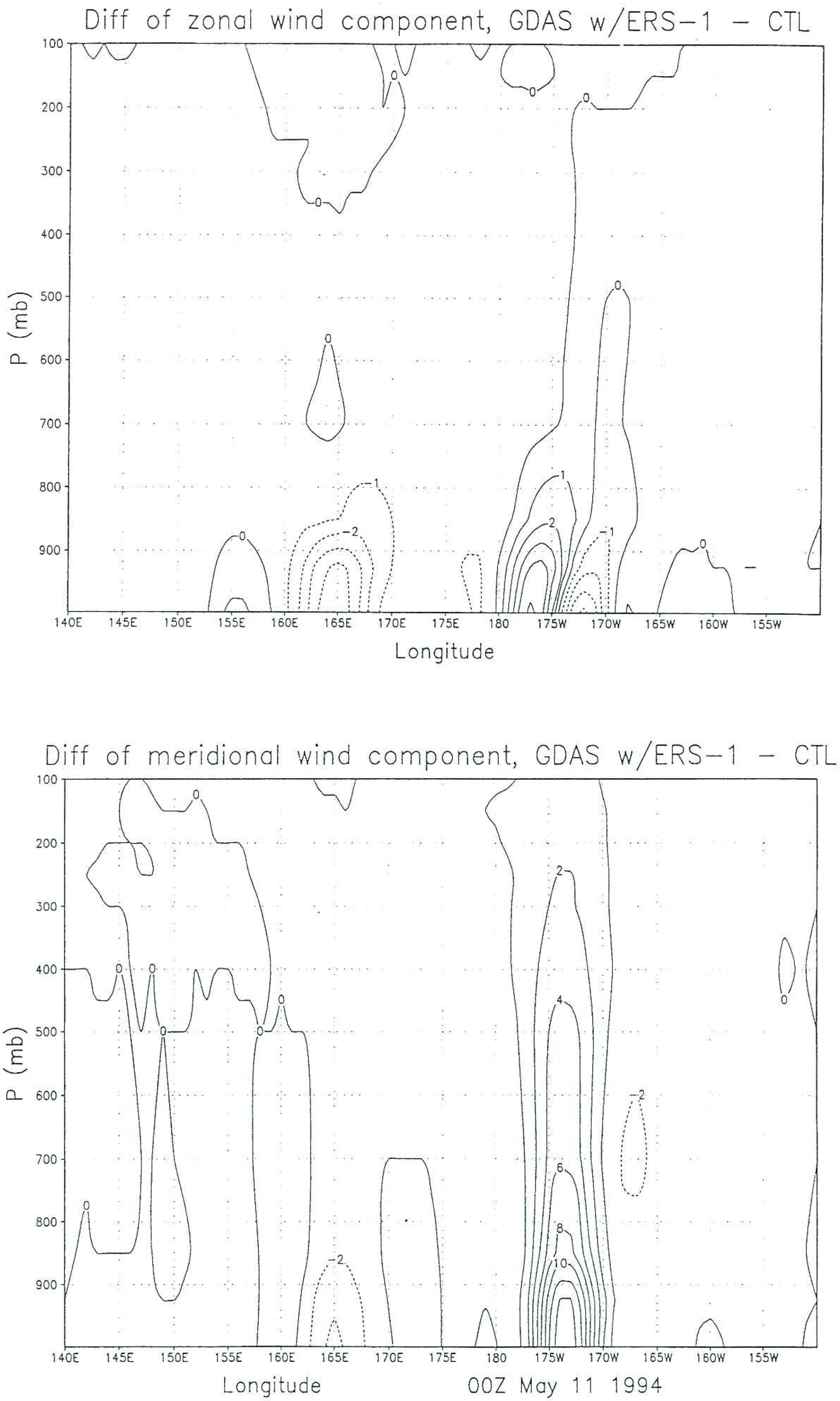


Figure 6: Cross section along 45 N, showing difference between GDAS analysis with ERS-1 data (SUBJECT) and control (no ERS-1). Top: zonal component of wind (m/s), bottom: meridional component of wind (m/s).

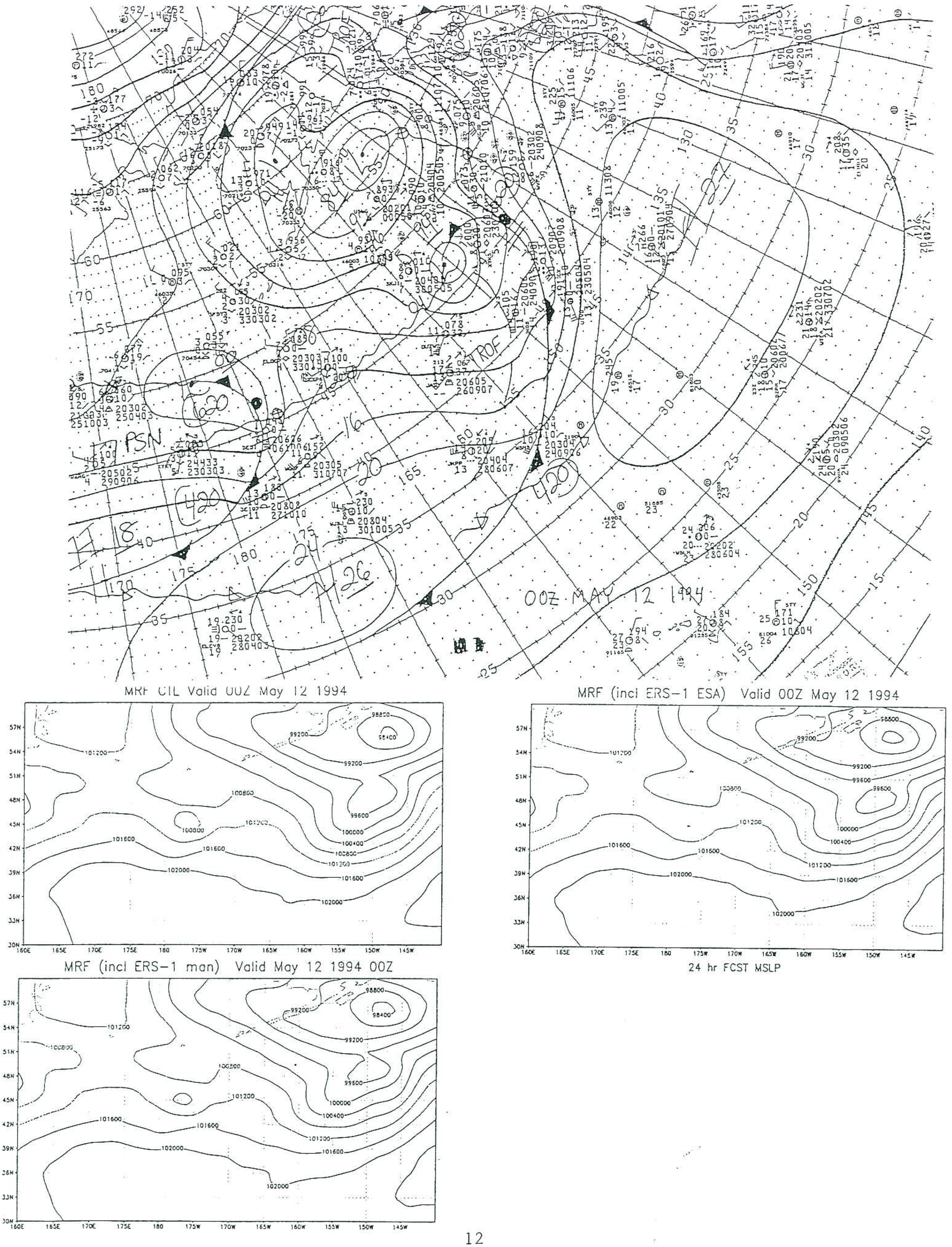
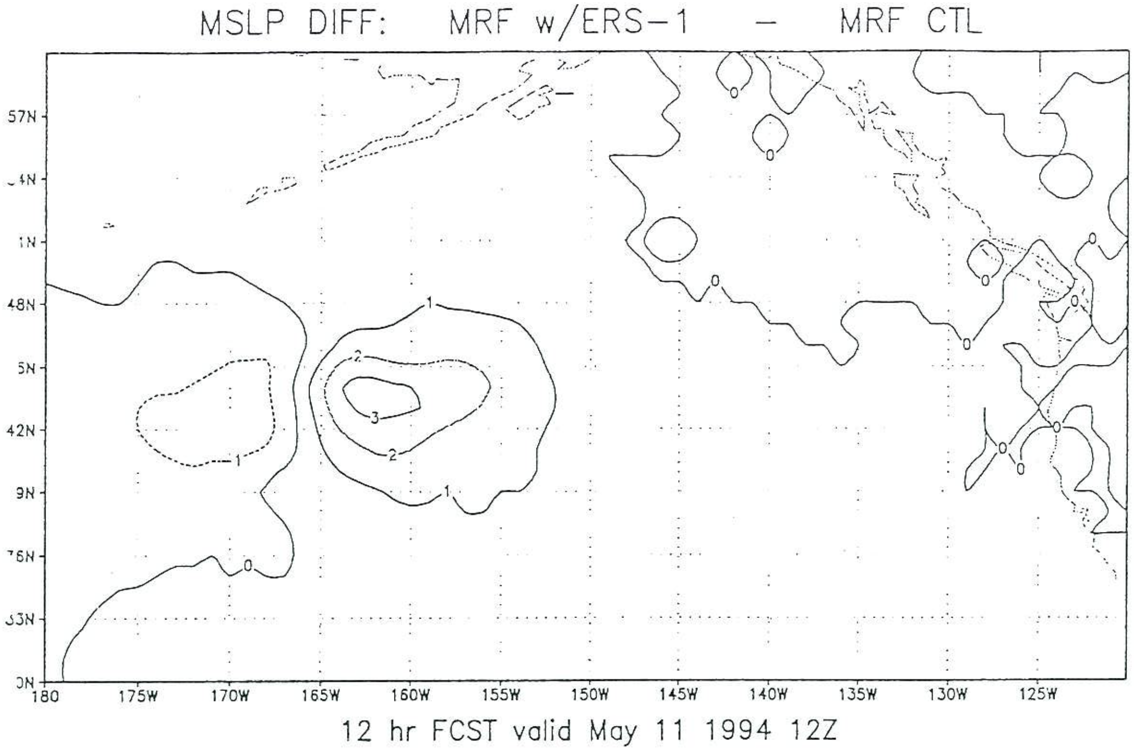
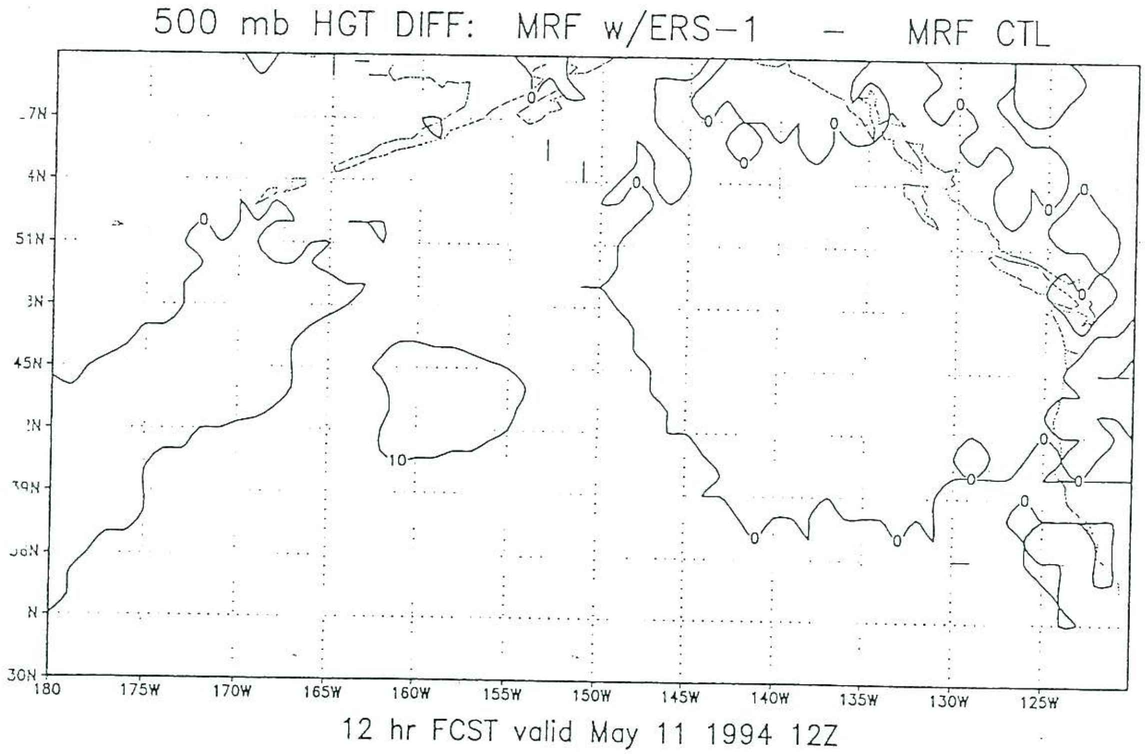


Figure 7 (a): NMC hand analyzed MSLP and fronts, valid 00Z May 12 1994. Bottom (counter clockwise from top left): b. MRF 24 hr forecast MSLP (Pa) verifying at same time; **c.** Same as b, but including ERS-1 subject winds; **d.** Same as b, including ERS-1 ESA winds.


MSLP DIFF: MRF w/ERS-1 – MRF CTL

12 hr FCST valid May 11 1994 12Z


500 mb HGT DIFF: MRF w/ERS-1 – MRF CTL

12 hr FCST valid May 11 1994 12Z

Figure 8: Difference plots showing 12 hour forecasts with ERS-1 winds minus control (no

However, by 48 hours, these dipoles weaken and become more diffuse (figure 9a-b), suggesting that the impact of the data on the forecast is decaying. It appears that for this case, at least, the later forecast of storm A as it evolved was not improved much by the inclusion of scatterometer winds in the analysis. Perhaps this is because the storm was in it's mature stage, and in the de-amplifying rather than the rapidly intensifying stage. While the addition of scatterometer winds to the analysis appears to have only marginally impacted the forecast of storm A, beneficial effects were seen upstream in an improved forecast of storm B. Also, the differing amounts of impact among the three sets of wind vectors used (ESA FD, NCEP/JPL, subjectively enhanced) demonstrates the sensitivity of the model and it's assimilation system to the choice of wind vector retrieval algorithm.

IV. Case 2

The second case studied occurred south of Australia, at 00Z May 2 1994. The general synoptic situation at the surface is shown in figure 10. There was a large and deep cyclone seen in the scatterometer data (NCEP/JPL retrievals) considerably further westward of the GDAS analyzed position. There was no independent surface analysis available for this region, but a visible image from the NOAA-12 satellite verifies the scatterometers' position (figure 11) and confirms the error in the GDAS surface mass field. One might expect to find more instances of large errors in the analysis in the southern hemisphere than in the north, where much more observational data exist. This case may then be typical of a data sparse region in the global model's analysis where assimilation of remotely sensed ocean surface winds has the greatest potential benefit.

As with the previous case described above, attention was first paid to the inclusion of scatterometer winds (using the three different methods of wind vector retrieval) into the model's data assimilation system. A close up of the NCEP/JPL retrieved winds reveals some troublesome areas similar to the problems noted in the May 11 1994 case (figure 12a). Note the generally consistent wind field, except in the area of the GDAS low, which is too far east and probably effected the ambiguity removal in this region due to the use of the GDAS winds in the ranking procedure. The speed minima evident in the scatterometer places the true low at about 149.5E, 55S (marked "L"). To the east and south of this area, some wind directions appear to be incorrectly chosen. This problem is consistent with known troubles with ERS-1 scatterometer winds at the low radar incidence angles (Woiceshyn, personal communication). In this case, the spacecraft was in a descending orbit (southward) and the low incidence angle region was on the inner right hand side of the swath, where the wind directions seem less coherent. The ESA fast delivery winds, shown in figure 12b, appear to be useless, with little coherency. Some manual enhancement of the winds was attempted to correct some of the problematic winds in the NCEP/JPL method (figure 12c). With only the satellite data to work with, however, this is a very subjective effort at best.

Scatterometer winds retrieved using the three different methods (NCEP/JPL, ESA FD, and subjective) were then used in the GDAS to produce a new analysis. Figure 13 shows the results of these runs, along with the control. The lowest sigma level winds are plotted along with the sea level pressure. It is again evident that the addition of the scatterometer winds to the analysis has the effect of weakening and placing the low pressure system more to the northwest, in agreement with the scatterometer winds. Notice that the control (a) has the low at about 57S,

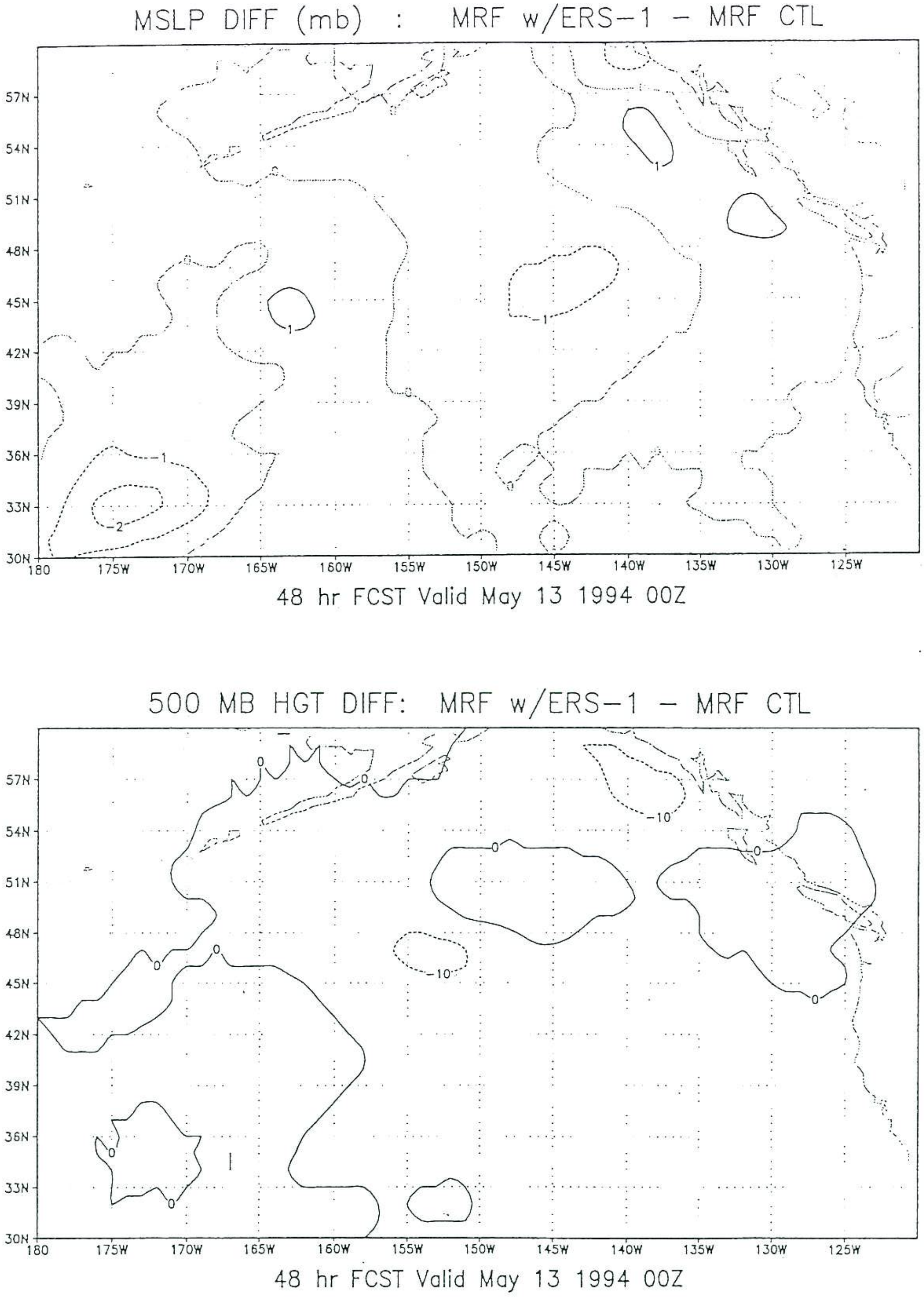


Figure 9: Difference plots showing 48 hour forecasts with ERS-1 winds minus control (no ERS-1), for a. MSLP (mb) and b. 500 mb Height (meters).

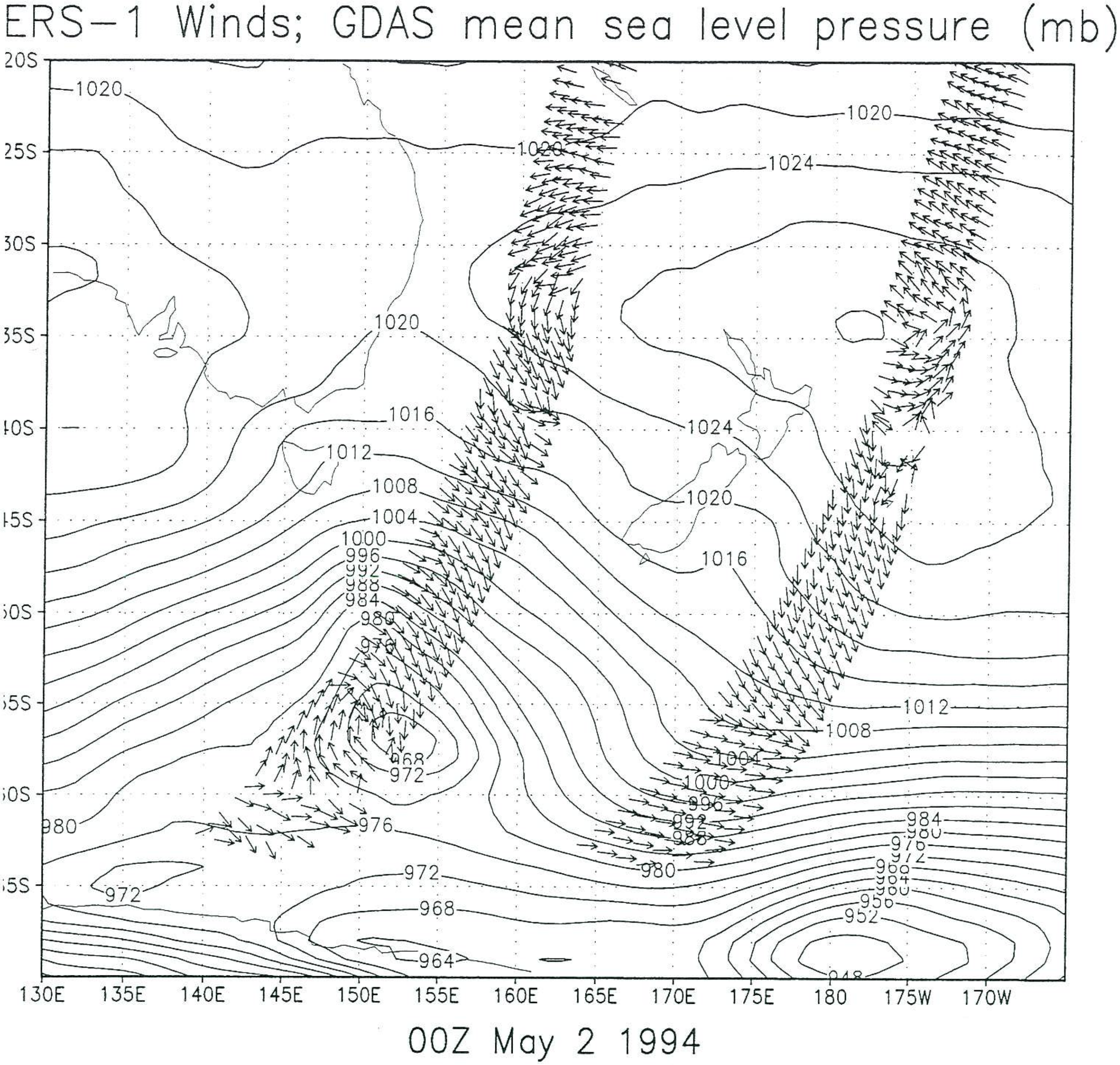


Figure 10: ERS-1 scatterometer winds (NCEP/JPL processing), background mean sea level pressure field from GDAS. Valid 00Z 2 May 1994.

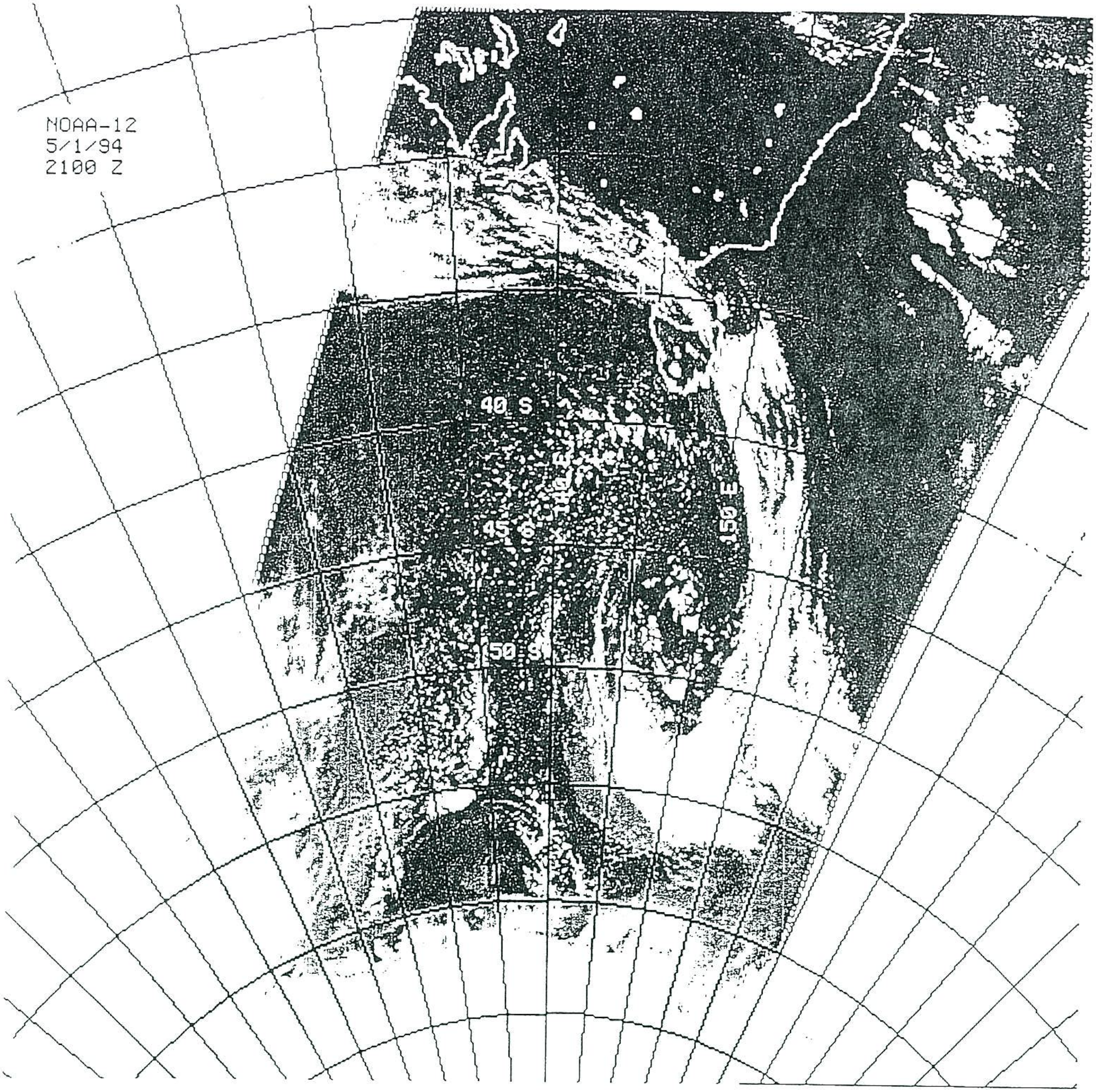
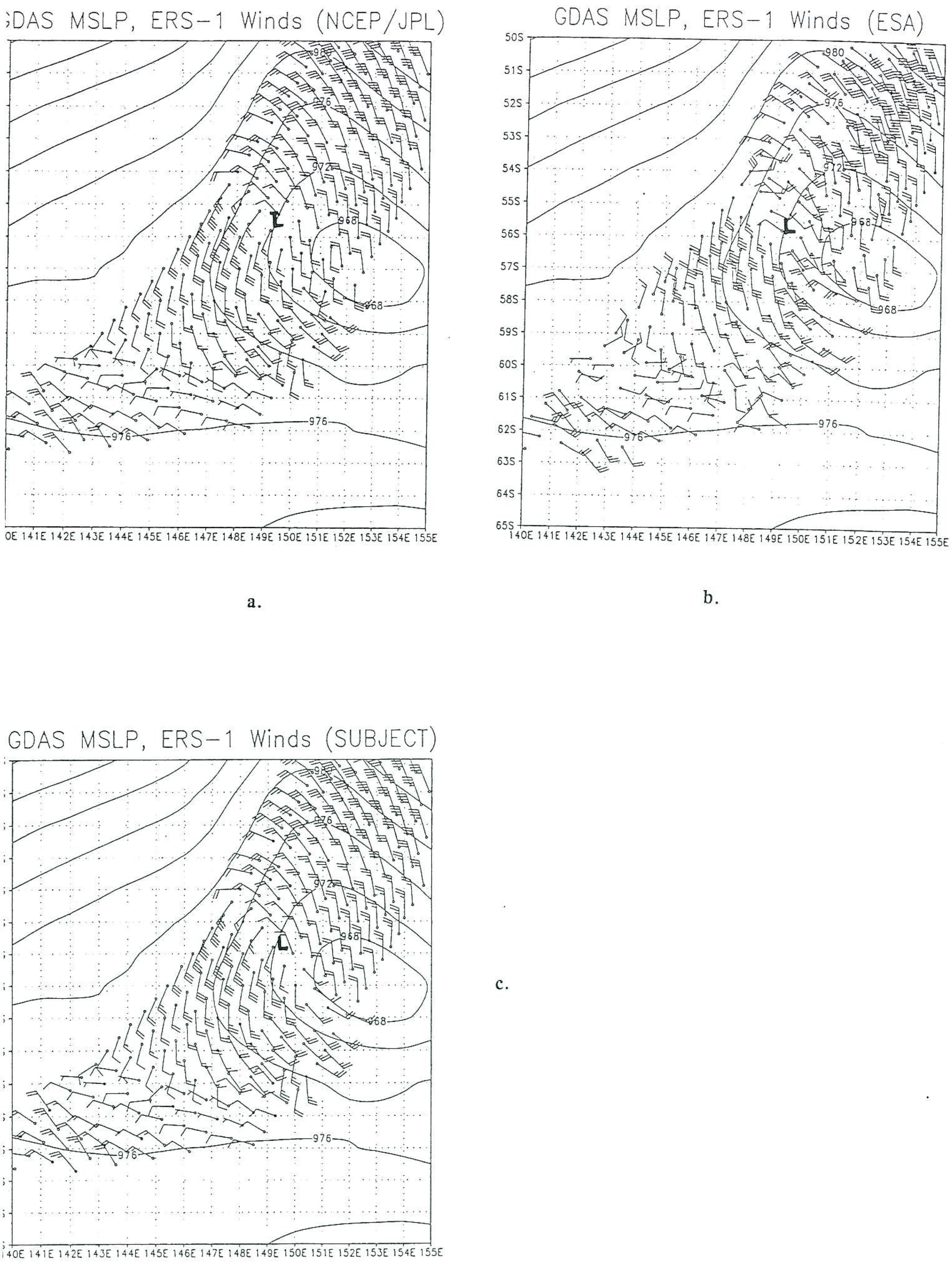


Figure 11: Visible satellite image from NOAA-12, 2100 GMT 1 May 1994 (Latitude lines are mislabelled, add 5 degrees to get correct latitude.)



a.

b.

c.

Figure 12 ERS-1 winds near storm, mean sea level pressure from GDAS (mb) a: NCEP/JPL processed winds, b: ESA FD winds, c: "subjectively" enhanced winds.

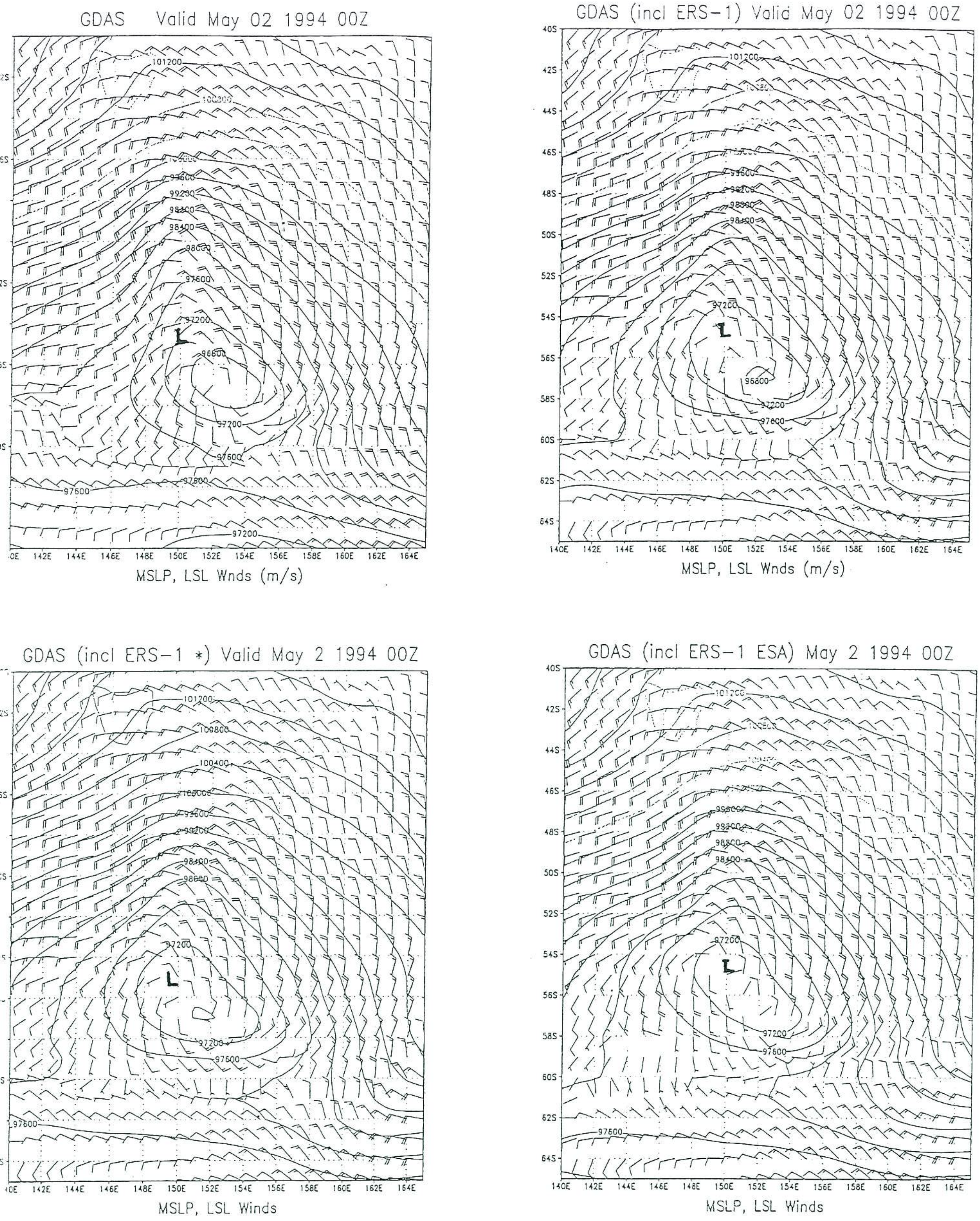


Figure 13: a. MSLP (Pa), surface winds from GDAS analysis valid 00Z May 2 1994 with no ERS-1 data, b. Same but including ERS-1 winds retrieved with NCEP/JPL method, c. Same but with subjectively enhanced winds included in analysis, d. Same but with ESA FD

153E, while the run with the NCEP/JPL winds (13b) pulls it back towards 55S, 150E. The subjectively enhanced winds (13c) have quite the same impact, stretching the whole low west and northward while leaving behind a closed center near 57S, 152E. The ESA winds also show a positive impact in the sea level pressure field (13d), but a look to the south and west of the storm reveals some odd looking winds, suggesting negative impact from the directional ambiguities seen in figure 12b. All three runs which include scatterometer data place the low more northwest towards it's proper position, but fail to totally remove the incorrectly located low pressure center to the southeast. In other words, they cannot totally correct the error in the GDAS, as was seen with the previous case. A cross section along 57S demonstrates the impact of the scatterometer winds on the analysis nicely (figure 14). Two dipoles are present in the difference field for the meridional wind component, each corresponding to a swath of ERS-1 data. In the vicinity of the storm (150E), the influence of the scatterometer winds is shown to extend vertically to about the 500 mb level. The difference field for geopotential height (figure 14, bottom) also shows the ability of the global model's data assimilation system to spread the influence of the surface level ERS-1 data both vertically and horizontally. The geopotential heights are raised east of 150W, and lowered west of 150W, which corresponds to a cyclone further west in the analysis which includes scatterometer winds.

In the previous case (May 11, 1994), the initial positive impact seen in the analysis tended to vanish later in the forecast. A look at the 30 hour MRF forecast from the 00Z May 2 1994 case, with and without scatterometer winds, shows a more encouraging result (figure 15). In the control (a), the low is centered nearly three degrees further eastward than the forecast which includes scatterometer winds (b). Evidently, in this case the inclusion of scatterometer winds in the analysis had a significant impact that persisted into the forecast. An infrared satellite image from the NOAA-11 polar orbiter (figure 16) valid at the same time (06Z May 3) indicates that the forecast with scatterometer data is more correct. The center of the occluded cyclone appears to be near 175E, 70S, which agrees more closely with the slower forecast produced with scatterometer winds in the analysis. Given this result, one might expect even larger impact later in the forecast, as the cyclone moved downstream. Looking at figure 17, we indeed see that differences between runs with and without scatterometer winds grow as the forecast progresses. Figure 17 shows the difference in the 500 mb height field between the control and the run with NCEP-JPL processed scatterometer winds, for 72 hour forecasts (top). Large differences on the order of 40 meters appear throughout the region impacted by the cyclone, and also upstream near it's original location. Note the greater magnitude of these differences than in the initial analysis (bottom), indicating a growing forecast error, and the potential of scatterometer winds to reduce this error.

V. Conclusions

An initial study of the ERS-1 scatterometer winds has identified several cases of significant errors in the position and intensity of cyclones in the Global Data Assimilation System. A more systematic study to determine the frequency of these errors has not yet been attempted, but the limited coverage of this satellite, which produces a relatively narrow swath of data, along with previous work (Atlas, 1996) suggests that errors such as these may be fairly

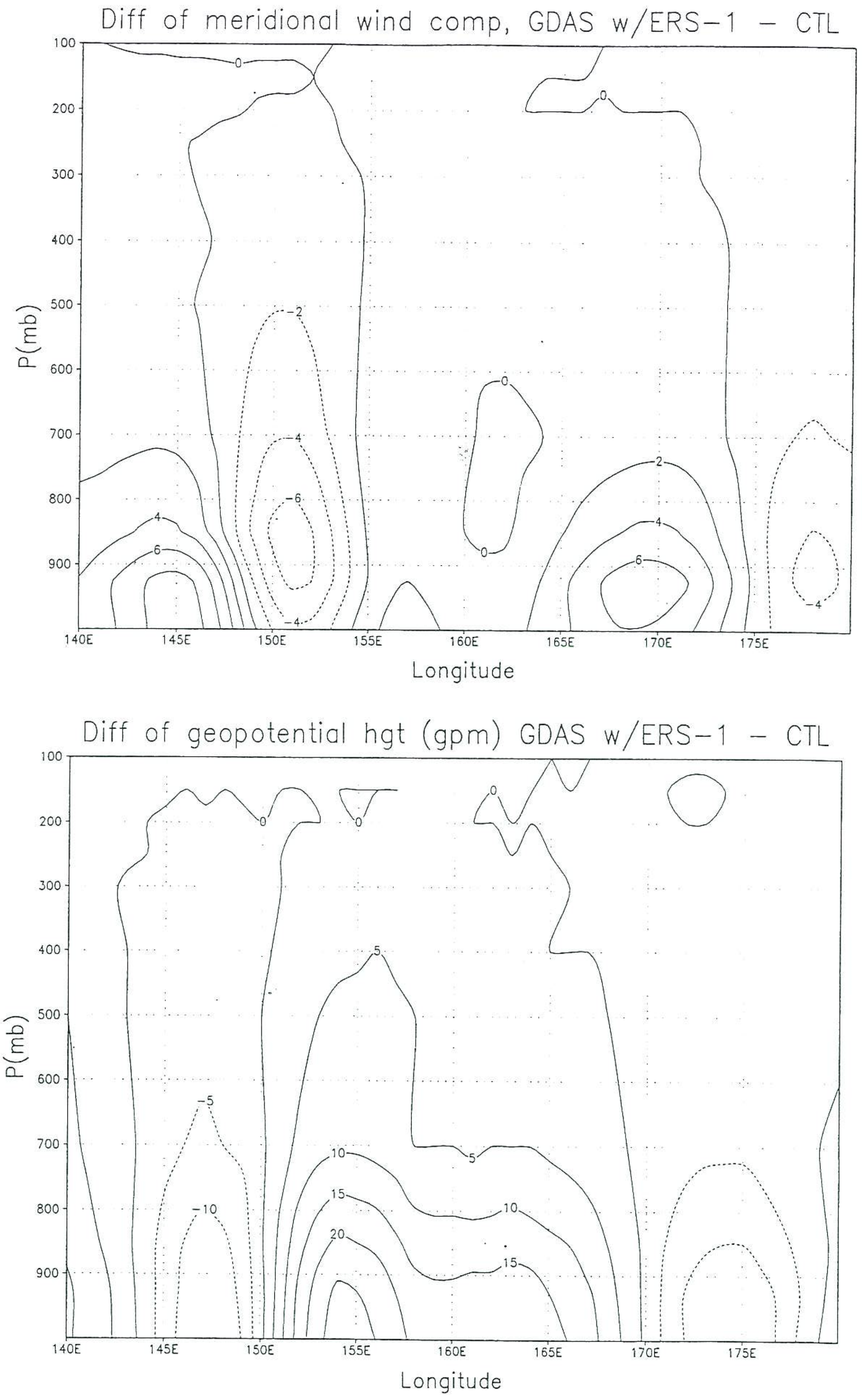
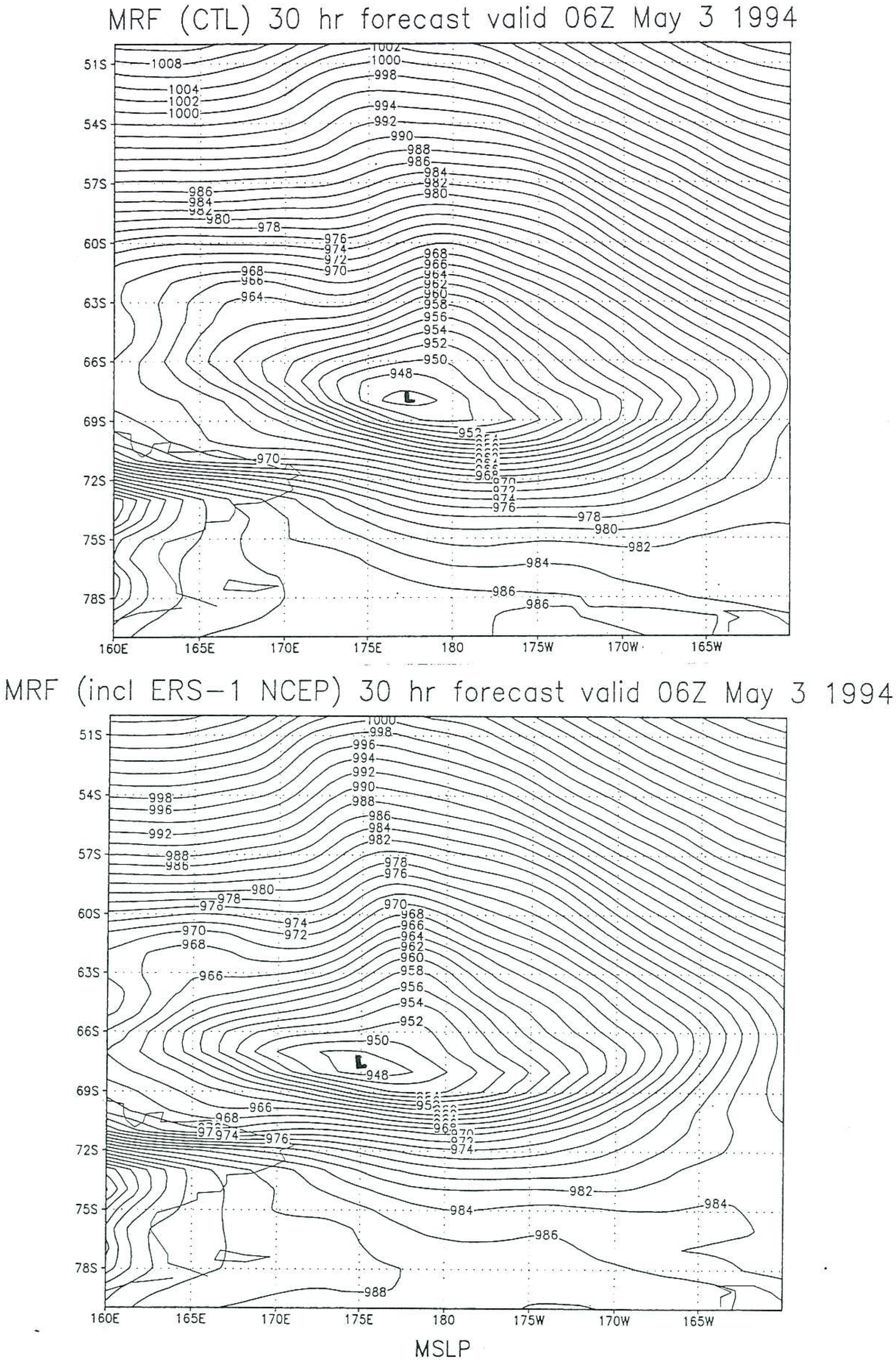


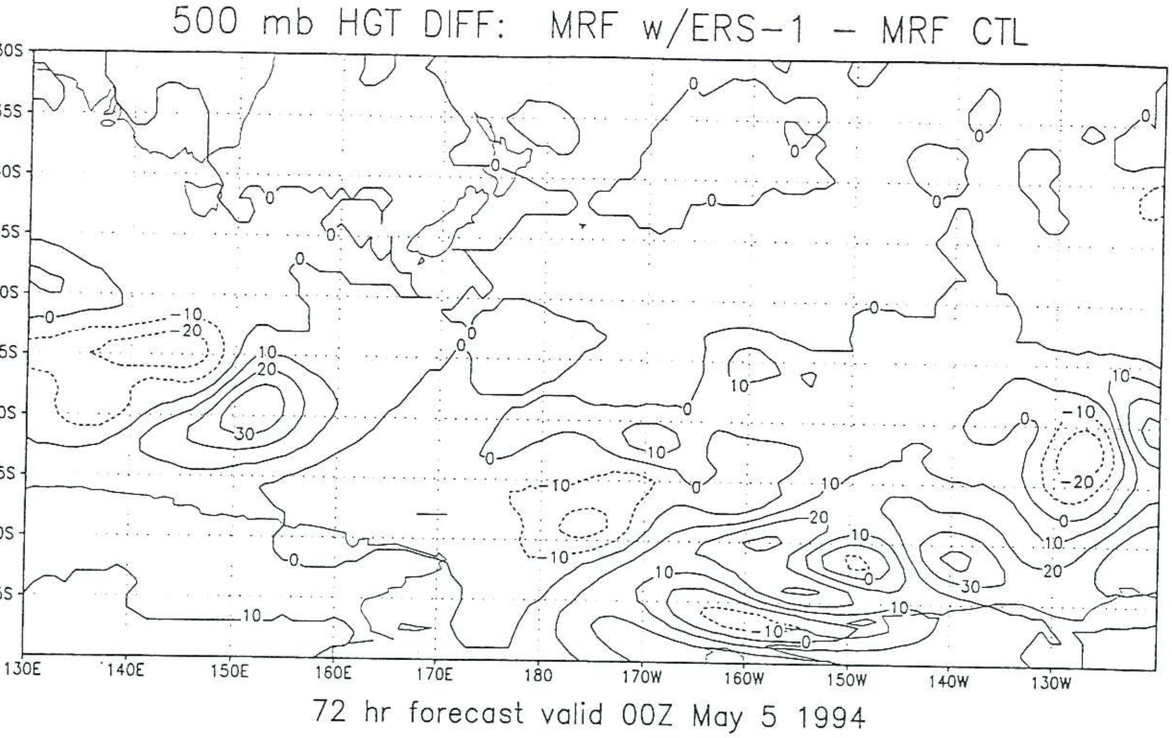
Figure 14: Cross section along 57 S, showing differences between GDAS analysis (00Z May 2 1994) with ERS-1 data (NCEP/JPL) and the GDAS control (no scat). Top: meridional wind component(m/s); bottom: geopotential height (m).


MRF (CTL) 30 hr forecast valid 06Z May 3 1994

MRF (incl ERS−1 NCEP) 30 hr forecast valid 06Z May 3 1994

Figure 15: MRF 30 hour forecast verifying at 06Z May 3 1994, **a.** no ERS-1 data; **b.** including ERS-1 winds (NCEP/JPL).

Figure 16: Thermal image produced by the NOAA-11 polar orbiting satellite, valid at 0558 GMT May 3 1994



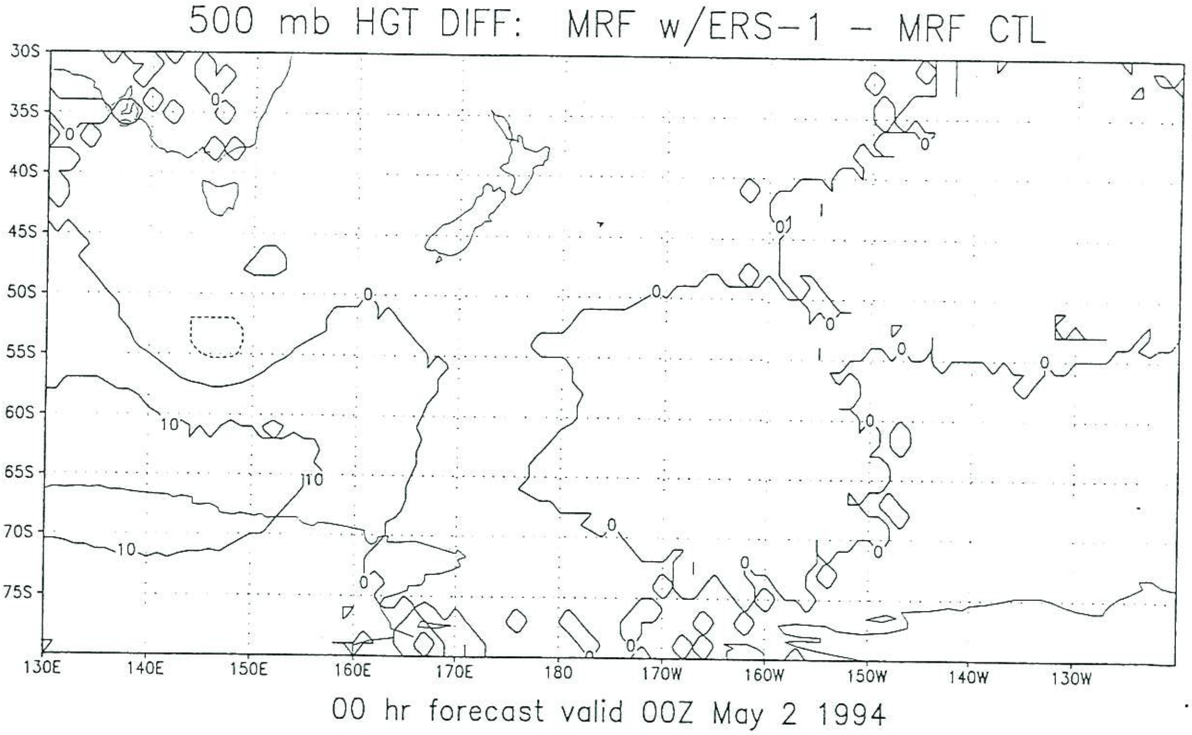


Figure 17: Difference plot of 500 mb height (m), MRF w/ ERS-1 NCEP - MRF control. Top: 72 hour forecast valid 00Z May 5 1994. Bottom: initial analysis on 00Z May 2 1994

common, particularly in the southern hemisphere. For two cases, the current NCEP T126 GDAS was run with and without scatterometer winds included in the assimilation. Various types of processed wind vectors were used to generate forecasts, including the NCEP/JPL retrieved winds now operational at NCEP, the ESA "fast delivery" winds, and the "improved" NCEP/JPL winds, where some areas of inconsistent data were repaired by hand. In both cases, inclusion of scatterometer winds in the GDAS improved the initial analysis by moving an incorrectly placed cyclone towards it's true position. Errors were not completely corrected, however, probably due to the relatively small width of the ERS-1 swaths, covering only part of the cyclone area. In the first case (May 11 1994), the initial correction to the GDAS did not seem to have much impact on the later forecast, indicating that this was not a case of a growing error. In the second case (May 2 1994), however, the impact of inclusion of ERS-1 winds on the later forecast was large and positive, demonstrating the potential of the data to improve the model forecasts. Varying the type of retrieval system used to produce winds for the analysis had the effect of changing the amount of correction to the GDAS error, demonstrating the sensitivity of the GDAS to the ERS-1 vector retrieval algorithm. In the first case, modification of a small number of the NCEP/JPL winds (where ambiguity removal appeared to have failed) resulted in a signifigantly greater correction to the error, suggesting that further refinements to the ambiguity removal process may be worth attempting.

These results are encouraging in that they demonstrate qualitatively the impact of scatterometer winds on the current NCEP global model system. The data are shown to be capable of at least partially reducing errors in the analysis, and in the second case had a significant, positive impact on the later forecast. Since the coverage of ERS scatterometer data is fairly small, one might need to design more sophisticated systems capable of spreading information about large cyclone position errors, such as the ones documented here, beyond the immediate area of data coverage. Also, the reliance of subjective ambiguity removal methods on the use of the model's own surface wind field remains a problem, especially in critical cases when there are large errors present in the model's analysis. The recent launch of the NASA scatterometer on board a Japanese satellite will provide a much larger sampling of the ocean surface wind field, with two 600 km swaths of surface winds along each side of the satellite track. This will hopefully lead to more investigation and answers to the question of impact of remotely sensed ocean surface winds on numerical weather prediction models.

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