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# Utilization of VAS Satellite Data in the Initialization of an Oceanic-Cyclogenesis Simulation

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# Abstract

A series of experiments was performed to test various methods of incorporating VAS-sounding data into the initial conditions of the Penn State University/National Center for Atmospheric Research mesoscale model. The VAS data for this oceanic-cyclogenesis case consist of 110 irregularly distributed temperature and humidity soundings located over the North Pacific Ocean and apply at approximately 1200 GMT 10 November 1981.

The use of the VAS data produced relatively large changes to the National Meteorological Center's (NMC) analysis, which was the only other source of meteorological data over the Pacific Ocean where the modeled cyclone developed. Both static and dynamic initialization procedures were tested. When using reasonable estimates of the vertical distribution of the latent heating associated with the models parameterized precipitation, the cyclogenesis process was only forecast well when the VAS data were used to help define the initial conditions for forecasts initialized during an early stage of cyclogenesis. When the model was initialized 12 h earlier with only large-scale data from the NMC analysis, a good cyclogenesis forecast was also produced. The use of dynamic-initialization and geostrophic correction procedures in order to provide mesoscale structure in the windfield based on the VAS-derived mass-field information, resulted in mixed success and proved to be unnecessary.

In addition to showing that VAS data were a useful supplement, in this case at least, to the operational meteorological analysis over a data-sparse region of the ocean, these results illustrate two other points. First of all, data-impact studies with numerical models frequently assume that the veracity of the initial data is the factor most-seriously impairing forecast quality. From an experimental design standpoint, this is convenient because it is

not feasible to perform a complete predictability assessment for each case in order to determine other limitations imposed by the model's numerics, physical parameterizations and boundary conditions. However, in this case we show that VAS data only had a positive impact when an apparently critical aspect of the precipitation parameterization was properly treated. A reasonable, but perhaps inconvenient, compromise is to perform a modest number of sensitivity tests on each case in order to identify any major "weak links" in the modeling system other than the initial data. Obviously the nature of these tests will depend on the meteorological setting.

Secondly, the need for mesoscale data in defining the model initial state for a forecast will depend on the development stage of the phenomenon (e.g. cyclone, mesoscale convective system) being forecast. In this case, VAS data were not needed in order to provide a good cyclogenesis forecast when the model was initialized in the precyclogenesis period with only a smooth analysis. This is because the model was able to provide the nonlinear interactions, response to surface fluxes, etc. that were necessary to define the precursor conditions for development. In contrast, initialization at a later stage in the development benefited from the additional information or structure provided by VAS because the model was not, in effect, used as a dynamic-initialization device. Thus, the impact of the VAS data was also dependent on the time of the initialization during the life cycle of the phenomenon.

## 1. Introduction

It is expected that the high-horizontal-resolution measurements of atmospheric temperature and moisture that are available from the VAS can be used to improve the analysis and modeling of mesoscale weather systems. This data source may be particularly useful over oceanic regions where the scarcity of data often results in large analysis errors that can adversely influence forecasts for the maritime atmosphere and for downstream land areas.

There are difficulties, however, associated with the incorporation of VAS data into the initial conditions of a numerical model. Because geostrophic adjustment theory predicts that the mass field will adjust to the momentum field more efficiently than the converse on the mesoscale, the combined use of mesoscale temperature data and synoptic-scale wind data presents a problem in assimilation. That is, the use of mesoscale mass-field data in a model does not guarantee the assimilation or retention of the data. However, certain numerical techniques may help avoid the loss of mass-field information that may result as the mass field adjusts to the momentum field during the model integration. Dynamic initialization (e.g Hoke and Anthes, 1976) can be used to force the development of a dynamic balance during a preforecast period, or a geostrophic wind correction (Hayden, 1973; Kistler and McPherson, 1975) can be applied to the model initial conditions. A separate problem relates to the inability of the infrared sounder to probe through clouds. This often results in an irregular spatial distribution and therefore irregular resolution of the VAS data, which creates problems in using the data effectively. Objective analysis techniques that utilize the high-horizontal resolution of the data while avoiding analysis of unrealistic gradients at the edge of the data are necessary. Additionally, four-dimensional data assimilation may be needed to take advantage of the good temporal resolution of the VAS data (Cram and Kaplan, 1985; Gal-Chen et al., 1985).

The primary objective of this study is to experiment with methods of incorporating VAS data into the initial conditions of the Pennsylvania State University/National Center for Atmospheric Research (PSU/NCAR) mesoscale model. The initialization techniques include static initialization, dynamic initialization and the application of a geostrophic wind correction. Using these methods, experiments are performed to investigate whether the VAS is a useful source of information over the ocean for this particular cyclogenesis case. The VAS soundings are located over the North Pacific Ocean and are only available at the initial time of the forecast. The influence of these data on the simulation of a polar low and the associated coastal mesoscale weather patterns is evaluated.

## 2. The polar-low case study

### a. Meteorological summary

A 36-h simulation period, which extends from 1200 GMT 10 November to 0000 GMT 12 November 1981, was used for the experiments. The 12-hourly National Meteorological Center (NMC) surface analyses for this period are shown in Fig. 1. At the initial time of the simulation, a well-developed low-pressure system with a central mean-sea-level (MSL) pressure of 944 mb is situated in the Gulf of Alaska (Fig. 1a). A polar low has begun to develop in the trough that extends southward from this low. During the first 12-h period, the polar low deepens 7 mb to 958 mb as it moves toward the Canadian coast (Fig. 1b). The Gulf low dissipates quite rapidly during this period, filling 14 mb in 12 h. The polar low continues to deepen as it moves northwestward along the Canadian coastline during the second 12-h period. At 1200 GMT 11 November, 24 h into the simulation period, this disturbance is situated in the Gulf of Alaska with a central MSL-pressure of 954 mb (Fig. 1c) and is producing coastal precipitation. A second polar low has begun to develop behind the front which has occluded. This developing low appears in the satellite picture for 1445 GMT 11 November (not shown) as an area of convection. The final 12-h period is marked by the gradual dissipation of the polar low and the movement of the associated fronts inland (Fig. 1d). The observed 36-h cumulative precipitation, most of which falls during the final 12-h period, is plotted in Fig. 2. using logarithmically scaled contours. The results of the simulations are verified with emphasis on the accuracy with which this polar low and the associated coastal weather patterns are predicted.

### b. Influence of VAS on the initial objective analyses

First-guess fields used in the development of all model initial conditions were obtained from the NMC global analysis. Over oceanic regions, this analysis is derived from the NMC 6-h spectral-model forecast and incorporates data from the TIROS-N polar-orbiting satellites. In this particular case, it can be shown that the influence of the TIROS-N data on the 1200 GMT 10 November 1981 global analysis is signicantly smaller than the effect of the VAS data on the anlaysis. Ship and buoy data were incorporated into this analysis to enhance the initial conditions over the ocean. The first-guess fields were supplemented with only radiosonde soundings for some analyses (NOVAS analyses) and with both radiosonde and VAS soundings in others (VAS analyses).

A successive-scan type of objective analysis procedure (Cressman, 1959) was used to enhance the first-guess fields in order to provide initial conditions for the PSU/NCAR mesoscale model. The NOVAS MSL-pressure objective analysis is presented in Fig. 3. The same general features are present in this analysis as in the NMC subjective analysis (Fig. 1a). However, the central pressure of the Gulf low is 12 mb higher in this objective analysis than in the subjective analysis. The apparent low quality of the initial MSL-pressure objective analysis is discussed in Section 6.

VAS data were used in addition to the radiosonde data to improve the first-guess fields for the VAS analyses. The VAS data consist of 110 irregularly but densely distributed soundings whose locations are presented in Fig. 4. The VAS retrievals were processed and edited at the Cooperative Institute for Meteorological Satellite Studies Madison, WI. A physical retrieval algorithm was employed in which the temperature and moisture profiles were determined using a radiative transfer model (Smith, 1983).

The NMC's 12-h Limited-Area Fine-Mesh model forecast was used as the initial guess in the retrieval algorithm. The high-resolution VAS-derived temperature and moisture data were incorporated into the objective analysis by increasing the number of scans of the objective-analysis procedure in the vicinity of these observations.

The incorporation of VAS data produced some marked changes in the initial analyses. The 850-mb NOVAS temperature analysis, with the VAS-minus-NOVAS temperature differences for this level overplotted, is shown in Fig. 5. With temperature differences as large as 5°C in some areas, the VAS data alter the temperatures rather significantly while introducing finer-scale structure into the analysis. Figure 6 shows the initial NOVAS 300-mb geopotential-height analysis with the corresponding VAS-minus-NOVAS height differences overplotted. The high-amplitude trough-ridge pattern depicted in the NOVAS analysis is amplified by the VAS data, which effectively deepen and lengthen the 300-mb trough. The significant VAS-minus-NOVAS differences reflect the VAS-induced changes to the mass field below this level. The 850-mb NOVAS mixing-ratio analysis, with the VAS-minus-NOVAS mixing-ratio differences overplotted, is presented in Fig. 7. The major effect of the VAS data is to shorten the dry intrusion that extends from the Alaskan peninsula into the middle of the domain in the NOVAS analysis.

In summary, the incorporation of the VAS data significantly modifies the standard objective analyses of height, temperature and mixing ratio. Whether these changes represent and improved analyses is, of course, to be determined. A comparison of the numerical simulations initialized both with and without the VAS data can provide a basis for this assessment. The experiments are divided into three categories: static-initialization experiments, dynamic-initialization experiments and sensitivity experiments. These are outlined in Table 1.

## 3. Summary of model features and parameters

The simulations for this study were produced using the PSU/NCAR mesoscale model. A general description of this three-dimensional, hydrostatic, primitive-equation model is found in Anthes and Warner (1978). A horizontal grid with 51 points in the east-west direction, 49 points in the north-south direction and a grid spacing of 86 km was centered at 49°N latitude and 140°W longitude. Use of a Lambert-conformal map projection minimized the distortion at these latitudes. The domain was sufficiently large so that the downstream advective effects of the VAS data could be observed in the forecast.

The mesoscale model employs the sigma vertical coordinate, where $\sigma = (p - p_t)/(p_s - p_t)$, p is pressure, $p_t$ is the constant pressure specified as the top of the model (100 mb in this case) and $p_s$ is the surface pressure. For this case, 12 sigma layer were utilized.

A high-resolution planetary boundary-layer parameterization (Zhang and Anthes, 1982) was used for the simulations. The ground temperature was predicted using a surface energy budget, while the sea-surface temperature was defined as constant in time and based on observations. The simulations were moist, with a stable precipitation module and a Kuo-type precipitation parameterization (Anthes, 1977). The vertical distributions of convective heating and moistening were constant in space and time. Relaxation boundary conditions (Davies, 1976) were used.

## 4. Static-initialization experiments

The static-initialization experiments consist of three 36-h simulations, each beginning at 1200 GMT 10 November 1981. In the control (NOVAS) experiment, EX1A, only radiosonde data were employed to enhance the NMC global analysis used for the first-guess fields. The second static-initialization experiment, EX1B, utilized VAS-derived temperature and moisture data in addition to the radiosonde data to enhance the first-guess fields. A third experiment, EX1C, was performed in which both types of data were used and a geostrophic correction, based on the VAS-derived temperatures, was applied to the wind field. The geostrophic wind correction is a local adjustment of the wind field using VAS-derived mass-field data and the geostrophic relationship. It is designed to prevent the loss of mass-field information that can occur on the mesoscale as the mass field adjusts to the momentum field during a model integration. The procedure consists of adjusting the initial observed winds based upon the difference between the geostrophic wind components calculated from both the VAS and NOVAS temperature analyses. The resulting initial wind field is in approximate geostrophic balance with the VAS-derived initial temperature field. Finally, dynamic balancing of the first two vertical modes of a 13-level (12 layer) version of the PSU/NCAR mesoscale model (Errico, 1986) was used to reduce the high-frequency gravity-wave noise resulting from the static-initializations.

### a. NOVAS simulation

The statically initialized NOVAS simulation, EX1A, which extends from 1200 GMT 10 November to 0000 GMT 12 November 1981, exhibits no polar-low development during this period. The simulated disturbance appears as a polar trough which exhibits the same direction of movement as the actual polar low. However, no low-pressure center develops in this trough. Figure 8 illustrates the movement of the polar trough in terms of the EX1A 12-, 24- and 36-h predicted MSL-pressures. These should be compared with the NMC surface analyses for 0000 GMT 11 November (Fig. 1b), 1200 GMT 11 November (Fig. 1c) and 0000 GMT 12 November (Fig. 1d). The observed rapid dissipation of the Gulf low during the first 24 h of the simulation period is also not accurately predicted in this NOVAS simulation. While the actual Gulf low fills 24 mb during this period, the simulated Gulf low fills only 8 mb. The 36-h predicted MSL-pressure field, however, agrees fairly well with the observations.

The upper-air long-wave pattern translated eastward during the 36-h simulation period, resulting in a breakdown of the high-pressure ridge over western U.S. and Canada. This was predicted reasonably well in the NOVAS simulation, however, moderately large NOVAS-minus-observed geopotential-height differences were calculated over land, where the simulation could be verified against analyses of radiosonde data. The 36-h 500-mb geopotential-height analysis with the NOVAS-minus-observed height differences overplotted are presented in Fig. 9. The largest height differences are located over northwest U.S. and southwest Canada where the negative values indicate that the NOVAS simulation overpredicts the extent to which the ridge has dimished in amplitude.

Most of the observed coastal precipitation occurred within the last 12 h of the 36-h simulation period, as the frontal system associated with the polar low moved inland. In the NOVAS simulation, the heaviest precipitation correctly occurs within this final 12-h period. The predicted 36-h cumulative precipitation is plotted using logarithmically scaled contours in Fig. 10.

This should be compared with the observed precipitation plotted in Fig. 2. The areas of maximum observed precipitation along the coast are predicted well, but the amounts are overpredicted in most areas.

### b. VAS simulations

The development of the polar low is not well-predicted in either of the VAS simulations. However, in EX1B (the VAS simulation without the geostrophic wind correction) a weakly defined pressure minimum appears in the polar trough 24 h into the simulation period, indicating that the VAS data have a slight but positive effect on the development. The introduction of the geostrophic wind correction in EX1C yields a less-well-defined pressure minimum in the polar trough but a 4-mb improvement in the prediction of the central pressure of the Gulf low. In both cases, the effect of the VAS data on the MSL-pressure simulation is small.

The influence of the VAS data is advected northward and eastward during the 36-h period. The downstream effects of these data can be examined by comparing the VAS-minus-observed geopotential-height differences over land. The effect of the VAS data on the error in the 500-mb predicted geopotential height is shown in Fig. 11a for EX1B and in Fig. 11b for EX1C. The plotted quantity is the difference between the absolute value of the NOVAS-minus-observed height differences and the absolute value of the VAS-minus-observed height differences. A positive value of this quantity indicates a positive VAS influence on the magnitude of the error. In EX1B (Fig. 11a), the effect of the VAS data is small and cannot be characterized as either positive or negative over the land portion of the domain. A greater influence of the VAS data is observed when the geostrophic correction is applied to the wind field in EX1C (Fig. 11b)., There is a positive VAS influence south of 55°N, but to the north of this, negative and positive areas exist. One effect of the VAS data in this case is to reduce the large height errors that exist over northwest U.S. and southwest Canada in EX1A. As in the NOVAS simulation, the precipitation is adequately predicted in both VAS simulations.

It is interesting that, even though the geostrophic correction reduced the noise generation by the VAS data, the verification was not improved. The noise, which is calculated in terms of the domain-averaged absolute value of the time derivative of surface pressure, is plotted versus time for EX1A and EX1B in Fig. 12a and for EX1A and EX1C in Fig. 12b. While the incorporation of the VAS data increases the amount of noise that is present during the early stages of the EX1B simulation, this is not the case for EX1C. This suggests that, in one context, the data are "better assimilated" into the model when the geostrophic wind correction is used.

The $S_1$ score (Teweles and Wobus, 1954) is used here as a measure of how accurately the geopotential-height gradients are predicted and is calculated for the land portion of the domain. The 500-mb and 250-mb $S_1$ scores for EX1A, EX1B and EX1C are given in Table 2 for 12, 24 and 36 h. The best $S_1$ scores are produced by the EX1C simulation.

## 5. Dynamic-initialization experiments

A Newtonian-nudging approach to dynamic initialization (Hoke and Anthes, 1976) was used in these experiments to combine the mesoscale VAS data and the synoptic-scale conventional data into a set of balanced initial conditions. Three experiments were performed in which a 36-h forecast period was preceded by a 12-h preforecast period during which certain of the variables were nudged toward 1200 GMT 10 November analyses. In the first of these experiments, EX2A, the temperature and moisture variables were nudged toward NOVAS temperature and moisture analyses. In the second experiment, EX2B, these same variables were nudged toward VAS analyses of these variables. In the third experiment, EX2C, only the u and v wind components were nudged toward a VAS-corrected wind analysis. This analysis was obtained by applying a VAS-derived geostrophic correction to the initial wind field. In this case, the VAS information was introduced into the initial conditions entirely in terms of information contained in the momentum field.

In the examination of the results of the dynamic-initialization experiments, the following questions will be addressed:

- Is dynamic initialization effective in providing a dynamically balanced initial state for, and improving the quality of, the simulations?
- Based on the response of the geostrophic adjustment process, how effective is nudging the mass-field variables relative to nudging the momentum-field variables for the scales involved?
- Does dynamic initialization enhance the assimilation of VAS data in the model, compared to the static-initialization techniques?
- How do the VAS data influence the accuracy of the dynamically initialized forecasts

### a. NOVAS simulation

A polar-low MSL-pressure minimum is predicted in EX2A, the dynamically initialized experiment in which temperature and moisture are nudged toward

NOVAS analyses. However, the development of the polar low is slower than observed and the intensity is less than observed. Even though the polar low has not yet developed by 12 h into the simulation period (Fig. 13a), by 18 h a closed isobar pattern exists (Fig. 13b). The Gulf low has migrated northwestward and is dissipating in agreement with observations. The 24- and 36-h MSL-pressure simulations show the polar low intensifying as it moves into the Gulf of Alaska (Figs. 13c and 13d). The EX2A forecast is also characterized by a reasonable precipitation field and smaller height errors than the statically initialized forecast.

These results represent an improvement over the statically initialized simulations. However, in order to determine if the dynamic-initialization process or simply the earlier initialization time caused the improved forecast, an additional experiment was performed that was statically initialized 12 h prior to the original initial forecast time. That is, it was initialized at the beginning of the preforecast period but did not use dynamic initialization. The development of the polar low is even slightly more accurately predicted in this 48-h simulation (EX2D) than in the above-described 36-h simulation with the 12-h preforecast dynamic initialization (EX2A) . The additional integration time alone was sufficient to allow the generation of mesoscale structure associated with this feature. Even though the improved prediction of the polar low in these NOVAS forecasts is apparently a result of the existence of the 12-h "preforecast" period rather than of the dynamic initialization, the usefulness of the dynamic-initialization procedure in incorporating the VAS data can still be examined.

b. VAS simulations

The successful assimilation of VAS data requires that the influence of the data be retained after the forcing associated with the nudging is turned off. The geostrophic adjustment process must operate in such a way as to cause the nonassimilated variables to adjust to the VAS-defined data that are being assimilated. Recall that one approach used here involved Newtonian nudging toward VAS temperature and moisture analyses while the other involved nudging only toward winds that had been geostrophically corrected using VAS temperature analyses. These two approaches toward dynamic initialization with VAS data were compared in terms of the amount of geostrophic adjustment that occurs during the preforecast period. In order to make this comparison, we define the following ratios.

Let the difference at a grid point between the value of a nudged variable at the end of the preforecast period and the value of the same variable at the end of the same period in the absence of nudging represent the total change in that variable caused by the nudging of that variable. If the nudging is moderately strong so that the nudged field at the end of the 12-h preforecast period is very similar to the analyzed field being assimilated, this difference represents the 12-h forecast error for that variable, that is being eliminated by assimilating that variable. It is then possible to calculate what percentage of this total change occurs through geostrophic adjustment when only the opposing variable is nudged. For example, the quantity

$$\sum_{i=1}^{N} \frac{|V_B - V_D|_i}{|V_C - V_D|_i} \quad ,$$

where N is the number of grid points, provides a measure of the response of the wind field to nudging temperature during the 12-h preforecast period.

At each grid point, $V_B$ is the wind speed that results at the end of the preforecast period during which temperature is nudged (EX2B), $V_C$ is the wind speed that results at the end of the preforecast period during which the wind components are nudged (EX2C) and $V_D$ is the wind speed that results from a 12-h integration without any nudging (EX2D). Similarly,

$$\sum_{i=1}^{N} \frac{|T_C - T_D|_i}{|T_B - T_D|_i}$$

quantifies the response of the temperature field to nudging the wind components in EX2C. Again, all values of the variables apply at the original initial forecast time and the subscripts refer to the experiment. Even though other variables could have been used to reflect wind- and mass-field changes, a comparison of these two quantities at each model level does provide a relative measure of the model atmosphere's response to the nudging at that level. Both quantities are plotted in Table 3 for each model computational level. Based on an unweighted arithmetic average for all model levels, 82 percent of the total change in wind speed that is produced by directly nudging only the wind is also introduced by nudging only the temperature. Analogously, an average of 81 percent of the total change in temperature that is produced by only nudging the temperature is also introduced by only nudging the wind. Clearly the changes produced in one variable by nudging the other are not entirely geostrophic in nature and are partly related to gravity modes rather than geostrophic modes. However, these results do imply that, on this scale, assimilation of wind and temperature data can be equally effective from a geostrophic adjustment standpoint.

Model noise parameters such as the one discussed earlier can be used as an indicator of dynamic imbalances in the initial conditions and can thus also provide information about how well the VAS data are assimilated. The noise parameter shown in Fig. 14 takes the form of the domain averaged magnitude of the second derivative of surface pressure with respect to time, and is plotted for the 36-h period of the three dynamically initialized simulations. In Fig. 14a, the NOVAS simulation, EX2A, is compared with EX2B in which temperature and moisture are nudged toward VAS-derived analyses. In Fig. 14b, the NOVAS simulation is compared with EX2C in which the u and v wind components are nudged toward a VAS-corrected wind analysis. Imbalances that result when the nudging term is set to zero in the predictive equations at the end of the preforecast period are manifested as an initial surge in the noise level in all three experiments. In both EX2B and EX2C, the preforecast assimilation of the VAS data produces only a modest additional increment in the magnitude of this noise statistic later in the forecast period.

The EX2B simulation, in which temperature and moisture were nudged toward VAS-derived analyses of these variables, is somewhat more accurate in predicting the development of the polar low than the corresponding NOVAS nudging experiment, EX2A. A plot of the differences between the central pressures of both simulated polar lows and of the observed polar low is presented in Fig. 15. This shows that the polar low correctly develops 12 earlier in the VAS simulation and also verifies better (by ~2 mb) in terms of the central pressure. Obviously neither of the simulated storms are deep enough, but the error diminishes considerably during the forecasts as the slower model cyclogenesis takes place. No polar-low MSL-pressure minimum is observed in EX2C, the VAS simulation in which the wind components were nudged.

The extent to which the VAS data affect the prediction of geopotential height in the dynamically initialized VAS simulations can be evaluated by comparing the NOVAS-minus-observed height differences with the

VAS-minus-observed height differences, as was done before. The difference between the absolute values of these two quantities at 36 h(not shown) indicates that VAS produced no systematic improvement or degradation in the forecasts.

The $S_1$ score is also used here to measure the accuracy with which the geopotential-height-field gradients are predicted. The 500 and 250 mb $S_1$ scores for the dynamically initialized experiments are given in Table 4 for 12, 24 and 36 h. EX2B, the VAS experiment in which temperature and moisture are nudged toward VAS-derived analyses, exhibits slightly better $S_1$ scores than the others.

In summary, nudging the temperature and moisture variables toward VAS-derived analyses produces a reasonably successful simulation that shows a slightly positive VAS influence with respect to the development of the polar low. Nudging the wind variables toward a VAS-derived wind analysis produces a simulation that is unsuccessful in generating the mesoscale polar low and also has a negative influence on the prediction of geopotential height.

## 6. Sensitivity experiments

Sensitivity experiments were performed to determine whether weak links in the analysis-forecast system other than initial-data quality may have lessened the impact of the VAS data on the forecast skill.

### a. Adjustment of the latent-heating profile

Consideration was given to the fact that the vertical partitioning of latent heating can be important for cyclone development by the model. In the Kuo-type cumulus parameterization scheme used here, the vertical distribution of convective latent heating is specified as constant in both space and time. The weighting function that is normally used to define the distribution in this model is based upon a modified Yanai et al. (1973) heating-rate profile that is appropriate for deep, intense convection. Figure 16a illustrates this normalized profile used in the original experiments. Note that the maximum heating rate is located at approximately 450 mb. Because the vertical distribution of convective latent heating can be a controlling parameter in the growth of cyclones (Anthes and Keyser, 1979), it was recognized that the polar low could possibly be simulated more realistically with a convective-heating profile that is more appropriate for middle and high latitudes than is the Yanai profile. Therefore, a new normalized heating-rate profile was constructed based upon the one used by Sardie and Warner (1985) in their successful polar-low simulations with this mesoscale model. They found from the use of a typical Pacific polar-low temperature and moisture sounding in a one-dimensional cloud model, that the convective-heating maximum appropriate for their case existed relatively low in the troposphere compared to the one in the modified Yanai profile. Based on these results, the new heating-rate profile has a maximum at about 700 mb (Fig. 17b); thus, the proportion of convective latent heat that is released in the lower troposphere is increased. Two experiments were performed using this new latent-heating profile. These consisted of a statically initialized NOVAS experiment, EX3A, (an EX1A analog), and a statically initialized VAS experiment, EX3B (an EX1C analog).

Despite this rather large modification to the normalized weighting function for convective heating, the predicted MSL-pressures in EX3A are quite similar to those predicted in EX1A, the other statically initialized NOVAS simulation that utilized the original heating profile; i.e. the polar-low development was forecast poorly. Use of the adjusted heating profile also has only a slight effect on the prediction of precipitation. However, the use of the VAS data now has a more pronounced positive effect on the simulation compared to when the old heating profile was used in EX1C. The 12-h MSL-pressure simulation (Fig. 17a) shows a pressure minimum developing in the polar trough. By 18 h (Fig. 17b), a polar low has developed with a central pressure of 967 mb. While the intensity of this disturbance is less than observed, the forecast shows considerable improvement over the previously discussed static-initialization experiments. The polar low continues to intensify throughout the remainder of the simulation period as it moves into the Gulf of Alaska. This is accompanied by the dissipation of the Gulf low and is illustrated by the 24-and 36-h MSL-pressure forecasts shown in Figs. 17c and 17d.

To compare the development of the polar low in EX3B with that of the observed polar low, the central pressure of each is plotted versus time in Fig. 18. For times prior to the development of the polar low in the simulation, the pressure in the polar trough, at the expected location of the polar low, is plotted. The large initial difference in central pressure decreases with time as the simulated polar low deepens more rapidly than the observed polar low and then continues to deepen while the observed polar low fills. The movement of the observed and simulated polar lows is plotted at 6-h intervals in Fig. 19. While the simulated polar low initially lags the observed polar low, the track is generally well predicted.

In summary, the lowering of the convective-heating maximum, in EX3A, does not, by itself, lead to the development of the polar low. Nor does simply the incorporation of the VAS data alone in EX1C. However, a combination of the two produces a reasonably successful polar-low simulation. This shows that the use of a reasonable latent-heating distribution is very important for the proper forecasting of the polar-low development. Also, because latent heating in the model can be highly sensitive to the initial moisture field (Anthes and Keyser, 1979), and because the cyclogenesis process can depend on static stability, it is reasonable that the VAS temperature and moisture data were able to have a positive impact and that the degree of this impact depended on the vertical distribution of the parameterized fraction of the latent heating.

### b. Refinement of the MSL-pressure initial conditions

In the second sensitivity experiment, the initial MSL-pressure objective analysis (Fig.3), defined using the standard PSU/NCAR software, was refined based upon the NMC subjective surface analysis for 12 GMT 10 November 1981 (Fig. 1a). Specifically, the large discrepancy was corrected between the central pressure of the objectively analyzed Gulf low and the subjectively analyzed Gulf low. The central pressure of this low is 956 mb in the original objective analysis but is 944 mb in the NMC surface analysis. It was recognized that interactions between the Gulf low and the polar low may have affected the development of the polar low. Thus, the accuracy with which the

Gulf low is initialized may influence the skill with which the polar low is predicted.

The initial MSL-pressure objective analysis was adjusted by incorporating 12 hypothetical surface pressures and temperature soundings into the objective analysis. In order to maintain hydrostatic consistency with the new sea-level pressures, the temperatures were adjusted through the depth of the atmosphere that was affected by the disturbance. The adjusted MSL-pressure field and the locations of the hypothetical soundings are shown in Fig. 20.

Two experiments were performed using the refined initial conditions. These are statically initialized without and with the use of VAS data and are referred to as EX3C and EX3D, respectively. The new accurate representation of the Gulf low in the initial conditions of EX3C allows the dissipation of this low to be predicted accurately, but only during the first 18 h of the simulation. The polar low is still not predicted, however. The effect of the VAS data in EX3D is small, resulting in a simulation quite similar to that of EX3C. The results indicate that the initial intensity of the Gulf low has little effect on the development of the polar low, at least in the model atmosphere.

## 7. Summary and conclusions

One important step in evaluating the usefulness of VAS satellite data in improving the forecast skill of atmospheric models is to determine how the data can be most effectively incorporated into the model initial conditions. Therefore, the primary objective of this study was to evaluate various methods of utilizing VAS data in the initial conditions of a mesoscale model. The VAS data that were used for this oceanic-cyclogenesis study consist of 110 irregularly but densely distributed soundings of atmospheric temperature and moisture. They are located over a region of the North Pacific Ocean where no conventional upper-air data are available and are valid at approximately 1200 GMT 10 November 1981. At this time, a polar low was developing in the VAS-data region. During the subsequent 36 h, this disturbance intensified quite vigorously. A series of numerical experiments was performed using the PSU/NCAR mesoscale model to investigate the effect of the VAS data on the forecast development of this cyclone and associated coastal weather patterns.

A straightforward use of the VAS temperature and moisture data in a static initialization of the mesoscale model had a small but slightly positive influence on the simulation. In spite of some rather large VAS-induced changes to the initial analyses, the overall effect of the data on the forecast skill was small. This suggested the possibility that the VAS-derived mesoscale mass-field information may have been lost as the mass field adjusted to the momentum field during the model integration. To lessen this possible loss of information, a geostrophic correction, based upon the VAS-derived temperature analyses, was applied to the initial wind field in a second static-initialization experiment that utilized the VAS data. The use of these adjusted/balanced winds in addition to the VAS temperature and humidity data had a small positive influence on the MSL-pressure, however there was little net improvement in other aspects of the forecast. The actual development of a pressure minimum associated with the polar low was not predicted in any of these statically initialized forecasts.

It is well recognized that the vertical distribution of latent heating can be an important parameter in controlling the growth of cyclones. Therefore, in order to determine whether the distribution function for the latent heating associated with the parameterized precipitation in this form of the model was limiting the impact of VAS-based improvements in the initial conditions, a sensitivity experiment was performed that used a latent-heating profile that was possibly more appropriate than the one used in the original experiments. While the NOVAS simulation was not sensitive to this adjustment, a polar low did develop in the VAS simulation. Thus, a significant positive influence of the VAS data, with respect to the polar-low development, was exhibited when these data were used in combination with the adjusted latent-heating profile and a geostrophic wind correction. The VAS-defined mesoscale detail in the initial moisture and temperature analyses may have only become important once the latent-heating distribution became less of a limiting factor.

In further studies, dynamic initialization by Newtonian nudging was used to assimilate the VAS data during a preforecast period in order to produce a set of dynamically balanced initial conditions that were consistent with the model equations. Two approaches toward dynamic initialization with VAS data involved nudging the temperature and moisture variables toward VAS-derived analyses of these variables and nudging the u and v wind components toward a VAS-corrected wind analysis. Both methods seemed to be equally effective in promoting an initial dynamic balance by forcing the geostrophic adjustment of the un-nudged variables to the nudged variables during the preforecast period. However, elevated inertial-gravity wave noise levels during the early stages of the simulations indicated that the incorporation of the VAS data did create some imbalances. Using the first approach, the development of the polar low and the evolution of the Gulf of Alaska low were reasonably well predicted. However, this was apparently a result of the extended integration period rather than of the dynamic initialization itself. In fact, when the integration period was extended by statically initializing the forecast 12 h earlier, this feature developed slightly more accurately without nudging than with nudging. Nevertheless, nudging toward the VAS-derived temperature and moisture analyses during the preforecast period showed an improvement over nudging toward the NOVAS temperature and moisture analyses. These results make most sense when it is recognized that the model-simulated physical and dynamical processes can and should provide realistic storm-scale structure to the meteorological fields as the forecast proceeds. Nonlinear interactions can introduce smaller scales to the solution, various instability mechanisms (baroclinic, barotropic, CISK) can produce storm-scale circulations and the simulated surface fluxes of heat, momentum and moisture can provide vertical structure not found in the initial conditions. So in some circumstances, the model itself may provide a "self-initialization" during a preforecast period that is as good as, or better than, a dynamic initialization during this same period in which the assimilation of data can introduce noise and possibly interfere with the normal dynamics.

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# FIGURE CAPTIONS

Fig. 1. NMC surface analyses for 1200 GMT 10 November (a), 0000 GMT 11 November (b), 1200 GMT 11 November (c) and 0000 GMT 12 November 1981 (d). Contour interval is 8 mb. Dashed lines represent contours at 4-mb intervals.

Fig. 2. Observed 36-h cumulative precipitation for the period 1200 GMT 10 November to 0000 GMT 12 November 1981. Contours are of $P = \ln(R + 0.01) + 4.6$, where R is rainfall in cm.

Fig. 3. MSL-pressure objective analysis (mb) for 1200 GMT 10 November 1981. Contour interval is 8 mb. Dashed lines represent contours at 4-mb intervals.

Fig. 4. NMC surface analysis for 1200 GMT 10 November 1981 with the approximate locations of the VAS soundings overplotted (*).

Fig. 5. NOVAS 850-mb temperature analysis (solid in °C) with the corresponding VAS-minus-NOVAS temperature differences (dashed in °C) overplotted. The contour interval of the isotherms is 2.5°C. The contour interval of the temperature-difference isopleths is 1°C.

Fig. 6. Initial NOVAS 300-mb geopotential-height analysis (solid in m) with the corresponding VAS-minus-NOVAS height differences overplotted. The contour interval for height is 120 m. The contour interval of the height-difference isopleths is 20 m.

Fig. 7. Initial NOVAS 850-mb mixing-ratio analysis (solid in g $kg^{-1}$) with the corresponding VAS-minus-NOVAS mixing-ratio differences (dashed in g $kg^{-1}$) overplotted. The contour interval for mixing ratio is 2 g $kg^{-1}$. The contour interval of the mixing-ratio-difference isopleths is 1 g $kg^{-1}$.

Fig. 8. Predicted MSL-pressure (mb) for EX1A at 12 h (a), 24 h (b) and 36 h (c). The contour interval is 8 mb. Dashed lines represent contours at 4-mb intervals.

Fig. 9. Observed 500-mb geopotential heights (solid in m) at 36 h with the corresponding NOVAS-minus-observed height differences from EX1A (dashed in m) overplotted. The contour interval for height is 120 m. The contour interval for the height difference isopleths is 30 m.

Fig. 10. Predicted 36-h cumulative precipitation from EX1A. Contours are of $P = \ln(R + 0.01) + 4.6$, where R is rainfall in cm.

Fig. 11. Difference between the absolute value of the NOVAS-minus-observed height differences (m) from EX1A and the absolute value of the VAS-minus-observed height differences (m) from EX1B (a) and EX1C (b) for 36 h at 500 mb. A positive value of this quantity indicates a positive VAS influence.

Fig. 12. Noise as shown by the temporal variation of $|\partial p^*/\partial t|$ in EX1A and EX1B (a) and EX1A and EX1C (b).

Fig. 13. Predicted MSL-pressure (mb) for EX2A at 12 h (a), 18 h (b), 24 h (c) and 36 h (d). The contour interval is 8 mb. Dashed lines represent contours at 4-mb intervals.

Fig. 14. Noise as shown by the temporal variation of $|\partial^2 p^*/\partial t^2|$ in EX2A and EX2B (a) and EX2A and EX2C (b).

Fig. 15. Difference (mb) between the central pressure of the observed polar low and the central pressure of the simulated polar low based on EX2A and EX2B, as a function of time (h).

Fig. 16. Normalized heating profile based on Yanai et al. (1973) (a) and Sardie and Warner (1985) (b).

Fig. 17. Predicted MSL pressure (mb) for EX3B at 12 h (a), 18 h (b), 24 h (c) and 36 h (d). The contour interval is 8 mb. Dashed lines represent contours at 4-mb intervals.

Fig. 18. Central MSL pressure (mb) as a function of time (h) for the polar low, based on observations and EX3B. Prior to the development of the polar low in EX3B, the pressure in the polar trough, at the expected location of the polar low, is plotted.

Fig. 19. Movement of the polar low based on observations and EX3B. The dots represent the 6-hourly observed and predicted positions of the center of the polar low.

Fig. 20. MSL-pressure objective analysis (mb) after adjustment, for 1200 GMT 10 November 1981. The contour interval is 8 mb. Dashed lines represent contours at 4-mb intervals. Circles indicate the locations of the hypothetical soundings.

Table 3. Response of the model variables to nudging.

| Model Level | Approximate Pressure (mb) | $\frac{\lvert V_B - V_D \rvert}{\lvert V_C - V_D \rvert}$ | $\frac{\lvert T_C - T_D \rvert}{\lvert T_B - T_D \rvert}$ |
|---|---|---|---|
| 1 | 150 | .86 | .85 |
| 2 | 250 | .81 | .86 |
| 3 | 340 | .77 | .91 |
| 4 | 440 | .72 | .84 |
| 5 | 540 | .72 | .90 |
| 6 | 640 | .83 | .74 |
| 7 | 740 | .95 | .69 |
| 8 | 820 | .92 | .66 |
| 9 | 883 | .98 | .90 |
| 10 | 937 | .91 | .84 |
| 11 | 982 | .76 | .84 |
| 12 | 995 | .61 | .73 |