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A manual method for calculating large scale tendency (LST) terms for the Navy Over-Water Local Atmospheric Prediction System (NOWLAPS) is adapted from an automated, central-site method utilizing forecast fields from the Navy Operational Global Atmospheric Prediction System (NOGAPS). This report describes the design and use of the LST terms, and compares NOWLAPS predictions for an oceanic weather station ship to those of the Navy Operational Local Atmospheric Prediction System (NOLAPS) and persistence. NOWLAPS, a one-dimensional planetary boundary layer (PBL) model, is designed primarily for shipboard use and was adapted to the Hewlett-Packard 9845 computer under a previous contract. Although it can be run as a single-station PBL forecast model, NOWLAPS can not be a competitive forecast tool until horizontal advection is included or parameterized.

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DETERMINING LARGE SCALE TENDENCY TERMS FOR THE NAVY OVER-WATER LOCAL ATMOSPHERIC PREDICTION SYSTEM (NOWLAPS)

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Publisher's Note

Attachments A and B to this report, referenced in text -- Surface Synoptic Analyses, and NOLAPS/NOWLAPS Sounding Plots, respectively -- will be of limited interest to most readers/users of this report, and therefore are published separately. Copies of the attachment(s) will be provided upon written request.

Attachment A (62 pp) comprises descriptions of the synoptic conditions of the 29 cases addressed in the main report, with accompanying surface synoptic analysis charts.

Attachment B (112 pp) comprises plots of soundings, versus height, for potential temperature, specific humidity, wind speed, and wind direction, for the 29 cases.

1.0 INTRODUCTION

1.1 Summary

The purpose of this final report is to document the development and testing of a technique for determining the large-scale tendency terms for the Navy Over-Water Local Atmospheric Prediction System (NOWLAPS). The delivery order (QE-02) which encompasses this work is partitioned into three tasks, discussed in Sections 2 through 4, which respectively describe the technique developed, its testing, and this final report.

1.2 Background

The NEPRF higher order closure (HOC) model is a one-dimensional, turbulence model designed primarily for shipboard prediction of planetary-boundary-layer (PBL) characteristics such as fog, boundary layer winds and atmospheric refractivity. This model has been adapted to the HP9845B, option 275, under a previous contract. Although now runnable as a single-station PBL forecast model, NOWLAPS's full utility cannot be attained until a method for determining the large-scale tendency (LST) terms of the momentum and thermodynamics variables is defined. Such a method has been available for mainframe, central site, HOC-model running. However, on board ship or at a remote land location there is no present way of accessing all of the numerical fields available on the central-site mainframe. As a result, there must be a means of determining, by hand or with microcomputer assistance, these LST terms from available shipboard data. The purpose of this contract is to determine and exercise such a technique.

1.3 Statement of Work

As specified in the Statement of Work for Contract No. N00228-84-D-3155, Delivery Order No. QE-02 consists of three tasks.

1.3.1 Task 1--"The contractor shall review the current, central-site method of determining the LST terms and define a manual method for determining these same terms from the 700 mb and 850 mb synoptic charts."

1.3.2 Task 2--"Using ocean-station soundings and accompanying synoptic charts, formulate and test a method for determining the LST terms for a forecast period of 24 hours."

1.3.3 Task 3--"A manual shall be written to teach the meteorologist in charge of running NOWLAPS the procedure for determining the LST terms. In addition, the contractor shall write a final report which details the results of all three tasks."

2.0 TASK 1

2.1 <u>Requirements</u>

As specified in the Statement of Work for Contract No. N0028-84-D-3155, Delivery Order No. QE-02, Task 1 and its requirements are:

> "The contractor shall review the current, central-site method of determining the LST terms and define a manual method for determining these same terms from the 700 mb and 850 mb synoptic charts."

> "<u>Requirements</u>: Although it is likely to be impossible to formulate an automated method for determining the LST terms on board ship, the method used on the mainframe may provide a basis for developing a suitable shipboard technique. The technique developed by the contractor may be quite different from, and superior to, the mainframe procedure."

2.2 <u>NOGAPS Products</u>

The source of the large-scale forcing parameters is the Navy Operational Global Atmospheric Prediction System (NOGAPS), version 2.1. This model predicts synoptic changes and produces analysis and forecast fields at 12-hour intervals. The automated, central-site method, interpolates these fields numerically, producing estimates of the large-scale field variables at 12-hour intervals for any desired location. The tendencies can then be computed by determining the change in the value of any variable from the analysis to the 12-hour forecast or from the 12- to 24-hour forecasts. The differences are essentially the local time derivatives of the variables concerned. When this task is performed at the central site, the values of the large-scale variables are interpolated from high-resolution fields and are determined very accurately.

The NOGAPS output was presented to us in the form of analyzed fields superimposed on a polar stereographic map background. On these maps, one-fourth of the Northern Hemisphere is displayed, with the North Pole at the upper left. The distance corresponding to one degree of latitude is not conserved. For each forecast case, 27 charts were presented; corresponding to the three forecast times (analysis, 12-hour forecast, and 24-hour forecast), the three heights (1000 mb, 850 mb, and 700 mb), and the three fields (geopotential height, temperature, and vapor pressure). The temperature fields were analyzed at 5°C intervals and the vapor pressure fields at 5 mb intervals. Geopotential height was analyzed at 30-meter intervals for the 1000 mb and 850 mb levels and at 60-meter intervals for the 700 mb level.

2.3 Template Development

To facilitate the extraction of data from the analyzed fields, a template, or clear plastic overlay is used. The template contains a cross-hatch, indicating the position of the ship, surrounded by four dots, oriented east-west and north-south, equidistant from the ship's location. The template is placed on the chart, with the cross-hatch at the latitude and longitude corresponding to the ship's position, and with the North-South dots pointing toward the North Pole, as shown.

```
                 .A

                                    ↑N
         .D       +       .C



                 .B
```

Depending on the latitude of the ship, the distance corresponding to the length A-B will vary. However, the distance represented by A-B will always very closely approximate the distance represented by C-D, if (1) the four points are equidistant from the cross-hatch and (2) if the projection is conformal. Nearly all NOGAPS/NORAPS products are displayed on conformal projections. A spherical projection is an exception and is nonconformal. For this projection, the distance A-B must be determined separately from the distance C-D. The distance in kilometers of the length A-B can be computed by determining the distance in degrees of latitude and multiplying by the factor 111.1 km/degree. The distance A-B should be well below the mean synoptic-scale wavelength. A recommended length is 5 to 10 degrees of latitude.

The cross-hatch marking the ship's location is used to extract the value of the temperature and the vapor pressure. The four points A through D are used to extract the geopotential height. The gradient of geopotential height across distance A-B is used to compute the U component of the geostrophic wind. The gradient of geopotential height across the distance C-D is used to compute the V component of the geostrophic wind. A total of six values are extracted from the three charts for each pressure level and forecast time. These values are entered into the worksheet shown in Figure 1.

The procedure for developing and using the template is discussed in greater detail in the manual "Determination of NOWLAPS Large-Scale Tendency Terms: A User's Guide."*

2.4 Large-Scale Tendency Development

Once the worksheet has been completed, the large-scale tendencies can be computed through a series of calculations. These calculations can be performed on a hand calculator or by the HP9845, using a small program developed for that purpose.

2.4.1 Temperature Tendency--The temperature tendency applied for the first 12 hours is simply the difference between the 12-hour forecast temperature and the initial temperature. The temperature tendency applied for the second 12 hours is the

*Published separately as NAVENVPREDRSCHFAC Contractor Report CR 87-08, April 1987.

CASE | |

Figure 1. Large Scale Tendency Worksheet

INPUT

Pressure (mb)	Time (hours)	Ht(A) (m)	Ht(B) (m)	Ht(C) (m)	Ht(D) (m)	Vapor Psr (E) (mb)	Tmp (T) (^{o}C)
1000	00						
1000	12						
1000	24						
850	00						
850	12						
850	24						
700	00						
700	12						
700	24						

difference between the 24-hour and the 12-hour forecast temperatures.

2.4.2 Moisture Tendency--The vapor pressure values determined from the NOGAPS output must be converted to specific humidity to be in units suitable for use in the NOWLAPS model. This conversion is accomplished using the following relationship, known as Teten's formula:

$$q = \frac{0.622 \times e}{p - (0.378)(e)} \times 1000$$

where

e = Vapor pressure (mb)

p = Total atmospheric pressure (mb)

q = Specific humidity (g/kg)

The initial 12-hour moisture tendency is then the difference between the specific humidity forecast at 12 hours and the initial specific humidity. The moisture tendency for the final 12 hours is the difference between the specific humidity forecast for 24 hours and that forecast for 12 hours.

2.4.3 Wind Tendency--The wind is expressed as two parameters, the u, or east-west component, and the v, or north-south component. These parameters are computed from the four point values, A-D, of geopotential height as follows:

$$u = -\frac{g}{f}\,\frac{(A-B)}{\Delta Y}$$

$$v = \frac{g}{f}\,\frac{(C-D)}{\Delta x}$$

where

u = Geostrophic wind in the east-west direction (m/sec)

v = Geostrophic wind in the north-south direction (m/sec)

g = Acceleration of gravity (9.81 m/sec^2)

f = Coriolis parameter (1/sec)

A,B,C,D = Points at which geopotential height is estimated (meters)

ΔY = Distance between points A and B (meters)

Δx = Distance between points C and D (meters)

The 12-hour tendency terms of the u and v components of the wind are computed from 12-hour differences as with the temperature and moisture parameters.

2.4.4 Use of Large-Scale Tendency Terms--The computations discussed above yield a total of 24 large-scale tendency terms. These are the u-component, v-component, temperature, and moisture tendencies for the first and second 12-hour periods for each of three levels. These values are input directly into the NOWLAPS forecast in response to prompts received from the software.

3.0 TASK 2

3.1 Requirements

As specified in the Statement of Work for Contract No. N00228-84-D-3155, Delivery Order No. QE-02, Task 2 and its requirements are:

> "Using ocean-station soundings and accompanying synoptic charts, formulate and test a method for determining the LST terms for a forecast period of 24 hours."
>
> "Requirements: In order to provide a control against which NOWLAPS can be compared, the contractor shall access and run the Navy Operational Local Atmospheric Prediction System (NOLAPS) on the Fleet Numerical Oceanography Center's (FNOC) SPC computer (CDC Cyber 175). Although general job control language (JCL) for running NOLAPS will be provided by NEPRF, running these jobs remotely will require a basic knowledge of Control Data Corporation (CDC) Intercom procedures and JCL."
>
> "Sounding data (both initializing and verifying) shall be provided by three North Atlantic Weather Station ships (Charlie, Lima, and Romeo) and shall be accessed through the running of NOLAPS (see Burk and Thompson, 1982 and Thompson and Burk, 1983--see Attachments A and B). This sounding data shall provide the basis for running both NOLAPS and NOWLAPS."

"The contractor's first step shall be to run a number of ocean station forecasts using NOLAPS in order to identify cases for the LST testing. The contractor shall use his or her discretion in determining the actual number of cases to be later tested using NOWLAPS; although, it is anticipated that this number will lie somewhere between twenty and thirty. In order to identify, from the initial NOLAPS runs, cases suitable for this study, the contractor shall utilize and divide cases equally between the following three ranges of synoptic conditions: cases in which the synoptic situation is changing markedly during the 24-hour period; cases in which the synoptic situation is stagnant; and cases which lie somewhere in between the first two categories. After isolating the test cases, the contractor shall delineate the cases for the COTR: briefly summarizing each case, specifying the category into which it falls, and the reason for its choice."

"Following the above contractor-COTR coordination, the COTR will then forward to the contractor synoptic charts (850 and 700 mb), both for the analysis, and the 12- and 24-hour forecasts for the appropriate periods and locations. These charts will have been generated from JCL (provided by the COTR) which the contractor runs coincidentally with the earlier specified NOLAPS forecast. The initializing ocean station soundings shall be the basis for running NOWLAPS. The accompanying synoptic charts shall provide the means for developing the onboard-ship method of defining the LST terms."

"The LST term determination, from the synoptic charts, must be amenable to description in a manual (see Task 3) and made to be 'objective.' We define 'objective' here as meaning minimization of the necessity to exercise individual judgment. We additionally define objective, in the case of this procedure, to mean reproducibility of results when a number of people apply the same procedure to identical input information."

"After developing a "first-guess" method for determining the LST terms, the contractor shall produce 24-hour forecasts using NOWLAPS for several of the chosen ocean-station cases. The contractor shall choose, based on the initializing sounding, which of the two NOWLAPS vertical grids will be used. Two 24-hour forecasts shall be run for each case: one with the LST terms set to zero, and a second using values defined by the above method. Both of these forecasts shall be compared to the verifying 24-hour sounding, the persistence forecast, and the NOLAPS 24-hour forecast. This comparison shall include for each case the root mean square (RMS) error for both potential temperature and mixing ratio. When verifying data are available, the RMS errors shall likewise be computed for both the wind speed and the wind direction. All RMS errors shall be computed over the entire depth (at each grid point) of the NOWLAPS forecast. The purpose of these comparisons is to determine the effect of the LST terms both 1) with respect to the initial and final soundings, and 2) with respect to the NOLAPS forecast."

"The above comparison will evaluate the effect of the manually-defined LST terms. If, after analyzing the results of several ocean-station predictions, it becomes clear that the developed procedure does not result in an improved forecast, compared to the no LST term case and the verifying sounding, the LST procedure shall be re-evaluated. When the procedure is improved, the general outline of this and the previous paragraph shall be repeated."

"Following the development of the best method for determining the LST terms, all of the chosen weather station cases identified earlier shall be run, analyzed, and evaluated. This evaluation shall include for each case the root mean square error for both potential temperature and mixing ratio for the persistence forecast, the no LST term forecast, the LST term forecast, and the NOLAPS forecast. When data are available, the RMS errors shall likewise be computed for the wind direction and speed forecasts. The RMS errors shall be computed over the entire depth of the NOWLAPS forecast."

3.2 Test Cases

Twenty-nine test cases were developed. These cases occurred during the period 16 February 1986 through 12 June 1986. Each case consists of an initial and verifying sounding, 24 hours apart, and all used data from weather ship "Charlie," located at latitude 52.7°N, longitude 35.5°W, in the North Atlantic. The cases have been subjectively broken down by degree of temperature change, as follows:

Large Warming	Small Warming	No Change	Small Cooling	Large Cooling
2	8	1	7	4
3	9	5	12	6
15	11	10	14	27
17	13	16	19	28
26	18	24	20	29
	23		21	
			22	
			25	

A discussion of the synoptic conditions of each case may be found in Section 3.2.1; synoptic analyses are available in Attachment A.*

A NOLAPS 24-hour forecast was run for each case using the Fleet Numerical Oceanography Center's SPC Computer. The forecast results were obtained in printout format through the mail along with the applicable NOGAPS analyses and forecast charts. Large-scale tendencies were computed as described in Section 2. Two 24-hour NOWLAPS forecasts were run on the HP9845 for each case, one with large-scale tendencies, and one without.

*Available separately upon request.

A program, developed to run on the HP9845, computed RMS error and bias comparisons for the initial and verifying soundings, the NOWLAPS forecasts (with and without large-scale tendencies), and the NOLAPS forecast. The initial state and the two NOWLAPS forecasts were read by the program directly from the history tapes produced by the NOWLAPS runs. The verification sounding and the NOLAPS forecast results were manually entered from the NOLAPS printed output and interpolated to fit the NOWLAPS 2250 m grid.

3.2.1 Synoptic Conditions of the Cases

CASE 1 CHARLIE 24-25 February 1986 12Z

The station initially lies in a ridge, with a 1038 mb high 500 miles to the north and a 995 mb low 500 miles to the WSW. The surface flow is light easterly. The sounding is slightly stable with a marked increase in stability at 3500 m. Twenty-four hours later, the surface low has deepened to 990 mb and has moved due north. An occluded front from this system is about 100 miles SW of the station. The surface flow is now strong SE. The sounding is still slightly stable, but the transition to marked stability is now 2300 m. When compared, the two soundings show virtually no change in temperature below 2300 m, with about 2 to 4° of warming between 2300 and 3500 m. There is no change in moisture content at any level.

CASE 2 CHARLIE 16-17 February 1986 12Z

The station initially lies in a weak ridge between two intense surface lows. The surface flow is strong westerly. The sounding shows a mixed layer of height 600 m. The sounding is quite unstable above that point until a capping inversion is reached at 2000 m. Twenty-four hours later, the low to the west of the station has deepened to 960 mb. An occluding warm front is approaching from the SW. The surface flow is strong SE. The sounding is somewhat unstable below 1000 m, with a strong inversion at that level. In general, the sounding has warmed 6 to 10°C, with the greatest warming aloft. It has also moistened significantly at all levels.

CASE 3 CHARLIE 2-3 March 1986 12Z

The station initially lies just to the north of an east-west stationary front. The surface flow is light southerly. A 986 mb low is on the west end of the stationary front. The sounding is generally stable, with a small (400 m) mixed layer. Twenty-four hours later, the low has moved rapidly northeastward and is 150 miles NW of the station. The stationary front has moved north of the station, which lies in a strong SW surface flow. The sounding is now very stable. Significant warming and moistening at all levels has occurred. The warming ranges from 5°C at the surface to up to 12° or more between 1000 m and 2000 m.

CASE 4 CHARLIE 3-4 March 1986 12Z

The station initially lies in the warm sector of a 978 mb low 150 miles to the NW. The surface flow is strong southwesterly. A strong cold front is just to the west. The sounding is very stable up to 3000 m, becoming unstable above that level. Twenty-four hours later, the low has deepened to 962 mb and is 600 miles to the north. The strong cold front has passed, and the surface flow is strong westerly. The sounding shows a mixed layer extending to 1200 m, and is stable above that level. Dramatic cooling and drying has occurred at all levels. Cooling ranges from 5°C at the surface to 15 to 20°C above 1000 m.

CASE 5 CHARLIE 5-6 March 1986 00Z

The station initially lies 600 miles southwest of a 956 mb low. A strong cold front is 400 miles to the east, and the surface flow is strong westerly. The sounding contains a mixed layer up to level 1000 m, and continues to be quite unstable up to 2000 m. Twenty-four hours later, the surface flow has become weaker and is light westerly. The sounding is rather unstable below 2000 m, but stabilizes rapidly above that level, with an inversion at 2700 m. There has been slight cooling (less than 2°C) below 500 m, and significant warming of 4 to 6° above 2700 m. Slight moistening has occurred below 2000 m.

CASE 6 CHARLIE 9-10 March 1986 12Z

The station initially lies 400 miles south of a 968 mb low. A strong cold front has just passed through, and the surface flow is strong westerly. The sounding is quite stable, with an inversion at 1000 m. Twenty-four hours later, the station lies 400 miles south of a 974 mb low, in a surface trough. The flow is strong westerly. The sounding is superadiabatic below 200 m, and is quite unstable up to 2800 m. There has been strong cooling at all levels, ranging from 7 to 8°C below 1000 m to up to 15°C above that level. The sounding has dried uniformly at all levels.

CASE 7 CHARLIE 1-2 April 1986 12Z

The station initially lies 300 miles ESE of a 982 mb low. An occluded front is approaching from the west. The surface flow is very strong from the southeast. The sounding is rather unstable in the lowest 1000 m, with an inversion at that level. Twenty-four hours later, the low has moved southeastward and is passing just to the south of the station. The surface flow is light easterly. The occluded front is analyzed to the east of the station. The sounding is rather unstable below an inversion at 2100 m. The sounding has cooled 4 to 6°C above 1000 m, with little change below that level. The sounding has dried appreciably above 1500 m with little change below that level.

CASE 8 CHARLIE 2-3 April 1986 12Z

The station initially lies 100 miles north of a 988 mb low. The surface flow is light easterly. The sounding is rather unstable below an inversion at 2100 m. Twenty-four hours later, a 987 mb low is 300 miles NW of the station. An occluded front is approaching from the west. The surface flow is light southerly. The sounding is very stable above 500 m. It has cooled 1 to 2°C in the lowest 1000 m, and has warmed 4 to 6°C above that level. There has been little change in the moisture content of the sounding.

CASE 9 CHARLIE 5-6 April 1986 12Z

The station intially lies 500 miles south of a 980 mb low. One cold front has passed through the area and another, weakening, cold front lies 200 miles to the west. The flow is light southwesterly. The sounding shows a mixed layer up to 1400 m. It is rather unstable above that level until an inversion is reached at 3500 m. Twenty-four hours later, the low to the north of the station has weakened rapidly to 1006 mb. A weak trough is 100 miles west of the station, which continues to lie in a light southwesterly flow. The sounding is quite unstable up to 3000 m. It has warmed slightly below 2700 m, with a maximum of 2°C at 1400 m. Moisture content is essentially unchanged at all levels.

CASE 10 CHARLIE 9-10 April 1986 12Z

The station initially lies slightly east of a low pressure trough. A 1048 mb high lies 600 miles to the northeast. The surface flow is strong easterly. The sounding is quite stable. Twenty-four hours later, the high has built southward. A 1013 mb low lies 200 miles to the south. The surface flow is still easterly. The sounding is somewhat less stable, with a weak surface inversion, and another inversion at 2600 m. Slight warming has taken place below 700 m, while cooling of 2 to 3°C has occurred above that level. Slight moistening has occurred below 700 m, while drying has occurred above that level. The drying above 2400 m has been significant.

CASE 11 CHARLIE 10-11 April 1986 12Z

The station initially lies 200 miles north of a weak surface low and 500 miles southwest of a 1044 mb high. The surface flow is easterly. The sounding is stable, with an inversion at the surface and at 2600 m. Twenty-four hours later, the high has built into the area of the station. The surface flow is light easterly. The sounding has a very pronounced surface inversion, but is rather unstable between 300 and 2100 m, with another inversion at the latter level. Except for 2°C of cooling at the surface, the sounding has warmed at all levels, with significant warming (4 to 6°C) above 2000 m. The sounding has dried slightly below 3000 m, with some moistening above that level.

CASE 12 CHARLIE 11-12 April 1986 12Z

The station initially lies 300 miles west of a 1040 mb high. The surface flow is light easterly. The sounding has a very pronounced surface inversion, is rather unstable between 300 m and 2100 m, and has another inversion at the latter level. Twenty-four hours later, the station is centered in the surface ridge. The flow is light northerly. The sounding is quite stable at all levels, with slight inversions at the surface and at 1100 m. The sounding has cooled 2 to 4°C below 1800 km, with little change above that level. Drying has occurred at all levels except between 2400 and 3200 m, where slight moistening occurred.

CASE 13 CHARLIE 13-14 April 1986 12Z

The station initially lies 100 miles east of a 1032 mb high. The surface flow is light northerly. The sounding reveals a 1000 m mixed layer with a dramatic inversion in the next 800 m. Twenty-four hours later, the high has strengthened and moved slightly southwestward. The surface flow is still northerly. The sounding is very similar. The mixed layer extends from the surface to 800 m, with a pronounced inversion from that level up to 1800 m. The moisture content of the sounding has changed little.

CASE 14 CHARLIE 14-15 April 1986 12Z

The station initially lies 300 miles northeast of a 1034 mb high. The surface flow is northerly. The sounding possesses an 800 m mixed layer capped by a pronounced inversion. The inversion extends to 1800 m. Twenty-four hours later, the surface situation is essentially unchanged. The sounding shows a mixed layer extending from the surface to 1400 m, with an inversion from that level to 2000 m. Significant cooling has occurred above 800 m, with little change below that level. Some moistening has occurred between 1400 and 2500 m, with slight drying above that level.

CASE 15 CHARLIE 17-18 April 1986 12Z

The station initially lies 500 miles north of a 1034 mb high. The flow is southwesterly. The sounding is quite stable and possesses a pronounced inversion at 2000 m. Twenty-four hours later, the high has moved well south of the area and a fast-moving, intensifying low is 200 miles to the north. An occluded front is just west of the station. The surface flow is strong southwesterly. The sounding is quite stable, and has warmed 4 to 6°C below 2000 m. There has been slight warming above that level. There has been significant moistening at all levels.

CASE 16 CHARLIE 24-25 April 1986 12Z

The station initially lies just northeast of a large surface ridge. A 998 mb low is 500 miles to the north, and a weak cold front is approaching from the northwest. The sounding is very stable at all levels. Twenty-four hours later, the low is still 500 miles north of the station and has deepened to 990 mb. The weak cold front has just passed and the flow is northwesterly. The sounding is still very stable, with an inversion between 400 and 1100 m. Slight cooling has occurred below 1000 m and above 3000 m with little change in between. The moisture profile has changed very little.

CASE 17 CHARLIE 1-2 May 1986 12Z

The station initially lies 300 miles north of a 1027 mb high. The surface flow is northwesterly. The sounding is rather unstable up to an inversion at 1800 m. Twenty-four hours later, the high has drifted southeastward, away from the station, and a strong warm front is 200 miles south of the area. The flow is light southerly. The sounding is unstable up to 1000 m, with a pronounced inversion at that level. The sounding has warmed noticeably at all levels, with a maximum of 6 to 8°C at 1500 m. Some moistening has taken place, especially in the lowest 1000 m and above 3300 m.

CASE 18 CHARLIE 2-3 May 1986 12Z

The station initially lies 200 miles north of a strong warm front, and is experiencing a light southerly flow. The sounding is unstable up to 1000 m, with a pronounced inversion at that level. Another pronounced inversion occurs at 3400 m. Twenty-four hours later, the warm front has become stationary just to the south of the station. High pressure well to the north has ridged into the area, and is producing a very light easterly flow. The sounding is quite stable, and has warmed at all levels. The maximum warming is 6 to 10°C between 2800 m and 3300 m. The sounding has moistened below 2800 m, while drying above that level.

CASE 19 CHARLIE 6-7 May 1986 12Z

The station initially lies in a ridge, with a 1036 mb high well to the north. A 997 mb low 400 miles to the west and its associated occluded front are approaching. The surface flow is light easterly. The sounding shows a mixed layer up to 1300 m capped by a pronounced inversion at that level. Twenty-four hours later, a large east-west trough of low pressure lies just to the south of the area. The surface flow is strong easterly. The sounding is rather unstable, with no inversions. Significant cooling above 1400 m (6 to 10°C) has occurred, while slight warming has been observed below that level. Slight moistening has occurred below 2700 m, with little change above that level.

CASE 20 CHARLIE 9-10 May 1986 12Z

The station initially lies 300 miles west of a strong 980 mb low. The surface flow is northerly. The sounding is rather stable up to 2300 m, but is very stable above that level. Twenty-four hours later, the strong low has moved further eastward, and a 1008 mb low has developed along a stationary front 400 miles south of the station. The surface flow is light northeasterly. The sounding is quite unstable with a remarkably uniform lapse rate for the lowest 3700 m. The sounding has cooled below 3100 m with marked warming above that level. Drying has occurred above 1000 m, with little change below that level.

CASE 21 CHARLIE 10-11 May 1986 12Z

The station initially lies 400 miles north of a weak, but developing 1008 mb low centered on an east-west stationary front. The flow is light northeasterly. The sounding is quite unstable, with a remarkably uniform lapse rate. Twenty-four hours later, the low has deepened to 992 mb, and has raced northeastward, passing south of the station and now lying 400 miles to the east. The surface flow is northwesterly. The sounding has a 1100 m mixed layer and is rather stable above that level. Cooling has occurred below 2800 m, most pronounced (3 to 5°C) between 500 m and 2000 m. The sounding has dried at all levels, with the maximum drying near the surface.

CASE 22 CHARLIE 11-12 May 1986 12Z

The station initially lies 400 miles west of a 992 mb low. The surface flow is northwesterly. The sounding has an 1100 m mixed layer and is rather stable above that level. Twenty-four hours later, the station lies to the west of a northwest-southeast trough. A 1035 mb high is ridging in from the west. The flow is strong north-westerly. The sounding is rather unstable below an inversion at 3000 m. Cooling has occurred at all levels, with a maximum of 6 to 8°C above 2000 m. Moisture content of the sounding is essentially unchanged.

CASE 23 CHARLIE 15-16 May 1986 12Z

The station initially lies in a weak east-west ridge. It is experiencing a light northwesterly flow. The sounding is rather unstable up to an inversion at 1600 m. Twenty-four hours later, a weak low is approaching from the northwest, and producing a southwesterly flow. The sounding is slightly more stable. Some warming has occurred between 800 m and 2000 m, with little change elsewhere. Very slight moistening occurs below 2600 m, with little change above that level.

CASE 24 CHARLIE 16-17 May 1986 12Z

The station initially lies 100 miles southeast of a 998 mb low and its associated occluded front. The surface flow is southwesterly. The sounding is quite stable. Twenty-four hours later, the low has strengthened to 988 mb, as is just east of the station. The flow is northwesterly. The sounding has changed very little, with slight warming between 1800 m and 2800 m, and slight cooling elsewhere. Slight drying has occurred at all levels.

CASE 25 CHARLIE 17-18 May 1986 12Z

The station initially lies 100 miles west of a 988 mb low and is experiencing northwesterly flow. The sounding is rather unstable below 1200 m, but stable above that level. Twenty-four hours later, a strong north-south trough has developed to the east with a weak ridge building from the southwest. The surface flow is northwesterly. The sounding has a mixed layer extending up to 1200 m with a capping inversion at that level. The sounding becomes rather unstable again above 2300 m. Some cooling has occurred below 1400 m, with very slight warming above that level. Drying has occurred at all levels, with the maximum drying above 1400 m.

CASE 26 CHARLIE 18-19 May 1986 12Z

The station initially lies on the western edge of a strong north-south trough. A weak ridge is building from the southwest, while a 988 mb low is 700 miles to the northwest. The sounding has a mixed layer extending up to 1200 m with a pronounced capping inversion at that level. The sounding becomes rather unstable again above 2300 m. Twenty-four hours later, the low to the northwest has moved rapidly eastward and is now 300 miles north of the station. A cold front is approaching from the northwest. The station is in southwesterly flow. The sounding is stable and significantly warmer. Maximum warming has occurred at 1000 m (6°C) and above 3200 m (8 to 10°C). Moistening has occurred at all levels, and is most pronounced below 1300 m.

CASE 27 CHARLIE 19-20 May 1986 12Z

The station initially lies 300 miles south of a 998 mb low. Its associated cold front is approaching from the northwest. The surface flow is southwesterly. The sounding is stable below 3300 m. Twenty-four hours later, the low has explosively deepened to 979 mb and is 500 miles northeast of the station. The cold front has passed, and the station is experiencing a strong north-westerly flow. The sounding contains a mixed layer extending up to 1500 m, capped by a pronounced inversion. Cooling has occurred at all levels, generally 4 to 8° above 500 m. Drying has occurred at all levels, especially below 1400 m.

CASE 28 CHARLIE 12-13 June 1986 12Z

The station initially lies 300 miles south of a 986 mb low. A strong cold front is just passing through the area. The surface flow is strong southwesterly. The sounding is rather stable, with a pronounced inversion at 2800 m. Twenty-four hours later, the low has deepened to 978 mb and has remained stationary. The cold front has swept through, and the station is in a strong westerly flow. The sounding is rather unstable below 1200 m. Cooling of 4 to 6°C has occurred at all levels below 2800 m. Rather uniform and significant drying has occurred at all levels.

CASE 29 CHARLIE 4-5 June 1986 12Z

The station initially lies 300 miles southeast of a 990 mb low. A strong cold front is approaching from the west. The surface flow is southwesterly. The sounding is stable with a pronounced inversion in the lowest 300 m. Twenty-four hours later, the cold front has swept through, and the station is experiencing a westerly flow. The sounding is quite unstable up to 1800 m, with an inversion above that level. It has cooled substantially at all levels, with the maximum cooling, 8-12° between 300 m and 1800 m. The sounding has dried substantially at all levels.

3.3 Test Results

The comparison of the NOLAPS and NOWLAPS forecasts will be presented from four perspectives. First, the computed large-scale temperature tendencies applied to NOWLAPS will be compared to those used for NOLAPS. Next, RMS errors for wind, temperature, and moisture parameters will be compared for NOLAPS, NOWLAPS (with and without LST) and persistence. A discussion of the performance of each forecast on a case-by-case basis will follow. Finally, plots of the initial and verifying soundings, the NOWLAPS forecasts and the NOLAPS forecast for temperature, moisture, wind direction and speed can be found in Attachment B.*

*Available separately upon request.

3.3.1 Comparison of Temperature Tendencies--Tables 1, 2, and 3 compare the temperature tendencies applied to NOLAPS and NOWLAPS for each of the 29 cases for 1000 mb, 850 mb, and 700 mb, respectively. The figures for the 00 to 12-hour period and for the 12 to 24-hour period are in °C per 12 hours. The total NOLAPS and NOWLAPS figures are in °C per 24 hours. The 29-case mean tendencies are provided to indicate that no appreciable bias exists between the two forecasts. The ensemble of cases does, however, represent some net cooling. A more significant comparison of the two sets of temperature tendencies is the absolute value of their difference. The mean of this value over 29 cases is 1.0°C for 1000 mb, 1.1°C for 850 mb, and 1.5°C for 700 mb.

Is this accuracy satisfactory? In theory, the two sets of tendencies should be identical, since they are derived from the same forecasts. The 1 to 1.5°C variance represents the uncertainty in the interpolation between temperature contours at 5°C intervals. This interpolation is performed visually, with the aid of a ruler, to approximate a linear interpolation between successive contours. A more rigorous interpolation cannot be justified, since linearity between contours is itself an approximation. In addition, many small closed contours exist without labeling. Using the available meteorological information, most could be identified as either maxima or minima. However, this determination was often a time-consuming venture, and a few cases remained ambiguous. The variance of 1 to 1.5°C between the

Table 1. 1000 mb Temperature Tendency

Case	NOLAPS 0-12	NOLAPS 12-24	Total NOLAPS	NOWLAPS 0-12	NOWLAPS 12-24	Total NOWLAPS
1	-2.8	-0.9	-3.7	-2.2	-0.3	-2.5
2	2.2	2.6	4.8	2.0	3.0	5.0
3	1.0	2.4	3.4	0.2	1.5	1.7
4	-3.1	-5.9	-9.0	-2.5	-4.5	-7.0
5	-1.0	-2.1	-3.1	0.4	-2.1	-1.7
6	-8.3	-0.1	-8.4	-6.0	-0.6	-6.6
7	1.8	-2.5	-0.7	1.2	-0.6	0.6
8	1.4	-3.1	-1.7	-2.8	-1.6	-4.4
9	-1.6	4.6	3.0	-1.0	3.5	2.5
10	-0.7	-0.2	-0.9	-1.0	0.1	-0.9
11	-3.3	-1.4	-4.7	-5.2	-0.1	-5.3
12	-3.4	-1.1	-4.5	-3.2	-1.0	-4.2
13	-3.7	1.4	-2.3	-3.6	1.3	-2.3
14	-3.3	-1.8	-5.1	-3.5	-3.1	-6.6
15	-1.2	2.7	1.5	-0.8	2.4	1.6
16	-0.7	-1.2	-1.9	-0.8	-0.2	-1.0
17	-2.4	3.3	0.9	-3.9	4.1	0.2
18	1.4	-2.1	-0.7	1.0	-1.5	-0.5
19	2.3	2.1	4.4	2.6	1.6	4.2
20	0.1	-1.5	-1.4	-0.1	-1.2	-1.3
21	-3.3	-1.1	-4.4	-3.3	-0.4	-3.7
22	-3.6	-0.8	-4.4	-3.6	-0.8	-4.4
23	-3.7	0.7	-3.0	-3.9	0.2	-3.7
24	1.3	-0.1	1.2	1.2	0.4	1.6
25	0.0	-3.2	-3.2	-1.2	-3.0	-4.2
26	-3.4	4.3	0.9	-3.8	3.7	-0.1
27	-1.1	-2.9	-4.0	-0.1	-1.5	-1.6
28	-3.1	-0.8	-3.9	-3.9	-2.1	-6.0
29	-2.8	-4.4	-7.2	-1.0	-4.2	-5.2
Mean			-2.0			-1.9

Table 2. 850 mb Temperature Tendency

Case	NOLAPS 0-12	NOLAPS 12-24	Total NOLAPS	NOWLAPS 0-12	NOWLAPS 12-24	Total NOWLAPS
1	0.4	0.8	1.2	0.8	-0.3	0.5
2	5.5	4.4	9.9	2.0	3.8	5.8
3	5.6	-0.7	4.9	3.3	1.0	4.3
4	-8.5	-6.7	-15.2	-6.5	-5.7	-12.2
5	3.1	1.9	5.0	4.5	0.2	4.7
6	-9.2	-2.3	-11.5	-7.5	-3.5	-11.0
7	-4.7	0.0	-4.7	-4.0	0.3	-3.7
8	2.2	2.2	4.4	1.6	2.5	4.1
9	3.7	0.6	4.3	2.8	0.4	3.2
10	-1.6	0.6	-1.0	-1.1	0.4	-0.7
11	3.0	1.0	4.0	1.6	0.1	1.7
12	2.2	-0.9	1.3	1.5	-3.1	-1.6
13	4.1	-0.8	3.3	3.8	-0.1	3.7
14	-4.5	-0.5	-5.0	-4.5	-0.2	-4.7
15	2.5	-0.3	2.2	1.0	0.1	1.1
16	-0.3	-0.6	-0.9	-0.7	-1.5	-2.2
17	6.9	-0.6	6.3	4.9	0.1	5.0
18	0.3	3.0	3.3	-0.8	3.0	2.2
19	0.3	0.4	0.7	0.5	2.5	3.0
20	-1.5	-0.3	-1.8	-2.1	0.5	-1.6
21	0.1	0.5	0.6	-0.2	-0.6	-0.8
22	0.2	-2.3	-2.1	-0.2	-1.9	-2.1
23	0.5	-0.4	0.1	0.6	-0.4	0.2
24	-1.1	-0.7	-1.8	-0.4	-0.3	-0.7
25	1.9	3.5	5.4	1.4	3.6	5.0
26	4.4	-3.3	1.1	3.1	-1.7	1.4
27	-1.5	-5.3	-6.8	-1.3	-5.0	-6.3
28	-2.8	-2.1	-4.9	-2.2	-2.0	-4.2
29	-4.0	-6.5	-10.5	-3.0	-5.8	-8.8
Mean			-0.3			-0.5

Table 3. 700 mb Temperature Tendency

Case	NOLAPS 0-12	NOLAPS 12-24	Total NOLAPS	NOWLAPS 0-12	NOWLAPS 12-24	Total NOWLAPS
1	-0.3	1.1	0.8	-0.4	2.6	2.2
2	6.8	3.6	10.4	5.5	1.6	7.1
3	3.1	4.1	7.2	3.1	2.9	6.0
4	-8.3	-10.0	-18.3	-6.6	-8.4	-15.0
5	2.3	2.7	5.0	2.7	-0.1	2.6
6	-9.7	-6.3	-16.0	-7.9	-6.4	-14.3
7	-2.8	-1.8	-4.6	-3.6	0.3	-3.3
8	0.9	2.1	3.0	3.4	-0.8	2.6
9	2.6	2.3	4.9	1.0	1.8	2.8
10	-2.5	0.6	-1.9	-1.6	3.0	1.4
11	1.1	-0.7	0.4	-0.1	0.1	0.0
12	-2.8	-0.3	-3.1	-2.1	-1.1	-3.2
13	-2.5	1.0	-1.5	-0.5	1.0	0.5
14	-4.4	-0.8	-5.2	-3.3	-0.7	-4.0
15	-3.1	1.5	-1.6	-0.9	1.0	0.1
16	-0.5	-2.5	-3.0	-2.6	-0.8	-3.4
17	1.8	1.7	3.5	2.0	1.6	3.6
18	2.4	0.1	2.5	1.3	-0.2	1.1
19	-6.4	-1.1	-7.5	-1.3	-3.0	-4.3
20	-0.7	-1.2	-1.9	-0.9	-0.7	-1.6
21	-0.1	0.3	0.2	0.9	0.3	1.2
22	-1.7	-4.8	-6.5	-1.0	-3.5	-4.5
23	0.2	0.6	0.8	-0.1	0.7	0.6
24	-1.1	-1.7	-2.8	-0.5	-0.5	-1.0
25	-1.5	0.7	-0.8	-2.6	1.1	-1.5
26	0.9	1.5	2.4	0.1	1.0	1.1
27	-4.3	-5.4	-9.7	-3.4	-4.4	-7.8
28	-3.4	-0.9	-4.3	-3.6	-0.7	-4.3
29	-3.5	-7.1	-10.6	-4.6	-2.5	-7.1
Mean			-2.0			-1.5

NOLAPS and the NOWLAPS temperature tendencies appears consistent with the uncertainties involved in the NOWLAPS LST derivation.

3.3.2 RMS Error Analysis--The RMS error statistics for the comparison of the verification and the initial state, NOLAPS forecast and NOWLAPS forecast (with and without LST) are presented in Tables 4 through 7, respectively. Cases 4 and 6 are omitted because of the failure of NOWLAPS to complete a 24-hour forecast. In those cases of strong cooling, the mixed layer exceeded the 2250 m grid, resulting in failure of the software logic. In Case 2, NOWLAPS without LST encountered a similar problem. The sounding at the time of failure (233 iterations) is used. The arithmetic means of the case RMS errors provide an overview of the four forecasts, where initial state, or persistence, is considered to be a forecast.

Over the 27 cases completed, both NOLAPS and NOWLAPS (with LST) produce mean RMS errors which are lower for all parameters than persistence. In the mean, then, both NOLAPS and NOWLAPS (with LST) produce forecasts superior in all respects to persistence. NOWLAPS (without LST) produces RMS errors comparable to persistence, thus illustrating the value of large-scale tendencies. With the exception of wind speed, NOLAPS is, in the mean, superior to NOWLAPS (with LST). Since the models are ostensibly the same, much of the difference between the NOLAPS and NOWLAPS results must rest either with the large-scale tendencies or the vertical model domain. However, several differences in the model results not directly attributable to the

Table 4. Root Mean Square (RMS) Error

INITIAL STATE VS VERIFICATION

Case	Temp. (°C)	Specific Humidity (g/kg)	Wind U-comp (m/s)	Wind V-comp (m/s)	Wind Speed (m/s)	Wind Dir. (degrees)
1	0.2	0.2	3.3	4.7	2.0	18.6
2	6.5	2.1	10.9	20.5	5.2	102.5
3	10.4	3.2	28.2	24.0	36.7	16.7
4	----	----	----	----	----	----
5	0.5	0.4	7.1	8.5	7.5	33.9
6	----	----	----	----	----	----
7	3.4	0.8	4.2	9.0	8.5	26.6
8	2.9	0.3	5.7	6.0	3.7	68.1
9	1.0	0.1	6.0	0.8	1.8	40.1
10	1.0	0.4	0.6	4.2	1.5	13.5
11	1.7	0.6	8.1	2.0	7.9	13.7
12	2.4	0.8	11.1	9.3	3.8	167.1
13	2.3	0.7	1.3	3.6	3.6	6.9
14	3.4	0.6	4.0	4.1	3.7	27.0
15	5.6	2.2	5.4	10.2	7.8	34.0
16	2.1	0.4	9.6	19.4	7.8	108.6
17	4.7	1.8	8.4	13.6	6.7	98.9
18	2.1	1.1	5.9	5.6	4.5	88.1
19	3.3	1.0	4.7	5.1	5.4	25.5
20	2.0	0.5	4.3	8.3	9.3	5.6
21	2.8	1.5	17.2	3.8	5.8	113.4
22	1.8	0.2	3.4	1.4	3.0	9.6
23	1.4	0.4	3.3	3.7	3.5	39.3
24	0.8	1.0	4.8	8.9	4.7	104.8
25	1.7	0.6	1.9	5.9	4.7	25.8
26	4.3	2.0	11.0	15.1	3.1	97.5
27	4.8	2.6	1.4	14.6	3.1	59.8
28	5.3	1.7	2.0	14.2	8.2	38.7
29	10.1	4.1	2.8	9.1	7.0	26.7
Mean	3.3	1.2	6.5	8.7	6.3	52.3

Table 5. RMS Error

NOLAPS VS VERIFICATION

Case	Temp. (°C)	Specific Humidity (g/kg)	Wind U-comp (m/s)	Wind V-comp (m/s)	Wind Speed (m/s)	Wind Dir. (degrees)
1	2.7	0.3	7.6	6.7	9.9	10.2
2	1.6	0.4	3.8	11.1	10.0	31.2
3	5.8	2.1	26.7	22.3	34.3	13.9
4	---	---	---	---	---	---
5	2.9	0.9	4.7	1.7	5.0	3.0
6	---	---	---	---	---	---
7	2.0	0.5	5.8	1.7	2.5	44.1
8	1.6	0.2	3.1	4.9	5.1	32.0
9	1.9	1.2	2.9	4.1	4.5	19.2
10	1.8	0.5	7.2	4.9	8.1	13.7
11	2.5	0.5	2.7	3.8	3.3	24.8
12	1.2	0.9	5.4	2.5	2.6	86.8
13	1.5	0.5	4.5	4.3	4.0	27.9
14	1.8	0.9	1.2	3.8	4.0	4.2
15	5.4	1.4	2.6	4.4	4.5	11.0
16	2.2	0.3	6.7	12.6	8.4	85.7
17	1.4	1.1	4.4	3.0	2.6	43.0
18	1.6	1.2	3.5	5.1	3.0	84.8
19	1.4	0.3	4.1	2.9	4.6	10.1
20	1.3	0.3	3.8	4.2	4.6	61.6
21	2.2	1.4	13.7	2.9	8.1	88.7
22	1.3	0.3	4.9	3.6	3.6	24.5
23	1.3	0.4	1.0	1.0	0.8	12.5
24	1.1	0.7	1.8	6.0	5.6	34.3
25	2.6	0.7	3.0	4.9	5.3	14.1
26	3.3	1.3	4.3	5.2	5.0	30.4
27	2.6	1.6	4.0	9.9	6.7	44.8
28	2.7	1.0	7.8	6.9	5.3	43.5
29	3.3	1.5	3.6	3.2	4.2	11.8
Mean	2.3	0.8	5.4	5.5	6.1	33.8

Table 6. RMS Error

NOWLAPS W/LST VS VERIFICATION

Case	Temp. (°C)	Specific Humidity (g/kg)	Wind U-comp (m/s)	Wind V-comp (m/s)	Wind Speed (m/s)	Wind Dir. (degrees)
1	1.8	0.4	1.7	6.1	3.6	18.0
2	3.7	1.1	8.2	9.6	5.3	45.8
3	8.4	2.5	32.0	20.8	34.9	41.5
4	----------	----------	----------	----------	----------	----------
5	2.2	0.5	3.4	5.0	3.0	24.6
6	----------	----------	----------	----------	----------	----------
7	2.0	0.9	3.9	4.7	5.3	18.2
8	2.1	0.5	4.8	8.2	1.9	78.4
9	0.8	0.4	2.5	1.1	1.1	15.1
10	2.7	0.8	2.9	6.7	3.4	23.2
11	3.7	0.8	5.9	3.5	5.1	23.0
12	2.1	0.8	7.1	5.9	2.4	159.3
13	2.5	0.3	1.7	2.9	2.9	9.7
14	2.4	0.9	3.3	3.9	3.8	24.1
15	6.7	1.8	5.3	7.3	7.8	15.4
16	2.1	1.2	8.0	17.5	6.6	109.7
17	2.9	0.8	6.8	6.4	3.6	69.3
18	2.5	1.5	1.7	1.2	1.5	31.1
19	3.0	0.8	1.1	3.6	1.4	16.7
20	2.2	0.7	3.2	7.2	6.8	24.6
21	1.8	1.0	17.1	4.7	6.1	109.8
22	1.3	0.3	1.5	2.4	1.5	9.3
23	2.1	0.5	3.0	4.1	3.5	42.1
24	2.2	1.7	1.7	4.9	4.8	17.0
25	2.4	0.7	2.1	5.1	3.7	24.6
26	4.1	1.4	5.2	11.5	3.8	61.6
27	1.9	1.6	3.1	11.0	5.3	47.8
28	4.0	1.1	5.2	9.0	2.7	40.3
29	6.5	3.1	6.7	2.9	2.7	40.3
Mean	3.0	1.0	5.5	6.6	5.0	42.2

Table 7. RMS Error

NOWLAPS WITHOUT LST VS VERIFICATION

Case	Temp. (°C)	Specific Humidity (g/kg)	Wind U-comp (m/s)	Wind V-comp (m/s)	Wind Speed (m/s)	Wind Dir. (degrees)
1	2.0	0.3	2.3	7.6	2.5	26.1
2	4.5	1.1	10.6	19.3	5.9	97.2
3	11.2	3.4	28.2	24.7	37.3	12.5
4	---	---	---	---	---	---
5	4.8	1.5	6.5	6.1	6.4	26.0
6	---	---	---	---	---	---
7	3.6	0.8	4.8	8.2	8.2	24.2
8	4.5	0.9	5.5	5.4	3.8	62.1
9	1.5	0.5	5.8	1.8	2.9	38.8
10	2.3	0.7	2.4	7.6	3.2	26.3
11	2.8	0.4	8.0	3.1	7.0	24.2
12	2.7	0.9	11.5	8.2	3.6	159.1
13	2.8	0.3	1.6	3.8	3.8	9.4
14	3.3	0.6	3.1	3.4	2.9	21.9
15	9.0	2.7	5.1	9.3	7.9	26.6
16	1.9	0.3	10.6	19.0	7.9	119.1
17	4.2	0.8	8.6	11.6	5.9	90.1
18	3.2	1.4	5.9	5.1	4.4	90.1
19	3.6	0.5	4.9	4.3	5.7	19.4
20	1.4	0.5	1.9	8.0	7.8	14.8
21	1.5	1.2	16.6	3.9	6.0	107.4
22	1.6	0.6	3.4	1.9	3.0	11.2
23	1.7	0.3	3.3	3.2	3.4	36.3
24	1.9	0.9	4.7	9.0	4.7	107.6
25	1.5	0.9	1.6	6.7	5.3	29.7
26	4.5	1.7	10.3	13.8	3.2	91.1
27	3.5	2.0	2.7	15.4	3.8	66.5
28	4.5	1.3	5.6	15.2	8.1	50.0
29	7.2	2.9	5.3	9.1	7.0	35.8
Mean	3.6	1.1	6.7	8.7	6.4	52.7

tendencies were noted. At least five cases (16, 20, 24, 28, and 29) resulted in saturation and cloudiness at the top of the 2250 m grid. Deficiencies in the NOWLAPS software result in an accretion of moisture, often despite a drying tendency, and warming resulting from the release of latent heat. Since the NOLAPS domain is 3750 m deep, this problem, even if it would exist at the top of the grid, is not encountered at 2250 m. In case 16, the top two forecast levels (NOWLAPS) warm 5°C despite a 2°C per day cooling tendency. Moisture content increases 2 g/kg despite 1 g/kg per day of drying tendency.

The NOWLAPS forecast is closely tied to the sea surface temperature. While the verification sounding occasionally indicates cooling of the lowest layers to values less than the sea surface temperature (cases 6, 11, and 22), NOWLAPS will not permit such cooling. Instead, a large mixed layer of constant potential temperature will result, almost invariably higher than that of the verification. This large mixed layer tends to negate the applied tendencies. A subjective breakdown of the deficiencies of the NOWLAPS temperature forecasts relative to the verification revealed the following. In 18 cases, the large-scale tendencies were in part inadequate. In 11 cases, an erroneous or excessive mixed layer was produced, and in 5 cases, the moisture accretion problem played a major role. In several cases, more than one factor was cited.

3.3.3 Case-by-Case Analysis--The following listing contains individual analysis of the 29 cases, focussing on the temperature forecasts and endeavoring to explain the relative strengths and weaknesses of the NOLAPS and NOWLAPS (with LST) forecasts, both relative to themselves and to the verification.

CASE 1--This case involves virtually no change at any level. As a result, persistence produces a significantly better forecast than either NOLAPS or NOWLAPS (with LST). NOWLAPS (with LST) produces a forecast superior to NOLAPS, especially in the lowest 500 m. There, NOLAPS cools excessively, perhaps due to the slightly larger cooling tendency which is applied.

CASE 2--This case involves significant warming at all levels. NOWLAPS (without LST) fails after 233 iterations as the saturated boundary layer reaches the top of the grid. However, NOWLAPS (with LST) completes a 24-hour forecast successfully. Both the NOLAPS and NOWLAPS (with LST) forecasts are superior to persistence. However, NOLAPS is 3 to 4°C warmer due to higher tendency terms above the surface, which produces a better forecast.

CASE 3--This case involves strong warming (8-12°C) at all levels. Both NOWLAPS with LST and NOLAPS fail to account for sufficient warming. NOLAPS does a better job, due in part to superior tendencies. However, the tendencies in both cases are insufficient.

CASE 4--This case involves dramatic cooling at all levels. The NOWLAPS (with LST) forecast fails after 252 iterations when the saturated boundary layer reaches the top of the grid. A comparison of the NOLAPS and NOWLAPS tendency terms reveals that NOLAPS provides 1 to 3°C per day more cooling.

CASE 5--This is a case involving virtually no change. Both NOLAPS and NOWLAPS apply cooling near the surface and significant warming aloft. Despite cooling tendencies near the surface, and a 1°C drop in the observed surface temperature, both forecasts warm at the surface. This warming is most likely because the initial 1000 mb temperature is below the observed sea surface temperature. Both forecasts warm the lowest level up to the vicinity of the sea surface temperature. With warming tendencies applied aloft, both forecasts are too warm. NOWLAPS does slightly better because less warming is applied. In this case, persistence is the clear winner.

CASE 6--This case involves dramatic cooling at all levels. The NOWLAPS (with LST) forecast fails after 246 iterations when the saturated boundary layer reaches the top of the grid. A comparison of the NOLAPS and NOWLAPS tendencies shows them to be comparable, with NOLAPS providing slightly more cooling.

CASE 7--This case involves little change below 1000 m with significant cooling above that level. Both the NOLAPS and NOWLAPS (with LST) forecasts are superior to persistence. The

NOWLAPS forecast provides slightly more cooling, and is thus slightly better than the NOLAPS forecast.

CASE 8--This case involves significant warming above 1300 m, with slight cooling below that level. NOLAPS tends to underestimate both the cooling and the warming. NOWLAPS (with LST), overestimates the low level cooling, while generally agreeing with NOLAPS above 1000 m. This overestimation can be attributed to the significantly higher cooling tendency applied to NOWLAPS (with LST) at the lowest level.

CASE 9--This case involves slight warming at all levels, with a maximum of 2°C at 1400 m. Warming tendencies of 3 to 5°C per day are applied to NOLAPS resulting in excessive warming, especially above 1500 m. The tendencies computed for NOWLAPS are lower, producing a superior forecast, although here too, the warming is excessive.

CASE 10--This case involves little temperature change, and is a case where persistence produces a better forecast than either NOLAPS or NOWLAPS. The large-scale tendencies diverge at 700 mb, with NOLAPS applying 2° of cooling and NOWLAPS applying 1.5°C per day warming. Cooling is observed at this level.

CASE 11--This case features slight cooling below 300 m with slight warming between 300 m and 2000 m. Significant warming occurs above 2000 m. Both NOLAPS and NOWLAPS receive strong cooling tendencies near the surface. NOLAPS produces a 200 m super-adiabatic region capped by a strong inversion. However, NOWLAPS produces a rather unstable layer extending to 1300 m. As a result, NOWLAPS produces significant cooling in the lowest 1300 m and is much inferior to the NOLAPS forecast in this region. Warming tendencies are applied to both forecasts at 850 mb, and the forecasts converge at 2000 m. The significant warming observed above 2000 m is not reflected in the 700 mb tendency of either forecast.

CASE 12--This case involves cooling below 1800 m with slight warming above that level. The NOLAPS and NOWLAPS cooling tendencies are very comparable at 1000 mb and 850 mb; however, the forecasts differ significantly. NOLAPS produces a small 200 m mixed layer capped by a strong inversion. NOWLAPS mixed layer extends to 600 m, and at this level, the NOWLAPS forecast is 4°C cooler than verification. Despite that fact, NOWLAPS recovers, and produces a superior forecast between 800 m and 1500 m.

CASE 13--This case involves surface cooling combined with mid-level warming. The result is a mixed layer capped by a pronounced inversion. NOLAPS produces a 1°C lower RMS, despite nearly identical tendencies. The NOWLAPS forecast cools excessively at low levels, and warms excessively above 1500 m; however, the overall structure of the sounding is well forecast.

CASE 14--This case involves significant cooling at all levels, especially strong at the surface. In both NOLAPS and NOWLAPS, strong surface cooling results in little actual cooling, but rather builds a higher boundary layer. This feature is not as apparent in the verification sounding. As a result, both NOLAPS and NOWLAPS underpredict the temperature in the mixed layer. Both forecasts do rather well above this layer.

CASE 15--This case produces pronounced warming, which is not well predicted by either NOLAPS or NOWLAPS. The large-scale tendencies, while quite similar for the two forecasts, grossly underestimate the degree of warming in the verification sounding.

CASE 16--In this case, the NOWLAPS forecast (with LST) produces an unphysical result. The initial state is saturated at 1800 m, and with the application of cooling tendencies, remains so throughout the forecast. However, despite very little moisture tendency, the NOWLAPS forecast (with LST) increases the total water content above 1300 m dramatically by 2 to 3 g/kg. Since the sounding is quite stable, it seems unlikely that this moisture was brought up from the surface. The source of this moisture remains uncertain at this time.

CASE 17--This case involves significant warming at all levels. Both NOLAPS and NOWLAPS (with LST) represent improvements over persistence. The NOLAPS forecast does significantly better than NOWLAPS (with LST), especially in the lowest 900 m. Despite similar surface warming tendency, NOWLAPS builds a much higher mixed layer than NOLAPS. While a similar structure exists in the verification, it is some 4°C cooler in NOWLAPS. NOLAPS has a mixed layer of only 300 m and then proceeds to warm, thus bringing it closer to the verification.

CASE 18--This case involves warming at all levels above 300 m. Both NOLAPS and NOWLAPS (with LST) build a mixed layer extending to about 1000 m. The verification does not contain this feature, and thus both forecasts are 4 to 5°C cooler at 1000 m. Both forecasts warm rapidly above this level and agree well with the verification. NOLAPS does slightly better than NOWLAPS, due to a 1°C greater warming tendency applied at 850 mb and 700 mb.

CASE 19--This case involves large cooling above 1300 m with some warming below that level. Cooling at 700 mb is 10 to 12°C. This value is significantly higher than either the NOLAPS or NOWLAPS LST. At this level, the NOLAPS applies 7°C per day of warming compared with 4°C per day for NOWLAPS and is thus the better forecast. The initial state contains a steep inversion at 1300 m. Both forecasts retain this feature, although NOLAPS moves the inversion up to 1900 m. The verification contains no evidence of an inversion.

CASE 20--This case features cooling at all levels, with a maximum of 5°C at 2400 m. Large-scale tendencies applied to NOLAPS and NOWLAPS are virtually identical, but the forecasts differ in two respects. NOWLAPS builds a higher mixed layer and encounters the accretion of moisture problem discussed in case 16. Because of the latter occurrence, NOWLAPS is much too warm and moist at the top of the grid.

CASE 21--This case involves cooling of 2-4°C at all levels. The degree of cooling is insufficient in both the NOLAPS and NOWLAPS with LST forecasts. Curiously, the NOWLAPS without LST displays more low level cooling then the NOWLAPS with 4°C per day cooling applied at 1000 Mb. The 32-meter virtual potential temperature is shown below for both forecasts over the 24-hour period.

Time in Forecast	NOWLAPS w/o LST	NOWLAP with LST
0	278.9	279.0
3	278.8	278.6
6	278.9	278.1
9	278.7	278.4
12	278.4	278.5
15	274.7	278.5
18	273.3	278.5
21	275.3	278.6
24	277.1	278.7

It appears that in the case w/o LST, low-level cloudiness/fog, without higher level cloudiness, radiates and cools the lowest levels at night. This trend reverses at dawn, but after 24 hours, a net cooling is noted. When large-scale cooling is applied, the boundary layer remains mixed, with no low level cloudiness. With a constant sea-surface temperature, little cooling of the boundary layer is noted.

CASE 22--This case involves cooling at all levels, greatest near the surface and above 2000 m. NOLAPS and NOWLAPS receive identical tendencies at 1000 mb and 850 mb, with NOLAPS receiving the greater, and more correct, cooling tendency at 700 mb. Both forecasts build a mixed layer of 1000 to 1200 m, as the surface temperature will not cool below the initial sea surface temperature. The verification cools 2°C at the surface and has little or no mixed layer.

CASE 23--This case involves slight warming between 800 and 2000 m with little change elsewhere. The tendency for both NOLAPS and NOWLAPS at 850 mb is virtually zero; thus, both forecasts fail to predict the region of warming. NOWLAPS applies 0.7°C per day more cooling to the surface than NOLAPS. This additional cooling builds an 1100 m mixed layer, which leaves NOWLAPS cooler than verification in the lowest levels.

CASE 24--This case involves little overall change. Slight cooling occurs between 900 m and 1900 m, with slight warming above that level. This case is another example where condensation at the top of the grid adds moisture to the NOWLAPS sounding and produces excessive warming. Insufficient cooling at 850 mb and a 2°C warming at the surface (compared to NOLAPS 1°C) results in a forecast excessively warm at all levels.

CASE 25--This case involves significant cooling below 1300 m with slight warming above that level. Both NOLAPS and NOWLAPS apply 3 to 4°C of cooling at the surface, but due to the relatively high sea surface temperature, cannot cool to the verification value. The verification contains a 1200 m mixed layer which is not duplicated by either model. Both models apply 5°C per day of warming at 850 mb, where there is, in fact, no change in the actual sounding. As a result, both NOLAPS and NOWLAPS are too warm at all levels.

CASE 26--This case involves significant warming at all levels. Neither NOLAPS nor NOWLAPS receives adequate warming tendencies at any level.

CASE 27--This case involves significant cooling at all levels. The verification sounding shows a mixed layer extending from the surface to 1500 m, with an inversion above that level. The NOWLAPS RMS error for temperature is slightly lower than that of NOLAPS. Both forecasts correctly predict the structure of the sounding. It should be noted that with drying applied to the NOLAPS forecast by the large-scale tendencies, the moisture content goes to zero above the mixed layer.

CASE 28--This case involves cooling at all levels. Both NOLAPS and NOWLAPS with LST produce insufficient cooling. Although the large-scale tendencies appear sufficient to account for the cooling, the accretion of moisture at the top of the grid negates much of it.

CASE 29--This case involves severe cooling at all levels. The LST applied to NOWLAPS and NOLAPS are similar; however, the NOWLAPS forecast is inadequate again due to condensation at the top of the grid adding moisture and excessive warming.

3.4 Tests of Alternative Techniques

3.4.1 Application of LST After NOWLAPS Forecast--Eight test cases were selected from the full 29 and used to test the following hypothesis: application of LST terms after completion of the NOWLAPS forecast will reduce unrealistically deep mixed layers and produce a superior forecast. Tables 8A through 8D show the bias resulting from the subtraction of four different forecasts from the verification for the parameters temperature, specific humidity and the u and v components of the wind. The summary line for each table is the mean of the absolute value of the bias, and thus is a measure of the overall variance of the forecasts, and not a measure of net bias.

It can be seen that the mean bias resulting from the application of LST after completion of the forecast (Table 8D) is very similar to that obtained from the conventional application of LST (Table 8C). However, for the eight individual cases, the two techniques produce significantly different results. In the case of temperature prediction, each technique can claim superior results in four cases. If further analysis could distinguish between those cases where the application of LST after the

Table 8A. Bias Analysis

VERIFICATION MINUS NOWLAPS WITHOUT LST

Case	T(°C)	Specific Humidity (g/kg)	Wind U-comp (m/sec)	Wind V-comp (m/sec)
1	11.4	3.5	29.2	24.7
13	2.4	0.1	-0.7	-3.5
14	-0.8	0.5	3.1	2.2
15	9.1	2.7	3.2	8.1
21	-1.0	-1.2	17.2	4.0
28	-4.0	-1.3	2.6	-15.7
27	-2.9	-2.0	0.6	-16.0
10	1.7	0.4	-1.0	7.0
Mean	4.2	1.5	7.2	10.2

Table 8B. Bias Analysis

VERIFICATION MINUS NOLAPS FORECAST

Case	T(°C)	Specific Humidity (g/kg)	Wind U-comp (m/sec)	Wind V-comp (m/sec)
3	5.8	2.1	27.8	21.0
13	0.1	-0.2	-4.6	-2.4
14	1.3	0.9	1.2	-3.6
15	5.3	1.4	2.2	4.3
21	-2.0	-1.4	14.1	2.4
28	-2.7	-0.9	5.5	-4.5
27	-1.1	-1.4	2.4	-9.9
10	1.4	0.3	-6.3	1.6
Mean	2.5	1.1	8.0	7.8

Table 8C. Bias Analysis

VERIFICATION MINUS NOWLAPS FORECAST (WITH LST)

Case	T(°C)	Specific Humidity (g/kg)	Wind U-comp (m/sec)	Wind V-comp (m/sec)
3	8.5	2.5	33.2	20.2
13	2.1	0.1	-1.2	-2.4
14	1.6	0.9	3.3	-0.1
15	6.6	1.7	4.2	5.5
21	-1.6	-1.0	17.8	4.7
28	-3.6	-1.0	2.9	-8.4
27	-1.3	-1.6	1.0	-11.4
10	0.4	0.0	-1.2	5.6
Mean	3.2	1.1	8.1	7.3

Table 8D. Bias Analysis

VERIFICATION MINUS (NOWLAPS WITHOUT LST) PLUS TENDENCIES

Case	T(°C)	Specific Humidity (g/kg)	Wind U-comp (m/sec)	Wind V-comp (m/sec)
3	7.7	1.8	33.3	19.5
13	1.2	-0.2	-1.2	-2.0
14	4.4	0.7	3.2	-1.6
15	8.0	1.5	4.0	3.8
21	0.4	-1.2	17.7	6.6
28	0.8	-0.7	3.2	-3.8
27	2.1	-1.9	0.6	-10.1
10	2.1	0.2	-1.7	5.4
Mean	3.3	1.0	8.1	6.6

NOWLAPS forecast represents an improvement over the conventional technique and those cases where it does not, this method would hold promise. However, as it stands now, the results of this alternate LST application do not promise improvement.

3.4.2 Direct Computation of Advection--Since the NOGAPS model contains some of the vertical mixing processes contained in NOWLAPS, it was suggested that perhaps these processes are duplicated by using LST terms derived from NOGAPS forecasts. As an alternative, geostrophic winds computed from the NOGAPS analysis and 12-hour forecast were used to compute temperature advection for the two 12-hour forecast periods of three cases. These temperature advection terms were then compared to NOLAPS and NOWLAPS large-scale temperature tendencies and to the observed temperature change in the soundings. Table 9 shows the results of this investigation.

Despite moderate success on Case 15, the temperature advection terms cannot compete with the derived large-scale tendency terms for accurately predicting the observed temperature change. It is clear that vertical advection in the NOGAPS model plays a significant role in temperature change, and that two-dimensional advection is not a satisfactory substitute.

3.4.3 Trajectory of Air Masses--As discussed earlier, the verification sounding periodically is seen to contain a surface temperature several degrees below the initial sea surface temperature. While the models do not seem to be able to produce

Table 9

24-Hour Temperature Tendency

Case 5

Pressure Level (mb)	NOLAPS Tendency (°C)	NOWLAPS Tendency (°C)	24-Hour Advection (°C)	Observed Change (°C)
1000	-3.1	-1.7	-7.7	-1.0
850	5.0	4.7	-3.2	0.0
700	5.0	2.6	-2.2	4.0

Case 11

Pressure Level (mb)	NOLAPS Tendency (°C)	NOWLAPS Tendency (°C)	24-Hour Advection (°C)	Observed Change (°C)
1000	-4.7	-5.3	3.0	-3.0
850	4.0	1.7	0.1	2.0
700	0.4	0.0	0.2	5.0

Case 15

Pressure Level (mb)	NOLAPS Tendency (°C)	NOWLAPS Tendency (°C)	24-Hour Advection (°C)	Observed Change (°C)
1000	1.5	1.6	1.8	3.5
850	2.2	1.1	1.3	7.0
700	-1.6	0.1	2.4	3.0

this result, it appears to be physically possible. One mechanism for producing this result at weather ship "Charlie" is for the station to experience strong winds at the surface and aloft from a northwesterly direction. This trajectory brings air from the Greenland Ice Cap and surrounding colder water and ice, less than 1000 miles away. West to southwest winds at "Charlie" may also have a trajectory from Greenland if a closed low pressure center lies northwest of the station. Of course, such a trajectory is longer and less direct.

Table 10 indicates the conditions which existed for seven cases in which the verifying surface air temperature is colder than the water. With the exception of cases 9 and 11, a strong trajectory from Greenland either exists or develops during the forecast period. In case 9, such a trajectory develops, but the flow is weak. Case 11, where southeasterly winds prevail, cannot be explained by trajectory. Forecasts for these cases could be improved by the use of a lower than observed sea surface temperature permitting the surface layer of the forecast sounding to cool commensurate with the verification.

Table 10

Analysis of Cases where Verifying Surface Temperature is Lower than Input Sea Surface Temperature

Case	Initial SST (°K)	Verifying Surface Temperature (°K)	Initial Winds 1000 mb Dir/Speed (knots)	Initial Winds 850 mb Dir/Speed (knots)	Verification Winds 1000 mb Dir/Speed (knots)	Verification Winds 850 mb Dir/Speed (knots)
4	278.1	277.2	220/35	235/82	280/35	Missing
5	277.9	275.1	290/32	285/42	250/18	260/28
6	277.9	273.0	240/25	220/62	260/25	255/38
9	277.2	274.6	195/14	235/22	240/15	195/16
11	277.1	275.3	115/34	115/26	125/18	120/16
22	278.4	274.8	330/20	290/21	280/25	275/27
27	278.7	276.7	245/23	265/29	310/29	320/33

4.0 TASK 3

4.1 Requirements

As specified in the Statement of Work for Contract N00228-84-D-3155, Delivery Order No. QE-02, the requirements for Task 3 state:

> "A manual shall be written to teach the meteorologist in charge of running NOWLAPS the procedure for determining the LST terms. In addition, the contractor shall write a final report which details the results of all three tasks."

> "Requirements: The primary goal of this contract is the production of a manual which will describe to the meteorologist running NOWLAPS how to determine the LST terms. As part of this manual, pertinent examples (to be chosen by the contractor) from the case studies shall be used as examples and illustrated in detail. The outline of the manual shall follow the guidelines as set forth in MIL-M-81273/7A(WP) of 25 April 1966. Separate from this manual shall be a final report which details all work in this contract. In particular, the final report shall summarize the work in all three tasks, shall detail the analysis of all cases, and shall explain the thought and rationale used to develop the LST method. Some of the rationale and case study analysis may necessarily be duplicated in the manual. The detailed analysis of each of the forecast variations (no LST,

LST, persistence, and NOLAPS) shall include not only the RMS statistics (as detailed in Task 2) but also graphic plots (variable vs. height) of the potential temperature, mixing ratio, wind speed, and wind direction. As much as can be plotted without sacrificing readability, the forecasts and verifying soundings shall be overlaid so as to illustrate the altitudes at which the forecasts fail or succeed. Suggestions for future improvements to NOWLAPS or to its utilization of the LST terms shall be included in the final report."

4.2 Final Report

This document constitutes the final report for this delivery order.

4.3 User's Guide

A User's Guide for determining the LST terms for NOWLAPS is available as a separate report.*

4.4 Synoptic Analyses and Sounding Plots

The surface synoptic analyses and the NOWLAPS/NOLAPS sounding plots (potential temperature, specific humidity, wind direction and speed) are available on request. These figures were referred to earlier as Attachments A and B, respectively.**

*Published separately as NAVENVPREDRSCHFAC Contractor Report CR 87-08, April 1987.

**Available separately upon request.

5.0 CONCLUSIONS

A technique to compute large-scale tendencies from NOGAPS output has been developed and tested. The following conclusions concerning that technique and the NOWLAPS model in general are drawn.

- o LST temperature terms developed manually from NOGAPS output agree within 1 to 1.5°C with those developed by NOLAPS. Given the contour interval provided on the NOGAPS charts, this agreement is considered an optimal result. A reduced contour interval would produce better agreement.

- o NOWLAPS (without LST) produces a forecast comparable to persistence. The addition of LST terms improves the forecast significantly.

- o The NOWLAPS forecast is deficient for cases which saturate at the top of the grid. Moisture accretion and resultant condensation and warming produce unphysical results.

- o The NOWLAPS model currently cannot cool the lowest layers below the initial sea surface temperature, despite observed cases where this apparently occurs.

- o The NOWLAPS software terminates execution prematurely when the mixed layer reaches the top of the grid.

- NOWLAPS with large-scale tendencies produces forecasts superior to persistence, but is inferior to NOLAPS for the above reasons.

6.0 RECOMMENDATIONS

- Eliminate moisture accretion problem by modifying NOWLAPS software.

- Permit a shallow surface superadiabatic layer, especially with light winds, to replicate observed cooling below sea surface temperature.

- Produce NOGAPS output with finer contour resolution to permit more accurate determination of LST terms.

- Consider installing a third, taller domain option in NOWLAPS to raise the upper boundary.

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