Diagnostic Indicators in Trough - Ridge Systems applied to Real Time Ship Routeing

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ABSTRACT

The need for the mariner to have better weather indicators for efficient ship routeing in the middle latitudes is demonstrated. The benefits of an early appreciation of the subtle changes in storm behaviour is shown in a case study. Monitoring of ship's performance through a frontal depression using a modified Tropical Storm Avoidance simulation, also developed by the author, shows the penalties of not minimising the effects of wind and waves. To accomplish the aims of this project diagnostic models are developed, firstly to show the overall movement of the frontal depression within the trough - ridge system and secondly to investigate the field structure appertaining to depression movement and development.

The graphical diagnostic model, an animated movie loop, allows the detail from two levels to be combined, surface fronts superimposed on the 500 mb flow, and played back in sequence showing the sophisticated nature of storm movement. This insight naturally lead to the development of a numerical diagnostic model to study simple elements such as wind fields. Analysis of these data enabled a movement indicator for the frontal depression, the"TEN" Indicator, to be formulated and is based on the 500 mb contours. Further improvements in the diagnostic numerical model allows the gradients of synthesised elements to be calculated without the loss of boundary values, and uses a cubic spline technique based on the Lagrange Interpolation.

Error analysis of the calculated wind fields is carried out to test the accuracy of the methods employed. The model is then used to analyse a number of depressions using various development techniques to test the model. The results from four occasions, of the many observed, are demonstrated showing the development ideas of Sutcliffe, Petterssen and the Q-Vector based on quasi-geostrophic theory. Divergence is also considered using gradient wind substitutions, adjusted for surface friction and modified to satisfy curvature effects in ridge systems. The four occasions illustrated demonstrates the similarities between each method, the location of vertical motion within a deepening depression is located slightly in advance of the warm front. The normalising of these vertical field indicators against the surrounding flow allows the visual and numerical appreciation of ascent in weak fields. This approach may be an advantage in further studies of cyclogenesis.

The model wind fields are tested using operational wind data, both being calculated from the same digitised pressure fields. The Oceanroutes Operational Routeing Model is employed, using these data, to produce two routes using both the analysis and forecast data. The case study demonstrates the usefulness of the "TEN" Movement Indicator as it provides the mariner with the tools to examine depression movement, to check forecasts and to give him the confidence to question routeing orders. This method requires data for the surface and the 500 mb level. Recommendations are suggested to modify the surface weather chart format for the mariner by including both movement and development information which would economise and optimise weather data transmission for greater shipboard efficiency.

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I should also like to express my thanks to the Meteorological Office who have collaborated to this research, the local weather centre for providing data not readily at hand and to Doug McWhan, PMO Southampton who has provided certain marine charts not available in Plymouth.

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CHAPTER ONE Introduction

1.1 Weather and Ship Movement

The early or on-time arrival of a vessel safely at its destination has always produced the best financial returns. Even in the days of sail the Master who took benefit of good winds and weather was seldom unemployed. His judgement was based on years of experience, a good knowledge of the "weather signs" and the ability to have the confidence to make drastic decisions. Effective voyage planning was achieved without up to date weather information, no daily weather reports were available until the 1920's and these were restricted.

With the advent of steam power the skill of weather avoidance became a lost art as ships operated at a designed engine speed and the speed made good dictated by the wind and sea. However sea times were drastically reduced, and over a period of thirty years the bulk of commercial and military movements were done by steam.

Subsequent to the loss of the "Titanic" in 1912, some preferred routes were established for the Atlantic between N. Europe (and the UK) and New York (and Canada). This was to a certain extent routeing, but was based on the seasonal avoidance of icebergs and fog near the Grand Banks, Newfoundland, and not to expedite early arrivals.

From 1960 prudent shipowners realised the benefits of "weather routeing", especially in the container trade where optimising the berth time against voyage time meant a more efficient service.

The oil crisis of 1972, when the price of oil fuel doubled, and also the increase in 1979, made weather routeing more attractive even to the most reticent shipowner. However, the 1986 collapse in oil prices generally, from 36 US\$ to 10 US\$ a barrel has been a major help in minimising freight rates. The Gulf Conflict 1990 certainly saw a rapidly fluctuating oil market with prices at a high of 40 US\$ a barrel but these prices have stabilised at 20 US\$ a barrel during the summer of 1991.

During the period 1972 to date the adoption of weather routeing as a norm has been encouraged, mainly by the requirements of the charterer. This is specified either to reduce insurance premiums, or more likely in the case of a claim have a fall-back mechanism, giving an independent source of weather data to reinforce shipboard records. Cargoes have become more valuable and more hazardous with complex chemicals carried in bulk.

1.2 Types of Weather Routeing

Weather change over the oceans tend to fall into three main categories, see Figure 1.1, continuous, bi-annual and constant.

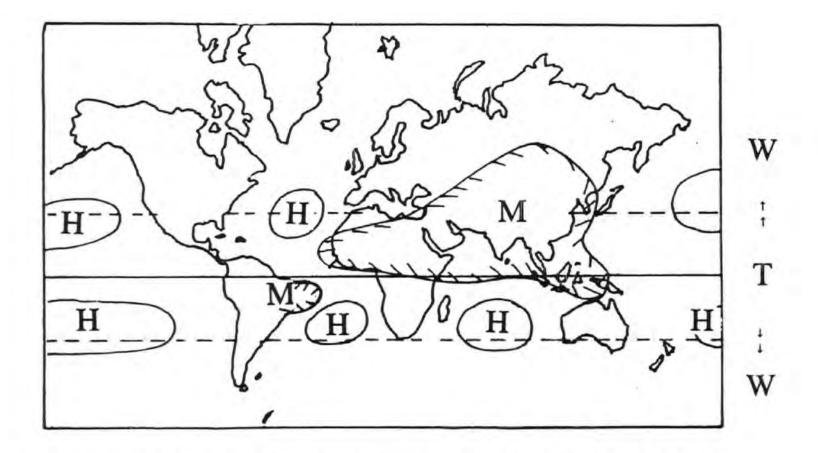


Figure 1.1 Scales of Global Weather, T - constant (Cat.c), M - six months (Cat. b), W - continuous (Cat. a) and H - high pressure areas

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Most meteorological publications show this to be the case, e.g. <u>Palmen & Newton, (1969).</u>

Category a: where frontal storms track mainly eastwards across the oceans, allowing for heat transfer from tropics to poles, the weather picture is seldom the same and varies from one day to the next and covers an area poleward of Latitude 25°. This area, with its complicated changes, affects the major routes in the North Atlantic and the North Pacific. Trade between Japan and America, also the trade between Europe and America and vice versa will be greatly hampered through bad weather with damage to goods and carrier plus any time delay caused.

Category b: only applies to the N. Indian Ocean which come under the influence of the seasonal monsoon. For six months winds blow from the north followed by six months of southerly winds. This significant change affects the ocean circulation but the changes are relatively slow.

Category c: the tropics, show little change at all. The trade winds are the most consistent wind fields on our globe.

However, within the areas of categories b and c, cyclones are encountered at certain times, but these can be allowed for given sufficient warning. Satellites can pinpoint the centre of these storms as they view the earth every thirty minutes.

Weather routeing techniques can be employed within the area of category a and climatic routeing in both b and c.

1.3 Methods of Routeing

It has generally been the policy for the data producing centres such as the British Meteorological Office to provide a ship routeing department and service. Competition has also arisen from independents, such as Ocean Routes Ltd. The available weather data being tailored to the needs for each ship (for a substantial fee), and usually update the shipmaster daily. This is similar to the procedures followed by airline pilots who are offered a number routes for selection. If none are satisfactory they must furnish their own, which is time consuming and generally not feasible.

There are no reasons unless restricted by commercial restraints to stop the shipmaster from weather routeing his ship should he have access to similar weather data as his land based counterpart.

The mariner can obtain excellent weather data through the marine facsimile service; <u>Admiralty list of Radio Signals</u>, <u>Vol. 3, 1987</u>, illustrating global coverage, with ample information for the N. Pacific and N. Atlantic Oceans. However, the UK Meteorological Office, also the other major centres, have a monopoly on data, and only transmit a selection, which is assumed to be adequate.

1.4 Ship running costs

Costs for an average sized container vessel typical of the N. Atlantic trade are supplied by the Shipping and Transport group in the Institute of Marine Studies. Table 1.1 show costs for three periods, before and after the oil price collapse and subsequent to the Gulf conflict.

	1985	1987	1991
Crew	920	1,200	1,500
Maintenance etc.	550	600	650
Insurance	690	700	750
Overheads	125	125	140
Capital	30,000	30,000	30,000
Premium (10%)	3,000	3,000	3,000
Fuel	4,550	1,830	2,730
Costs per year	9,835	7,445	8,770
per day	27.0	20.5	24.0

Table 1.1 Ship Running Costs

All costs are expressed as thousand f units.

Fuel	Breakdown		No. of days at s		r	260
			Fuel consumption	per day		70t
		- 9	Cost per tonne,	1985 - £2	250	
				1987 - £3	100	
				1991 - £1	150	

Adverse weather from frontal storms can cause as much as 30 per cent extra fuel to be consumed and an equivalent ratio of added time per voyage. <u>Motte and Calvert, (1988)</u> also maintain that one North Atlantic operator has calculated a £450,000 annual service cost for an average of 20 delayed passages which are directly attributable to these storms.

1.5 Financial Advantages of Optimising Voyage Time

Land based routeing agencies claim on average six hours saving per crossing of the North Atlantic, <u>Ocean Routes Ltd.</u> A saving of 70 hours for the occasional crossing was also claimed. Bearing in mind these savings, the Master of the ship with an understanding of "weather signs" can come to the same decisions as land based agencies, thus minimising the cost of the service and maintaining the Master's role and responsibilities. <u>Motte, (1981)</u>, has maintained that shipboard routeing can be achieved by the Master to a comparable standard to that offered by land based operations, but no study into this claim has as yet been conducted (automatic systems will facilitate this).

1.6 Objectives of this research.

This study is to provide the Master with up to date indicators of storm characteristics to enable on-board routeing decisions to be made or to enable the master to fully understand routeing instructions from an outside agency.

To accomplish these objectives an exhaustive literature survey was conducted and covers the existing guidelines available to the mariner, Chapter 2, the mathematical theory applied to the atmosphere and 'the state of the art' regarding diagnostic modelling, Chapter 4. The need for this research is demonstrated in Chapter 3 where early recognition of a frontal storm off Newfoundland would greatly improve voyage time, reduce damage and generally make the last part of the voyage more agreeable for those onboard.

The development and the construction of the diagnostic model is explained, Chapter 5, and incorporates a novel solution of fitting a curve through each row or column of data to enable the gradients at each grid point to be obtained without losing any boundary values common to finite differencing. The diagnostic model employs standard geostrophic wind relationships which are expanded to obtain gradient wind relationships with adjustments for surface friction. These parameters are tested against real The application of the model time data, Chapter 6. to investigate indicators of depression characteristics is explained in Chapter 7. A practical indicator for storm movement, which utilises the 500 mb contours is described and tested against traditional methods. Development indicators using established theory are tested and compared showing interesting comparisons. The introduction of a strength factor which compares the ascent at the grid point to a mean surrounding value is demonstrated. The use of the developed movement indicator to improve the mariners comprehension of storm movement is applied to data which was used operationally by

Ocean Routes Ltd. in their ship routeing model, Chapter 8. The operational data of surface wind velocities are compared with the model output. A summary of the research conducted with conclusions and recommendations are found in Chapter 8.

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CHAPTER TWO The Mariner and Bad Weather in the Baroclinic Zone

2.1 Understanding of Depression Characteristics

A knowledge of the general behaviour of depressions has always been essential to the mariner and a set of general guidelines have been at hand for many years. Most nautical publications carry these in some detail, see Admiralty Manual of Navigation, Vol.II, 1954, which may be summarised as follows:

- the depression generally moves in a NE'ly direction in the eastern North Atlantic;
- ii, over the sea the depression will continue its direction if this has been maintained over the previous twelve hours;
- iii, the movement is usually parallel to the warm sector isobars and at a speed approximately equal to the geostophic wind in the warm sector;
- iv, the probable movement will be towards the isallobaric low and away from an isallobaric high;
- v, the depression is filling or slowing down when the barometric tendency is greater behind rather than in front;
- vi, the depression is deepening or speeding up when the barometric tendency is greater in front than behind;
- vii, a depression which has the same pressure gradient on all sides is stationary;

- viii, a depression tends to move in the direction of the strongest winds;
- ix, small depressions tend to move quickly;
- x, a secondary depression rotates cyclonically around the primary in the northern hemisphere;
- xi, depressions having wind speeds less than normal tend to deepen and those with winds greater tend to fill.

2.2 General Comment

Over the last thirty years observational techniques have improved, knowledge of the physical coupling and the dynamic structure of the troposphere has increased. This has been aided by the use of high speed computers to enhance numerical forecasting and by observations from space. Satellites give extra data input for the numerical models and a clearer graphical representation of the evolving systems. At least the cloud mosaics show areas of depression activity. Significant improvement has come from the high speed telecommunication links between World Meteorological Organisation participating countries enabling data to be transferred very quickly. Any comparison between the weather charts of yester-year and today would reveal that the systems are more complex than originally drawn. Good examples can be found in many old meteorological publications, see page 223, Admiralty Manual of Navigation, Vol.II, 1954. Although this is an example of the International Analysis Code (IAC) it does show a simplistic view of the systems analysed.

Bearing in mind that storm guidelines were supposed to aid the mariner it might be sensible to appreciate the weather data at hand in those days and to evaluate their usefulness. The mariner could receive by wireless telegraphy weather reports and weather observations of both ships and shore stations. He could then construct a surface weather chart by analysing this data. Also the International Analysis Code allows the mariner to put together a weather chart as an artist paints a picture to numbers. This method is still available to seafarers but the ship report method has been curtailed due to Governmental financial constraints. Facsimile data was not available and did not appear until later, initially a few merchant ship operators had the foresight to install this equipment as it was not required under the International Safety Rules. Even today facsimile receivers are not fitted as standard to British owned ships and the response to questioning of students preparing for professional qualifications reveals about 60% have sailed with this equipment.

These general rules would indeed be hard to use considering the difficulties in actually obtaining a weather chart.

2.3 Particular Comments on Guidelines

<u>Guideline i</u>: this is a very general statement, certainly from my experience, depressions on occasions do not follow this instruction and move NW'ly or SE'ly.

<u>Guideline ii</u>: from my observations it is apparent that movement can be erratic, see section 2.4.

<u>Guideline iii</u>: this is again a broad statement, depressions can be quite active with strong winds in the warm sector yet may be stationary.

<u>Guidelines iv,v,vi</u>: weather charts do not show tendency directly.

<u>Guidelines vii,viii</u>: any weather chart constructed aboard, usually by an inexperienced junior officer would not necessarily pick up the areas of strongest gradients.

<u>Guideline ix</u>: this is most likely true for the western part of the ocean, but cyclogenesis off Europe when the cold front lies north south the reverse is true.

<u>Guideline x</u>: secondary depressions* have become more difficult to recognise on recent charts.

<u>Guideline xi</u>: it is difficult to visualise a depression with normal winds, let alone being able to make comparisons.

Ships having the benefit of facsimile receivers allow the mariner to receive forecast charts which make some of the guidelines irrelevant.

* Secondary Depression is defined in the Meteorological Glossary, as forming within the region of circulation of another depression with a higher central pressure.

2.4 Examples of the Life History of Depressions

Examples of the part-life cycle of two depressions in midwestern North Atlantic were chosen from the many situations analysed.

These were typical, not extreme cases, Figure 2.1 shows the problems of movement and development. Data regarding these examples as shown in Table 2.1 indicate:

- a, depression A moves quickly to the North East;
- b, depression B slows down in the middle of the sequence and then turns North before returning to a Easterly direction.

Date	Time	9	Position				Pressure	
	Depressio	on A						
	13-2-89	0000Z	4'2°	00'N	60°	00'W	1012	mb
	13-2-89	1200Z	45°	30'N	52°	30'W	1005	mb
	14-2-89	0000Z	54°	30'N	37°	30'W	999	mb
	14-2-89	1200Z	62°	30'N	18°	00'W	976	mb
	15-2-89	0000Z	67°	00'N	00°	00'W	950	mb
	Depressio	on B						
	6-2-87	00 <u>00</u> z	43°	00''N	46°	00'W	989	mb
	6-2-87	1200Z	50°	00''N	40°	00'W	985	mb
	7-2-87	0000Z	55°	00'N	40°	00''W	969	mb
	7-2-87	1200Z	56°	00'N	38°	00'W	955	mb
	8-2-87	0000Z	60°	00'N	32°	00'W	964	mb
	8-2-87	1200Z	61°	00'N	3 0°	00'W	974	mb
	9-2-87	0000Z	62°	00'N	25°	00'W	980	mb

Table 2.1 Position and Pressure Data.

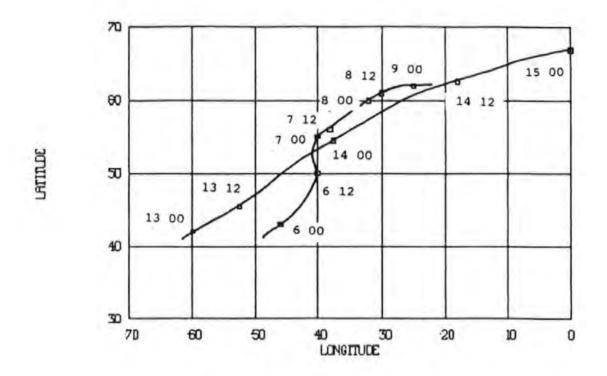


Figure 2.1 Stormtracks, Position indicated with date and time

Pressure changes occur:

a, depression A when moving at a high speed;

b, depression B when moving at a slow speed.

2.5 New Guidelines

The comparison demonstrates the need to update the current quidelines.

Two further examples are given in the next chapter:

- a, early appreciation of weather movement changes during a trans - ocean voyage;
- b, improvement in ships performance when encountering a storm.

CHAPTER THREE Application of this research

This research is primarily intended to aid the process of ship routeing but will be useful to various sea users as it will provide general guidelines for system evolution within the baroclinic zone. This information is not generally forthcoming, mariners are aware of the importance of depressions and the problems they might cause but are only given a small insight to the complex structure and development. It is not sufficient for the pure meteorologist to say that the charts produced today are adequate. Occasionally the mariner experiences the bad weather that the meteorologist misses on the forecast chart. The furore that the October '87 storm over SE England created is often repeated at sea but is never highlighted.

My experience of teaching future shipmasters is that they distrust any external instruction on ship routeing. They argue that the practice is generally good but sometimes they are directed, presumably unintentionally, into bad weather when they can see from the weather charts available a slight alteration of course made a day earlier would have minimised the effects of the storm.

3.1 Practical Applications of this Research

Two separate examples are used to demonstrate the need for better guidelines / rules. The first situation is applied to

a hypothetical vessel on a westbound voyage across the North Atlantic. The second seeks to demonstrate how vessel performance may vary when engaging a depression.

3.2 Trans - Ocean Crossing

The vessel, a general cargo / container type, half loaded departs from Liverpool at 1800Z on the 31st December 1981 for Halifax, Nova Scotia.

The vessel is provided with facsimile equipment and it is assumed that the following weather charts are received:

Surface Analysis, twice daily. Surface Prognosis for 24 and 48 hrs.,daily. Sea State and Ice Coverage, daily. Sea Temperatures, daily.

It is also assumed that the upper air charts are not received, if taken their importance is not recognised.(My daily contact with serving mariners reinforces this belief.)

The synopsis at the time of departure, 1st January 1982, from Northern Ireland, see Figures 3.1 and 3.2 (constructed using the graphical model see Chapter 5), indicates a complex low over the N.Atlantic from Newfoundland to N.Ireland.This system has three centres, 57°N 15°W, 50°N 33°W and 46°N 43°W with the 990 mb isobar enclosing these positions. Winds to the north of these postions are easterly between 25 and 35 knots with a

generated wave pattern from the north-east with heights between 3 and 6 metres. Although this is the winter period the sea ice has not developed off Newfoundland at this stage.

The forecast charts available indicates that this weather pattern is likely to persist over the next two days as the system moves slowly towards the UK. The master bearing this in mind decides on the great circle route and course is set from position 55° 30'N 7° 00'W at 0645Z on the 1st January.

The record of the voyage, Table 3.1, shows the 12002 position each day. Good time is made with the following wind and sea for the first three days of the voyage. Speed of the vessel is estimated from sea state and performance curves, see Figure 3.4. From the 5th January, see Figures 3.3, 3.5 and 3.6, the speed of the vessel is greatly hampered by the heavy head seas generated by the depression centred to the west of Newfoundland and the estimated time of arrival is extended. However as this depression moves away the better weather allows the vessel to arrive at its destination, Halifax on the 7th January at 1640 local time. If the vessel had maintained an average speed of 15.5 knots for the crossing the ETA would have been some thirteen hours earlier.

The master who understands the importance of upper air flow on storm steering could on the 4th January with the receipt of the 24 hour surface forecast and 500 mb charts make a better assessment of the current situation.

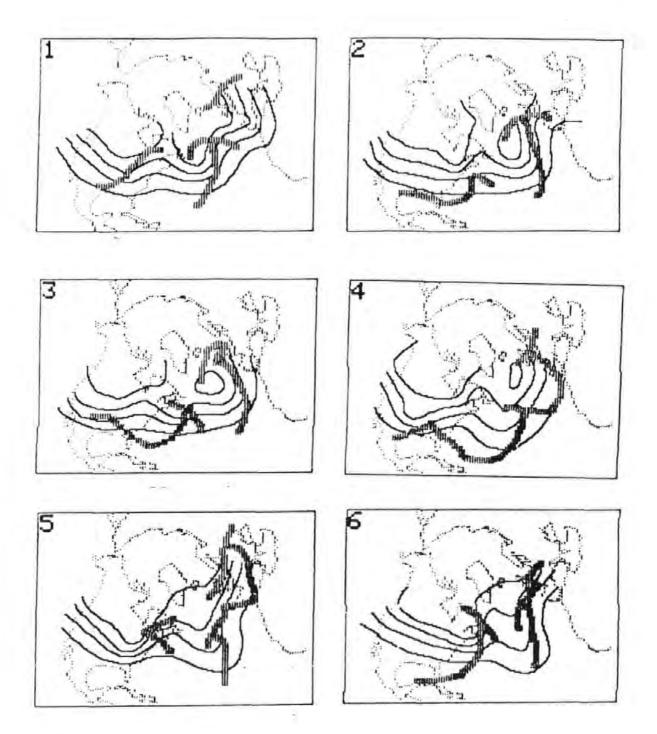


Figure 3.1 Weather: 1st January 1982 to 6th January 1982 500mb Height Contours - lines Surface Fronts - Shaded Lines

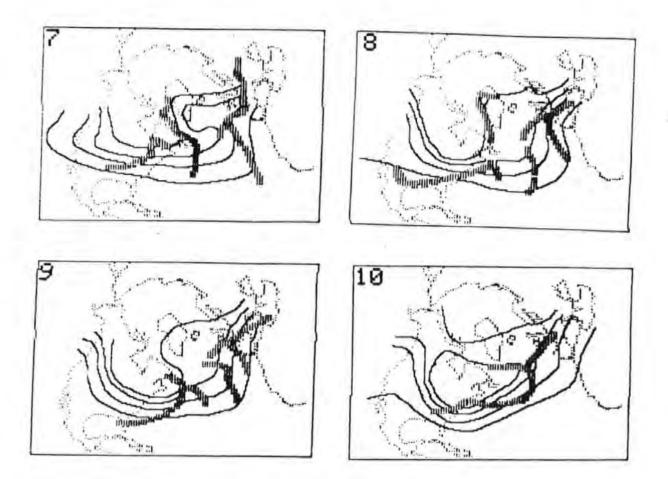


Figure 3.2 Weather: 7th January 1982 to 10th January 1982 500mb Height Contours - lines Surface Fronts - shaded lines

From his present basic knowledge he assumes quite falsely that this depression is likely to move across Newfoundland and out into the Atlantic hoping still to benefit from favourable winds in the northern half of the depression. The improved guidelines would show graphically various states of upper air flow. The master relates the actual pattern to the best likeness and obtains future movement details such as angle to the 500 mb flow and an indication of speed.

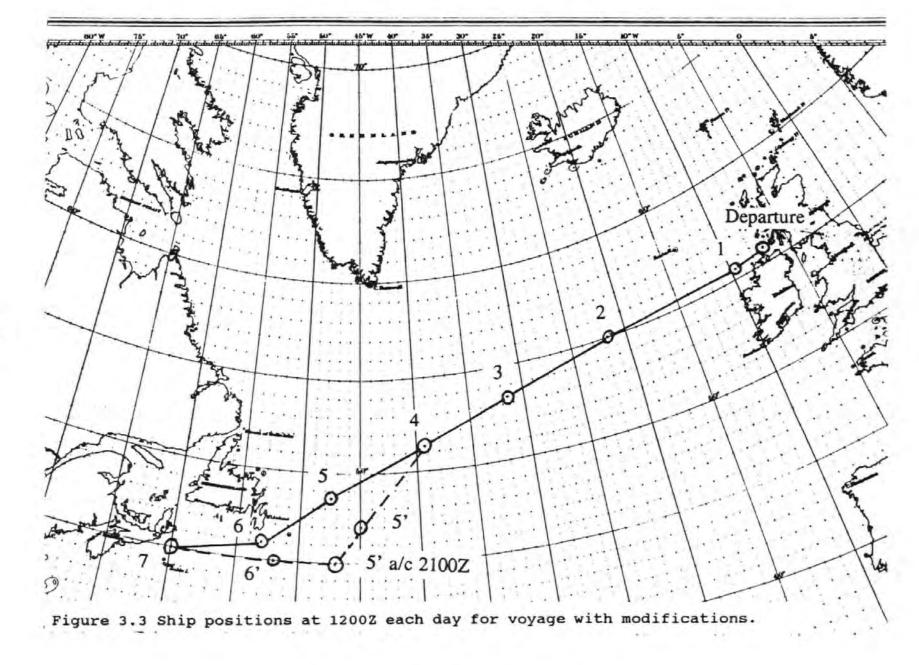


Table 3.1 Voyage Record

Date	Time	Position	Pres	sure	Wil	nd	Se	a	Can	ments
1.1	1200z	55 22'N 9 46'W	1006	F	SW	5	S	1-2	Beam	16.5K
2.1	1200z	55°00'N21°30'W	987	F	S	15	S	2	Beam	16K
3.1	0000z		975	F	SE	15	E	3	Quart	: 15K
3.1	1200z	53°30'N31°24'W	985	S	ENE	40	NI	5 5	Foll	14.5K
4.1	1200z	51°30'N39°12'W	1010	R	NNE	5	N	5	Foll	14.5K
5.1	1200z	48°40'N47°40'W	1025	S	NE	5	NI	E 3.5	Foll	15K
	* Ne	at depression over	er New	York	assu	nes	mos	ment NE		
6.1	0000z		1005	F	SW	25	S	4.5	Head	9K
6.1	1200z	46 00'N53 00'W	998	R	W	20	S	5.5	Read	9K
7.1	1200z	45°00'N60°00'W	1016	S	S	15	S	2	Beam	15K

.

TO HALIFAX 155 n.miles ETA at 15 knots:2140Z or 1640 local time

Table 3.2 Modified Voyage Record

Date	Time	Position	ion Pressure Wind S		Sea	Connents
			1010 R	NINE 25	N 5	Foll 14.5K
	a/c 2	15 ^o T				
5.1	1200z	47°00'N45°00'W	1021 R	NINE 25	NNE 3	Foll 15.5K
5.1	2100z	a/c_270 T @ 45 N	1015 F	SSE 10	SE 1	Beam 16.5K
6.1	1200z	4500'N5200'W	1002 R	W 20	SW 5.5	Head 9K
7.1	1200z	45°00'N60°00'W	1010 F	W 10	W 2	Head 16K

TO HALIFAX 155 n.miles ETA at 15 knots: 2140Z or 1640 local time

These guidelines would quickly indicate to the master that as the upper air flow is weak and that contours are aligned northerly the depression will move towards Labrador and thus cause unfavourable winds and seas along the planned track. If the master acts prudently by taking early action, on the 4th, such as a more southerly course the vessel will track around the limits of the depression and thereby encounter less severe winds and sea.

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Figure 3.3 shows this deviation and Table 3.2 the modified voyage record which puts some distance on the voyage but as speed increases it makes very little difference to the arrival time and that damage to ship and cargo would probably be reduced.

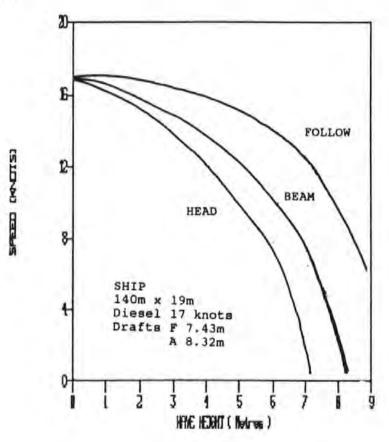
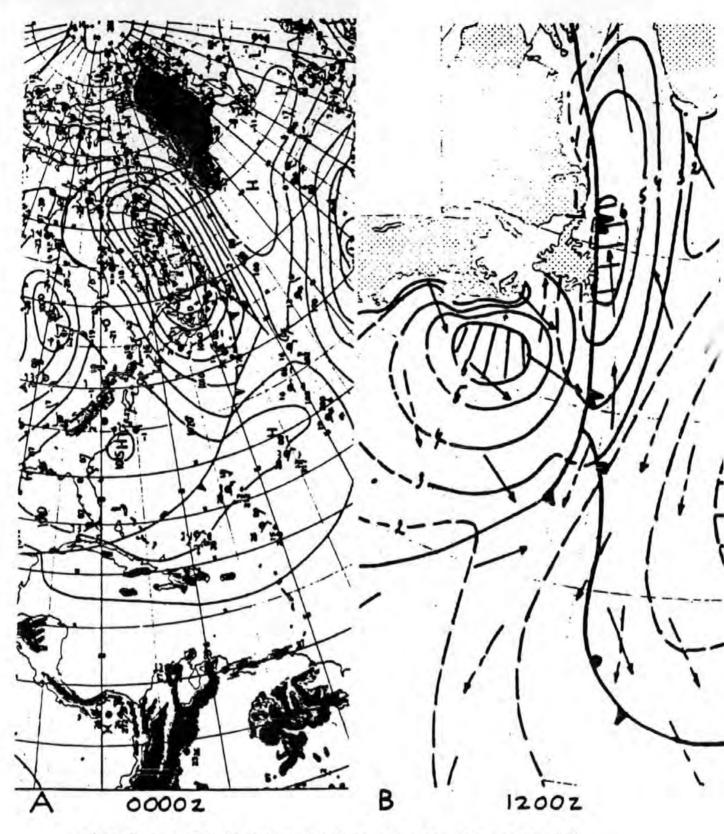


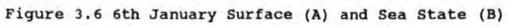
Figure 3.4 Ship Performance Curves.



Figure 3.5 5th January Surface (A) and Sea State (B)

Note: Certain diagrams have not copied correctly due to their unusual quality from either their fugitive colours or poor facsimile reception.





3.3 Ship Performance and Depressions

A second demonstration, which has been developed from my "Tropical Storm and Ship Avoidance Simulation", allows the performance of a vessel to be monitored whilst traversing a depression. The model depression used is of average dimensions and can move in any direction with any speed. In this example the direction is kept constant (070°T) with the speed set either at zero or 30 knots.

Three situations are investigated using the two speed criteria, they are :

- i, vessel heading into approaching depression;
- ii, vessel running with the depression;
- iii, vessel crossing the path of the depression.

In the first two situations three vessels are used, one on the path of the storm whilst the others are some two hundred miles north and south of the track. In the crossing situation five vessels are considered with two ahead i.e. to the east of the depression, two behind and one abreast.

3.3.1 Simulation Details

A set of algorithms are used to describe the storm which are calculated as a distance measured radially from the storm centre.

Wind strength, V(R), knots, and wave height, W(R), metres, are obtained at a radial distance, R, nautical miles, as follows

$$V(R) = \frac{380000}{R^{2.3} (\exp(2000/R^{1.6}) - 1)}$$
 3.1

$$W(R) = 0.018V(R)^{1.57}$$
 3.2

Radial Wind Velocities, Equation 3.1, were obtained by fitting a curve through plotted wind magnitudes obtained from synoptic depression data. The curve which produced the best fit, Correlation Coeff.0.7, was the Planck Radiation Equation, however the constants in this equation were modified. Wave heights, Equation 3.2, were obtained using the relationship of mean wind and significant wave heights from the Beaufort Wind Scale.

Profiles of wind and wave heights from these algorithms are are shown in Figure 3.7.

Ship performance curves, see Figure 3.8, are obtained using the following

$$SPEED_{BEAM} = SPEED_{CRUISE} \cos\left(\frac{\pi}{24} (W(r) + 0.5)\right)$$
3.3

$$SPEED_{HEAD} = SPEED_{BEAM} - \frac{\theta}{180} W(R) \qquad 3.4$$

$$SPEED_{FOLLOW} = SPEED_{BEAM} + \frac{\theta}{180} W(R)$$
 3.5

Where θ represents the angle in degrees of the wave direction from the beam bearing, with a beam sea $\theta = 0$, but with the sea on the bow $\theta = 45$ degrees.

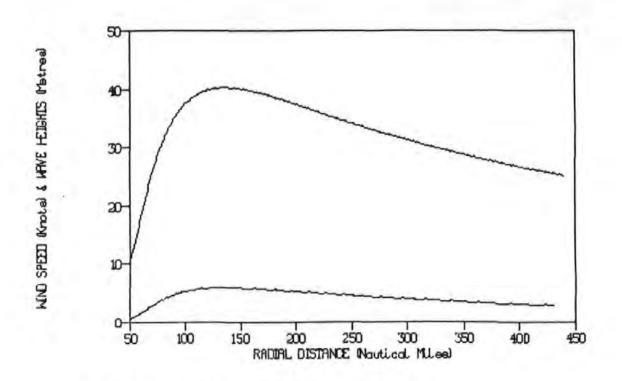
These ship performance curves after scaling do fit an actual vessel, the Gladys Bowater, which traded regularly across the North Atlantic.

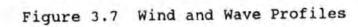
Correlation Coeffs.: Head 0.97, Beam 1.0 and Following 1.0

This hypothetical yet realistic frontal depression model is divided into four quadrants, leading, trailing, top and bottom. The bottom quadrant represents the warm sector and has straight isobaric contours and the other three having circular contours. Wind direction is obtained from the bearing of the storm but remains constant in the warm sector.

3.3.2 Method of Simulation

Both the vessel's departure and the storm location positions are input. A time interval for progression is input and both the vessel and the storm progress. The storm movement is set and remains constant throughout the run. The vessel's speed is





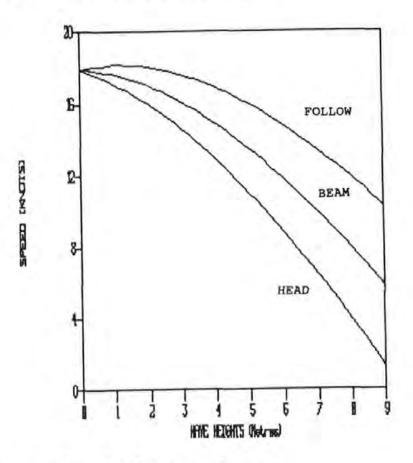


Figure 3.8 Ship Performance Curves

obtained by first calculating by Plane Sailing the bearing and distance of the vessel from the storm. The distance obtained can be fed into the wind equation, 3.1, this result is then fed into the wave height equation, 3.2.

The wind direction and the vessel's course allows the relative sea state to be obtained. Entering the performance equations, 3.3, 3.4 & 3.5, speed can be obtained. The vessel progresses at this speed along the set course for the next time interval until the run time is achieved, in the demonstration fortyeight hours is used. Appendix A shows the data for one run. Figure 3.9 shows the vessel's performance heading into the storm. Positions are indicated by squares, letters A, B and C represent three separate vessels and S the storm. The number in the bracket represents the distance made good and the suffix

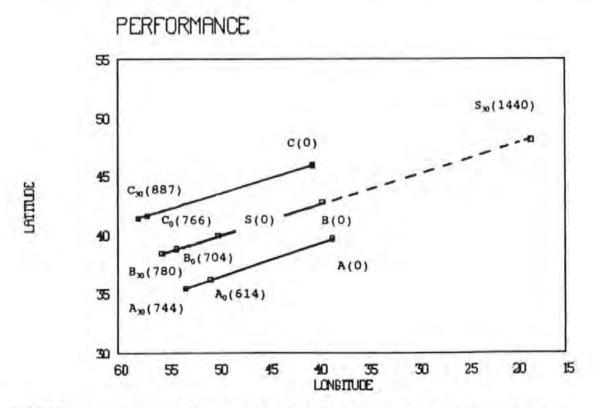


Figure 3.9 Performance Monitoring : Heading into Storm

indicating whether the storm is stationary (0) or moving (30 knots). The results show quite clearly all vessels make good a better distance when the storm is moving. On the trackline an extra distance of 76 nautical miles, nm, is covered (780 nm to 704 nm). On the north side of the depression, vessel C, with the following seas for both speed conditions extra distance is achieved. Distance made is greater with the moving depression, 887 nm as against 766 nm. The southerly route taken by vessel B is hampered by the head seas but again the moving depression causes least resistance to vessel progression (744 nm to 614 nm). Figure 3.10 shows the performance with the vessel moving through the storm or in the direction of the moving storm albeit at a slower speed. Three vessels are considered being indicated as in the previous case. Vessel B is on the trackline line, C to the north with adverse conditions and A to the south with favourable conditions. Obviously greater distance made good will be found with the storm pulling away from each vessel. However, with the storm stationary the greatest distance made good is found on the trackline where the wind fields gradually decrease to zero and then increase with a reversal in direction. On the south side speed is hampered throughout simply because of the strong maintained following wind and seas.

The crossing case, Figure 3.11, gives more complex results with the two examples behind the depression initially making good more distance with the depression moving and the two cases in advance of the depression initially making good more distance

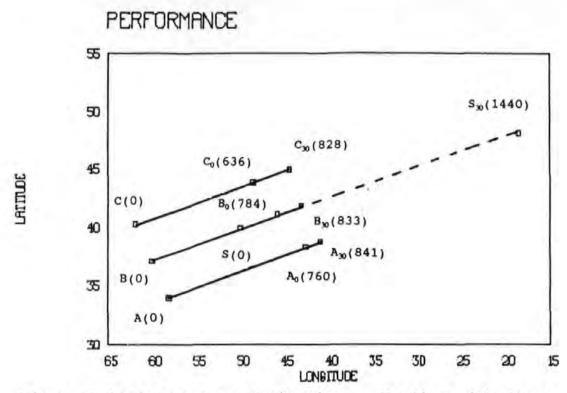
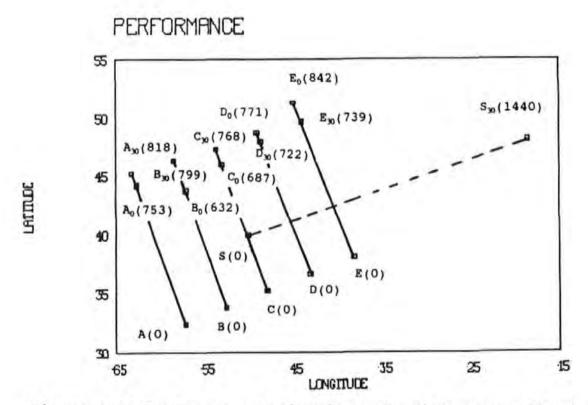


Figure 3.10 Performance Monitoring : Heading with Storm





with the storm stationary.

These three situations demonstrate the need for the mariner to have better guidelines regarding depression characteristics especially movement as this effects ship performance probably far more than changes in pressure. The extent of a major depression changes little over a short period even when the depression's central pressure is changing. This model can be further adapted to indicate what course alteration should be made at each time interval to obtain the 'best' speed, although this increases distance somewhat. This aspect is not considered here as only the shortest distance is taken.

It should be noted that for any increase in distance the proportional increase in speed to maintain the same arrival time is given by :

New Speed Factor = New distance / Old distance

Example - Speed made good 18 knots Old Distance 1000 nm Deviation 100 nm

> New speed factor = 1100 / 1000 = 1.1 New Speed = Speed made good × New speed factor New Speed = 18 × 1.1 = 19.8 knots

3.4 Comment

It is important that any new depression guidelines for mariners must accomodate their current knowledge of meteorology and be easy to apply. The two examples demonstrated indicate that movement characteristics of depressions related to the upper air flow can help the mariner positively with voyage planning either as a weather routeing aid or as a general guide to storm avoidance and to enhance ship performance. It is with these aims in mind this research was conducted. A literature survey, Chapter 4, was implemented to help in assessing the possibility of using a micro-computer to build a diagnostic model incorporating detail of the depression.

CHAPTER 4 Diagnostic Modelling

The term diagnostic modelling is used within this research to cover the description of the synoptic situation. Knowledge of models previously developed have aided in the construction of the diagnostic model used in this investigation.

4.1 Literature Survey

Diagnostic modelling is in its infancy, <u>Hoskins, (1983)</u>, the first realistic diagnostic models were developed by the Norwegian School, descriptively explaining the possible development, structure and movement of storms.

This technique, developed during the First World War, has been commonly referred to as the Polar Frontal Theory of Depressions or Bjerknes Model.

At a 1920's meeting in Bergen, Bjerknes argued with Shaw, that cyclone development was related to vorticity concentrated along fronts and afterwards spread over the depression, <u>Douglas, (1952)</u>.

Frontal Zones were not published on the "Daily Weather Report" until 1933. Bergeron referred to these areas in terms of isosteric-isobaric solenoids, this is synonymous with baroclinic zones. Upper air knowledge increased as aviation

became more popular and J.Bjerknes, (1932), included the first dynamical relationship between upper air divergence and the flow round an upper trough. Scherhag introduced ideas on divergence and convergence. Rossby (1939) and <u>Sutcliffe</u> (1939, <u>1947</u>, 1950), incorporated the improvements in upper air data. Rossby described the upper air flow in terms of conservation of absolute vorticity whilst Sutcliffe described the structure of the baroclinic zone in terms of thermal winds, vorticity and divergence.

using simple Descriptive models analysis techniques, Petterssen, (1941), outlined the occurrence of depressions on the leeside of the Appalachian Mountains, USA. Austin, (1941), described favourable conditions for cyclogenesis near the Atlantic Coast. "Cyclogenesis occurs from frontogenesis, this process is characterised by the creation of a temperature contrast as well as cyclonic vorticity". An empirical study of North American weather charts, Austin, (1947), showed cyclone movement parallel to upper air flow but intensity was not directly related to temperature contrasts across the cyclonic centres. <u>Spar.(1956)</u> closely looked at the surface weather (pressure, temperature and rainfall) in a fast-moving rapidly-deepening cyclone over Eastern America. Frontal zone development, using the Boussinesg equations and integration techniques, was attempted by <u>Williams, (1967)</u>. A Diagnostic Balance Model, giving improvement of ascent using quasi-geostrophic theory given by the " ω " equation, used twelve

forcing terms, <u>Krishnamarti, (1968</u>). This study of a frontal cyclone developing over mid-western United States showed the contributions of each of the forcing terms and revealed that upper air development is followed by surface cyclogenesis. Later the intense rising motion being associated with the differential vorticity advection by the non-divergent part of the wind. <u>Sanders, (1971</u>) states "For some years now the specific study of cyclones and anticyclones has been almost abandoned with the feeling that all questions would be answered in due course by generalised numerical prediction".

Mid-tropospheric frontogenesis was investigated, <u>Bosart, (1970)</u>, who explained that initial development was accompanied by a thermally indirect circulation.

The review of aspects of cyclone development in the lower troposphere, <u>Petterssen & Smebye,(1971)</u>, classified cyclone growth into two types:

TYPE A

Usually development occurs with a straight upper air flow, the jet being east-west in the zone of maximum baroclinicity (the polar front). Little vorticity advection takes place, with no upper cold trough. This develops as the low level cyclone intensifies. Vorticity advection remains small and intensification is related to thermal advection.

TYPE B

Development occurs within an existing upper trough, with strong vorticity advection on its leading side which spreads over a low level area of warm advection. The separation between the upper trough and low level system decreases as depression intensifies (trough line cant). Large vorticity advection is found aloft initially but decreases as thermal advection increases.

A case study outlining " ω " effects for two storms, type A over mid-western states and a type B over the American eastern seaboard reinforced this classification. Both these forms of cyclone decay in the classical manner and it would appear that these pure cases are more likely to be combined in reality.

The presidential address to the Royal Meteorological Society, <u>Pearce,(1974)</u>, stressed that diagnostic studies were the essential means of establishing mutual understanding between the theoretician and the weather analyst or forecaster. This enthused researchers to re-establish diagnostic practices, resurrecting techniques or improving the accepted techniques of Sutcliffe, Petterssen. The Q-vector theory, <u>Hoskins, et al.(1978)</u>, suggests certain compensation and cancellation between the forcing terms in the equation as implied by Williams.

Further diagnostic studies, <u>Hoskins and Pedder, (1980)</u>, using

the Q-vector and " ω " equations, analysed the structure of a well developed frontal cyclone in the western N. Atlantic.

Explosive development where pressure falls more rapidly than normal in excess of 1 mb hr-1 for 24 hr, termed the "bomb", was outlined by <u>Sanders & Gyakum, (1980)</u> and is predominantly a maritime cold season event formed downstream of the upper air trough. The President's Day snowstorm of the 18-19 February 1979 which caused record snowfall in the mid-Atlantic coast states was caused by a frontal depression formed in the baroclinic zone which extended from Texas to Cape Cod, Mass. <u>Bosart, (1981)</u> pointed out this event was missed on the models used at the National Meteorological Centre, similar to the hurricane force winds which struck the UK in October 1987. Further work, Pagnotti & Bosart, (1984), looked at two cases of east coast cyclogenesis using a diagnostic ten-level non-linear balance model. Results indicated the importance of forcing from thermal advection and latent heat release on low level convergence and vorticity production for a weak cyclone event. Differential cyclonic vorticity being crucial to the deeper, more intense development.

An analysis of a cold front using Q vectors, <u>Thorpe,(1985)</u>, showed the cross front structure. Further east coast of America studies, <u>Keshishian & Bosart,(1986)</u>, looked at a "zipper" low, this terminology is used by many researchers, which form in a pre-existing baroclinic zone along the coastal region, where large temperature contrasts exist between the cold

land and warm sea.

The synoptic-dynamical evolution of the intense depression of the 15/16 October 1987 which caused widespread damage across southern England is described using Petterssen's development and " ω " equations in conjunction with a series of composite charts using parameters obtained from the Meteorological Office operational numerical prediction models, <u>Morris, (1988)</u>. A study of frontogenesis, <u>Bennetts, et al. (1988)</u>, describes development as a positive feedback mechanism, where synoptic-scale horizontal deformation fields tighten the thermal gradient. Thermal wind balance along the front implies acceleration which induces an ageostrophic cross frontal circulation which increases the thermal gradient, etc., etc.

Other studies of particular events, severe weather damage or exceptionally a bad forecast event, using large computing capacity have shown changes with time of a frontal depression, <u>Nuss & Anthes.(1987),O'Handley & Bosart.(1988)</u> and <u>Rogers & Bosart.(1990)</u>. The latter paper analyses two intense oceanic storms using Q-Vector and " ω " techniques to study fields at 500 mb and 850 mb. The authors use of a new unit, the Bergeron, to define strong intensification is given as:

1 Bergeron = 24 mb dy⁻¹ x sin(ϕ) /sin (60) where ϕ is the latitude of the storm.

Diagnostics have been used by the Austrian Meteorological Service for a number of years, <u>Zwatz-Meise,(1980)</u>. Using vorticity and thermal indicators in conjunction with satellite

imagery frontal zones are located and estimation of cloud depth is made for snowfall forecasts. Climatological studies of cyclogenesis and of storm tracks, <u>Whittaker & Horn, (1981)</u>, <u>Rheitan, (1979)</u> and <u>Hayden, (1981)</u>, show only general trends.

4.2 Comment

The literature survey revealed very little with regard to the problems that sea users encounter, but has proven invaluable as it has provided the basis for the construction of the diagnostic model developed in this project. The <u>Forecasters'</u> <u>Reference Book</u> makes little reference to cyclone development and movement especially well to the west of the UK, but does cover much of the ideas of Rossby, Petterssen and Sutcliffe. The publication <u>Meteorology for Mariners, (1978)</u> shows lack of emphasis in the interaction between upper and surface air circulations. Movement of frontal depressions is related only to continuity of flow and to the geostrophic wind in the warm sector.

The literature survey shows that in recent years, 1975 onwards, most diagnostic studies have used extremely powerful computers, with researchers studying the changes taking place within depressions as they evolve. Early research mainly covered the movement of storms, the solution of complicated development equations could not be attempted until the advent of larger memory and faster computers but this was not the vogue initially as much emphasis was placed on large scale forecasting techniques.

CHAPTER 5 Diagnostic Modelling of Depressions in the Baroclinic Zone

Improvement in the mariners knowledge of the circulation of the atmosphere in the weather zone from the general rules, see Chapter 2, is long overdue. The updated movement rules will allow clearer decision making aboard and better acceptance of instructions from the routeing agency because the mariner will be able to understand how the forecast chart has evolved. To up-date these basic ideas a number of synoptic situations need to be analysed.

This can be achieved through:

- i, graphical models;
- ii, diagnostic (structure) models.

Graphical modelling is described in section 5.1 and the structure model which comprise of a digitising package, is explained in section 5.2 and the analysis model in Chapter 6.

I have developed these models independently, the evolution has been based on ideas gained through my experience as a lecturer and from the literature survey, see published paper Appendix B.

5.1 Graphical Diagnostic Models

Visualisation of the evolving atmosphere in way of the baroclinic zone is complicated as it involves four

dimensions (t, x, y, z). Viewing published charts separately causes continuation problems, an event is difficult to follow over a few days. This is further complicated if flow at different layers is also to be comprehended. To circumvent these problems I have developed computer software using a drawing tablet on an Apple II micro-computer to display in sequence events as they evolve. Each chart/picture was traced and shows pertinent features with surface fronts superimposed on the 500 mb flow.

It is possible to do this for any level or for any synoptic weather sequence, such as tropical cyclone movement against the anti-trades or the development of the NE and SW monsoons of the Indian sub-continent. This latter example shows three levels and indicates the jet stream reversal near the Equator. Many sequences of middle-latitude N.Atlantic atmosphere circulations have been drawn up and these show quite clearly movement and development at various times of the year. The graphical model showing multi-level flow was developed prior to any other published package and has been used by many students of meteorology at Polytechnic South West, especially the mariners who find it invaluable for understanding evolving systems.

For convenience of rapid playback the computer generated sequence of pictures have been transferred to a video recorder, the Apple computer being compatible with the video recorder. A typical sequence is included, Figures 5.1 and 5.2, used earlier but repeated here for clarity, show a typical

winter pattern for the period 1st to 10th January 1982. Upper air contours, representing the height of the 500 mb pressure level, are drawn at 5760, 5600, 5440 and 5280 metres (geopotential metres) with their associated polewards gradient. The surface fronts are indicated by the thick shaded lines and coincide with strongest flow at the upper level.

This set of pictures indicate at the 500 mb level a pronounced trough, a common seasonal feature, over the east coast of America. The flow trends poleward towards Greenland lessening in strength as the contours diverge. Over the indicated ten day period the exit region, beyond Greenland, undergoes considerable change. Midway through the sequence the flow in mid-Atlantic, south of Greenland bifurcates, but later towards the end of the period the flow strengthens with a resumption of the continuous jet. It is apparent from this sequence that cyclones form within this narrow zone, generally in the poleward moving air downwind of the upper air trough. They are advected and intensify as they move across the Atlantic, contained within the 'control' of the strong upper air flow. The upper flow weakens by the 5th January and the cyclone formed to the west earlier escapes out of the flow and progresses in a northerly direction up the west coast of Greenland on the 7th and 8th January. Temperatures could be increased by 25° C, as the warm sector of the depression passes over West Greenland causing rapid snow melt At the end of the sequence the cyclones are again etc. constrained by the upper air and move across the Atlantic into NW Europe.

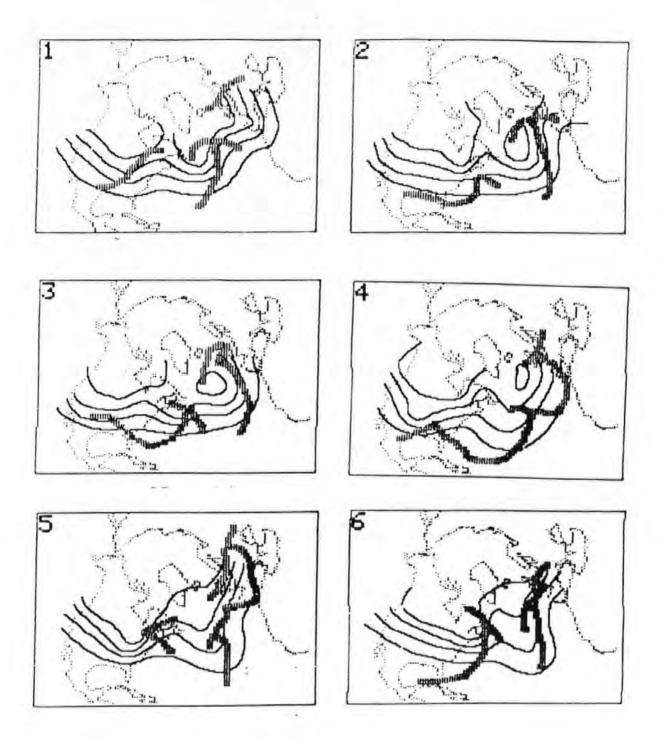


Figure 5.1 Weather: 1st January 1982 to 6th January 1982 500 mb height contours - lines Surface Fronts - shaded lines

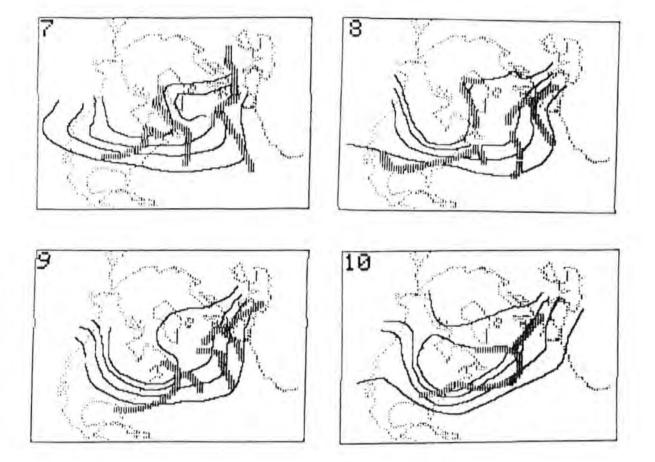


Figure 5.2 Weather: 7th January 1982 to 10th January 1982 500 mb Heights contours - lines Surface Fronts - shaded lines This particular sequence outlines some of the forecasting difficulties involved over the oceans in middle latitudes, which may be summarised and categorised as follows:

- A. detection of initial cyclone growth (cyclogenesis);
- B. movement and development related to a continuous upper air jet pattern;
- C. movement and development related to weak upper air jet pattern when the upper low centre is enclosed with two or more contours.

Ship routeing, whether intuitive or formal, involves avoiding the worst effects of frontal cyclones and the extremes of generated sea wave patterns. This means traversing them on the "favourable" side, other factors permitting. If the weather situation relates to case B, with each cyclone forming on the trailing cold front of the preceding cyclone and crossing the ocean within the control of the narrow zone of the upper air jet the process of cross ocean ship routeing is reasonably straightforward. When this sequence is broken new cyclones can form away from the previous pattern. This situation is typical of case C, cyclones may escape from the weak jet flow or become stationary. The advantages of early recognition of this type of synoptic situation in its early life by the mariner was demonstrated in Chapter 3. Awareness of these subtle changes, involving areas of cyclogenesis and undue deviations in the track of these cyclones, can assist in route planning.

5.2 Diagnostic Model Development

The study of the field relationships within the depression / baroclinic zone requires basic weather data such as surface pressures, contour heights and temperature fields. It was thought preferential to use similar information to that available to the mariner. Certainly digitised data are available, but these are not presently or planned to be transmitted to the marine world. The data available at present was not sufficient for this research and organising such a package through the UK Meteorological Office was not feasible due to expense. The data for this research was obtained as follows.

The usual practice is to overlay a regular grid on the chart and then digitise each grid point value. This may seem good practice when all charts used are the same scale and size but when these alter a varying grid is necessarily employed, based on latitude and longitude.

The data as supplied by the radio facsimile broadcast from Bracknell, UK, shows various chart sizes, see Table 5.1. All map projections are polar stereographic but scales vary from 1:20 to 1:40 million. Published data, daily weather reports from UK Meteorological Office and the German Weather Centre are readily available and also use the polar

Table 5.1 Weather Charts and Map Sizes, from

<u> </u>
F
с
A
G
D

Admiralty List of Radio Signals, Vol. III, 1987.

stereographic projection. The European Meteorological Bulletin from the latter has been mainly used, as it contains both surface and upper air data, unlike its British counterpart and are purchased by this Institute.

The digitising package has a menu display and allows data to be viewed, stored and updated as required. The flowchart for this package is shown in Figure 5.3.

The digitising software developed will also allow surface pressure adjustment to the 1000 mb level, this aids the analysis technique, see Chapter 6 and is based on the hydrostatic equation

$$\frac{dp}{dz} = -\rho g \qquad 5.1$$

and assumes a mean density, ρ , of 1.2 kg m³. Adjustment gives the height in metres of the 1000 mb pressure contour

$$Ht = 100 \frac{(p-1000)}{1.2 \times 9.81}$$
 5.2

Example - Within a cyclone surface pressure of 970 mb the height of the 1000 mb surface equals - 255m.

The digitising software has also the facility to adjust grid point values, such as for surface friction.

Arithmetic manipulation of variables or constants is a feature of this programme and comparison of the central grid point variable can be made with the surrounding values.

The number of data points chosen initially were 11 in the east /west direction and 9 in the north /south direction.

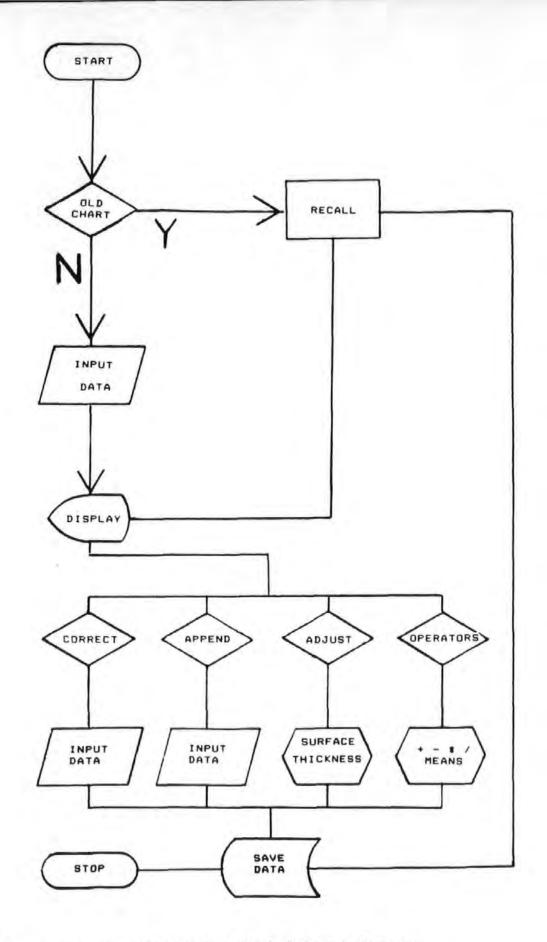


Figure 5.3 Flowchart for digitising software.

This was because of the set limit of 40 characters per line in this type of computer (1980).

5.2.1 Finite Difference Methods

Finite difference methods were employed to calculate any variable and the network of geographical grid points give a constant separation distance in the north / south , j, direction. The east / west distance between grid points, i, is constant for the same latitude, but changes with latitude, d cos θ , see Figure 5.4. The distance, d, is the data point separation and has been set at 5° degrees although variations on this interval have been tried and θ is the latitude.

Distance	between	latitude grid points555 km	l
Distance	between	longitude grid points	
Latitude	20°	521.5 }	km
Latitude	60°	277.5	km

The forward-backward finite differencing method takes into account these scale variations. During the initial stages of development when considering the basic variables it was thought reasonable to use the grid data either side of the point in question. As the variables became more complex and as each differencing procedure loses the boundary values the actual area analysed reduces so that after the first differencing the grid becomes 9 by 7, subsequently after the second 7 by 5. Thus the 50 by 40 degree section is reduced and the exercise becomes

pointless.

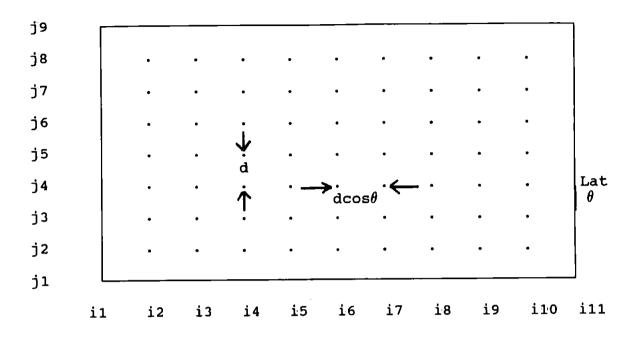


Figure 5.4 Finite Difference Grid.

Gradients or the spatial rate of change of a given variable at a grid point using finite differencing is measured over two divisions, ignoring the central point, this distance is ten degrees, the length of the UK. This distance will create major errors as synoptic systems of smaller scale can pass through undetected.

To resolve these problems two alternative solutions were at hand:

- i, to reduce the grid interval and to increase the number of data points;
- ii, to retain the existing grid and fit curves horizontally and vertically through each line of data.

53·

The first alternative did not appeal, firstly the constraints of the computer display and secondly the time taken to digitise 99 values was exhaustive. The increase in data points would consequently restrict the number of possible situations I could consider later.

The second alternative seemed a viable solution as it allowed the gradient to be obtained at each grid point without any reduction in the number of points considered.

5.2.2 Curve fitting

Utilising the Lagrange interpolating polynomial technique, see <u>Conte and de Boor, (1981)</u>.

The Lagrange formula

$$pol(x) = \sum_{k=0}^{n} f(x_{k}) l_{k}(x)$$
 5.3

is a polynomial of degree \leq n which interpolates at x_0, \ldots, x_n . With four pairs of data, a cubic is the highest degree polynomial possible.

Using a table of data, of x and f(x) values:

x	f(x)
x,	f
x ₂	f ₁ f ₂ f ₃ f ₄
x ₁ x ₂ x ₃ X₄	f_3
X	f4

The interpolated value x is obtained from

$$Pol_{3}(x) = \frac{(x-x_{2})(x-x_{3})(x-x_{4})}{(x_{1}-x_{2})(x_{1}-x_{3})(x_{1}-x_{4})} f_{1} + \frac{(x-x_{1})(x-x_{3})(x-x_{4})}{(x_{2}-x_{3})(x_{2}-x_{4})} f_{2} + \frac{(x-x_{1})(x-x_{2})(x-x_{4})}{(x_{3}-x_{1})(x_{3}-x_{2})(x_{3}-x_{4})} f_{3} + \frac{(x-x_{1})(x-x_{2})(x-x_{3})}{(x_{4}-x_{1})(x_{4}-x_{2})(x_{4}-x_{3})} f_{4}$$
5.4

This method is employed to obtain values at $x_{2.05}$ and $x_{2.95}$ along either a meridian or parallel. Assuming the gradients are required for a slice i.e. along a parallel of latitude, dummy values are inserted at i_0 and i_{12} using the boundary values at i_1 and i_{10} . Two interpolated values are obtained for each section of four values. Using i_0 , i_1 , i_2 and i_3 interpolated values are obtained at $i_{1.05}$ and $i_{1.95}$.

Using i_1 to i_4 produces values at $i_{2.05}$ and $i_{2.95}$.

The gradient obtained at the boundary grid point is obtained using:

$$=\frac{\operatorname{value}_{i_{1.05}}-\operatorname{value}_{i_{1}}}{\operatorname{dist}(i_{1.05}-i_{1})}$$
5.5

and at grid point i_2

$$=\frac{\text{Value}_{i_{2.05}}-\text{Value}_{i_{1.95}}}{\text{Dist}(i_{2.05}-i_{1.95})}$$
5.6

Further interpolations along the parallel gives the gradient at each grid point. Thus a number of curves are spliced or splined together to pass through all grid points in that direction. A slice of data at Latitude 50°N giving 500 mb height fields against longitude is shown in Table 5.2.

Table	5.2	500	mb	Height	contours	at	Latitude	50°N
-------	-----	-----	----	--------	----------	----	----------	------

Long.(x)	Heights=f(x)
60	504 dm
55	504
50	520
45	531
40	539
35	538
30	535
25	529
20	529
15	534
10	542

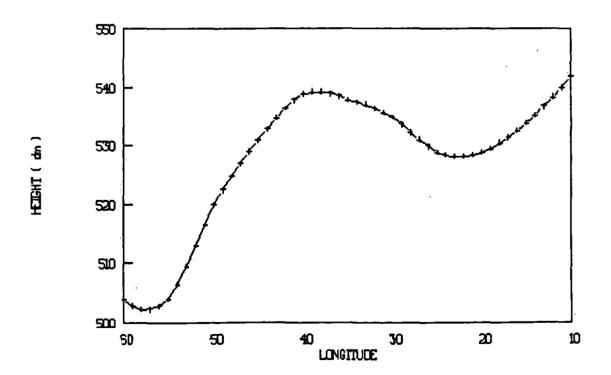
A comparison of the gradients at grid points between the two schemes is shown in Figures 5.5 and 5.6. Two points are chosen to show the variations between the two methods and are shown in Table 5.3.

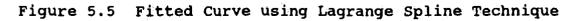
Table 5.3 Differences in Gradient values at two Grid Points, Units m per m.

÷.

	50°N 55°W	50°N 35°W
Grid Pts.	2.2425E-4	-5.6046E-5
Lagrange	2.3598E-4	-7.0072E-5

Although the computer solution in this form is time consuming, about thirty minutes for one data set (11×9) , better results accrue as the smoothing errors are reduced, all data points are considered and none are lost at each differencing.





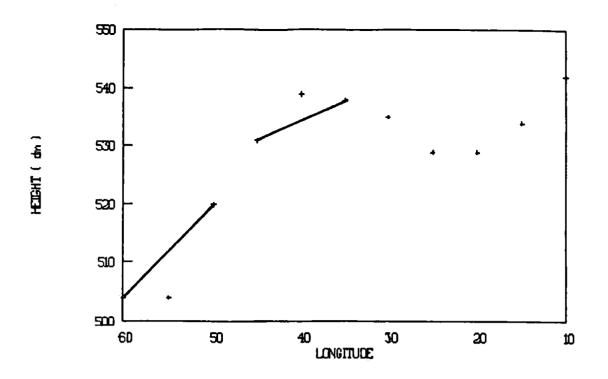


Figure 5.6 Data Points showing Forward/Backward Differencing

The Lagrange interpolating spline technique has been employed in the diagnostic model, is an independent process and can be replaced with any other curve fitting technique reasonably quickly. The diagnostic model is explained in the next chapter and tested against basic wind fields. Chapter 6 The Diagnostic Model

The model has gone through a series of development stages and tuning, therefore it is appropriate to discuss the following:

- i, the reasons for development;
- ii, a general description of the model;
- iii, the mathematical equations employed;
 - iv, the accuracy of the wind fields obtained.

REASONS FOR DEVELOPMENT

The interactive structure model constructed allows analysis of synoptic situations by producing wind fields and other parameters. Incorporating these data with those for other occasions statistically, indicators or rules are designed to estimate frontal cyclone behaviour.

This will aid the mariner, ship router or others who are interested in weather movement and supplement the excellent weather information available by showing how the forecast is related to the previous data. It will provide the shipmaster with updated decision rules, see Chapter 2, to aid voyage planning.

The diagnostic model employs standard mathematical equations which express the physical coupling in the atmosphere. Finite difference methods as described in Chapter 5 are employed to solve the diagnostic parameters.

6.1 Standard Equations, <u>Holton, (1979)</u>

Horizontal Momentum Equations

$$\frac{Du}{Dt} - fv + \frac{1}{\rho} \frac{\partial p}{\partial x} = 0$$
 6.1

$$\frac{Dv}{Dt} + fu + \frac{1}{\rho} \frac{\partial p}{\partial y} = 0 \qquad 6.2$$

Hydrostatic Equation

$$g + \frac{1}{\rho} \frac{\partial p}{\partial z} = 0 \qquad 6.3$$

where

D/DT	is the total derivative following the fluid
	particle
u, v, w	are the wind components along the cartesian
	co-ordinates x, y, z
f	coriolis parameter
р	pressure
ρ	air density
g	gravitational acceleration

Ideal Gas Equation

$$p = \rho RT$$
 6.4

where

R Planetary Gas Constant

Total Derivative

$$\frac{D}{Dt} = \frac{\partial}{\partial t} + u \frac{\partial}{\partial x} + v \frac{\partial}{\partial y} + w \frac{\partial}{\partial z}$$
 6.5

6.2 Simple Diagnostic Indicators and the Model

The following basic parameters are used: Geostrophic wind velocities, u_g and v_g , which assume the terms Du/Dt and Dv/Dt are small in Equations 6.1 and 6.2. The geostrophic velocities are:

$$u_{g} = -\frac{1}{f\rho}\frac{\partial p}{\partial y} = -\frac{g}{f}\frac{\partial z}{\partial y} \qquad 6.6$$

$$v_g = \frac{1}{f\rho} \frac{\partial p}{\partial x} = \frac{g}{f} \frac{\partial z}{\partial x}$$
 6.7

They are in this form as surface weather charts show contours of equal pressure (isobars) and upper air charts show contours of equal height etc.

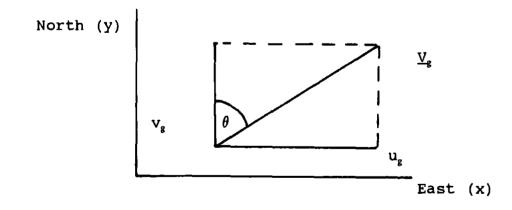
The hydrostatic equation, 6.3, relates the two methods

$$\frac{1}{\rho}\frac{\partial p}{\partial x} = g\frac{\partial z}{\partial x} \quad ; \quad \frac{1}{\rho}\frac{\partial p}{\partial y} = g\frac{\partial z}{\partial y}$$

The resultant geostrophic wind is obtained from the relationship

$$\underline{\mathbf{V}_{g}} = \sqrt{\mathbf{u}_{g}^{2} + \mathbf{v}_{g}^{2}}$$

and the direction from



where θ = tan⁻¹ (u_g / v_g)

Air flow is to the north east but the wind direction is "from whence it blows". Wind direction, w_d , is 180° + θ °.

The thermal wind, \underline{V}_T , the difference between geostrophic velocities at two levels, is represented

$$\underline{\mathbf{V}}_{\mathrm{T}} = \underline{\mathbf{V}}_{\mathrm{IS}} - \underline{\mathbf{V}}_{\mathrm{IO}}$$

where \underline{V} is a vector having magnitude and direction and the subscipts 15 and 10 are the upper and lower level winds.

$$\partial u_{g} = -\frac{g}{f} \frac{\partial}{\partial y} (z_{15} - z_{10})$$

$$\partial v_{g} = -\frac{g}{f} \frac{\partial}{\partial x} (z_{15} - z_{10})$$

6.9

The depth of air between two pressure levels, $z_{15} - z_{10}$, is a convenient way of determining the thermal structure and may be obtained from the Integrated Hydrostatic Equation

$$\Delta z = z_{15} - z_{10} = R \frac{\overline{T}}{g} \ln (p_{15}/p_{10})$$

Replacing the height difference, $z_{15} - z_{10}$, in Eq.6.9 with

the Integrated Hydrostatic Equation and then dividing gives

$$\frac{\partial u_{g}}{\partial z} = -\frac{g}{f\overline{T}}\frac{\partial T}{\partial y}$$

$$\frac{\partial v_{g}}{\partial z} = \frac{g}{f\overline{T}}\frac{\partial T}{\partial x}$$
6.10

Horizontal Divergence of air at a level is given by

$$\nabla \cdot \underline{V} = \frac{\partial u}{\partial x} + \frac{\partial v}{\partial y}$$
 6.11

The vertical component of relative vorticity (a measure of fluid spin) ζ , is given by

$$\nabla \times \underline{V} = \frac{\partial \mathbf{v}}{\partial \mathbf{x}} - \frac{\partial \mathbf{u}}{\partial \mathbf{y}}$$
 6.12

.

The solution for gradient wind values are obtained from Equations 6.1 and 6.2 by including the ageostrophic contribution.

The Total Derivative, Du/Dt, assuming the terms $\partial u/\partial t$ and $w\partial u/\partial z$ are small, is reduced to

The Gradient Wind Equations are

$$v_{s} = \frac{1}{f} \left(u \frac{\partial u}{\partial x} + v \frac{\partial u}{\partial y} + \frac{1}{\rho} \frac{\partial p}{\partial x} \right)$$
$$u_{s} = -\frac{1}{f} \left(u \frac{\partial v}{\partial x} + v \frac{\partial v}{\partial y} + \frac{1}{\rho} \frac{\partial p}{\partial y} \right) \qquad 6.13$$

6.3 Solution of Basic Variables

The solution of the geostrophic wind components at any level makes use of the Lagrange interpolating technique, see section 5.2.2, Equations 6.4 and 6.5 are modified

$$u_{g_{i,j}} = -\frac{g}{f_j} dz/dy_{i,j}$$

$$v_{g_{i,j}} = -\frac{g}{f_j} dz/dx_{i,j}$$
6.14

where dz/dy_{ij} and dz/dx_{ij} are the gradients.

Similarly using the gradients of the geostrophic wind components the following can be obtained:

- i, gradient wind components;
- ii, geostrophic vorticity.

From the gradients of the gradient wind it is possible to obtain divergence.

Gradient wind components are obtained by inserting geostrophic wind components and their gradients for the curvature terms in Equations 6.13 as follows

$$v_{s} = \frac{1}{f} \left(u_{g} du_{g} / dx + v_{g} du_{g} / dy + \frac{1}{\rho} \frac{\partial p}{\partial x} \right)$$

$$u_{s} = -\frac{1}{f} \left(u_{g} dv_{g} / dx + v_{g} dv_{g} / dy + \frac{1}{\rho} \frac{\partial p}{\partial y} \right)$$

6.15

Thus a first approximation to gradient wind component values are obtained. The next stage is to obtain a first approximation of their gradients using the Lagrange interpolating technique. These values are now inserted as before and the process is repeated, thus producing a second approximation of gradient wind components and their gradients. It was found that most grid point values remained the same after the first substitution but some did not (four from the ninety-nine grid). To reduce this instability both the wind components and gradients were averaged over the first two approximations and these results were used. Much larger values did occur occasionally with anti-cyclonic flow when the curvature term controlled the flow rather than the pressure term. This is the situation where the maximum wind strength in anticyclonic flow is equal to fr/2.

The solution for this condition is dependent on the radius of curvature, r, which is obtained as follows

$$DV/Dt = V^2/r = f (V - V_e)$$

However as V in this case is the gradient wind velocity the radius of curvature is always over-estimated. A better fit was obtained after comparing fifteen super - geostrophic cases to substitute geostrophic wind values in the curvature term. This in fact under-estimates the value r which is increased by a factor of 2.2, the solution then takes the form

$$r = 2.2 V_g^2 / f (V - V_g)$$

The solution for relative geostrophic vorticity, Equation 6.12, can alternatively be solved using

$$\zeta_{g_{i,j}} = \frac{g}{f_j} \nabla^2 z \qquad 6.16$$

where the Laplacian, $\nabla^2 z$, <u>Haltiner & Martin, (1957)</u> indicates

$$\frac{\partial^2 z}{\partial x^2} + \frac{\partial^2 z}{\partial y^2}$$

The finite difference solution for relative geostrophic

vorticity using initial grid point data is

$$\zeta_{g_{i,j}} = \frac{4 g}{f_j} (d \cos \theta_j)^{-2} (\langle z \rangle - z_{i,j})$$

Where $\langle z \rangle$ is the mean height of four points equal distance from the central point, z_{ij} , in the i and j positive and negative directions. Distance is between east/west grid points, d cos θ_j , and values for the north and south grid points are calculated.

 $\mathbf{z}_{N}^{*} = \mathbf{z}_{i,j} + (\mathbf{z}_{i,j+1} - \mathbf{z}_{i,j}) \cos \theta_{j}$

$$\mathbf{z}_{s} = \mathbf{z}_{i,j} + (\mathbf{z}_{i,j-1} - \mathbf{z}_{i,j}\mathbf{i}) \cos \theta_{j}$$

where z_N^* and z_S^* are the interpolated north and south grid point values.

The mean height value is given by

$$z = (z_N^* + z_{i,j+1} + z_S^* + z_{i-1,j})/4$$

6.4 Frontal Indicators

The analysis model is used to inspect several synoptic situations over the North Atlantic Ocean. The results of one synoptic event showing basic variables is demonstrated. The area covered by this model is 40° of latitude by 50° of longitude (9 x 11 grid points) which is large enough to enclose any synoptic feature of interest. Events were chosen at random with frontal depressions at various stages of their life cycle.

Frontal location indicators similar to those utilised by the Austrian Meteorological Office, <u>Zwatz-Meise</u>, (1980), are used :

- a) Thermal Front Parameter (TFP), fronts are located where the change in horizontal temperature structure is maximum, i.e. indicated by the proximity of the temperature contours, where the temperature gradient is maximum;
- b) zero line of relative vorticity at the 500 mb level;
- c) zero line of relative vorticity of the 500-1000 mb thickness.
- 6.5 Running the Analysis Model to observe basic features

Digitising the surface and 500 mb flow over the pertinent section to be analysed is a time consuming exercise. It takes approximately thirty minutes using the digitising programme to enter the 99 bits of data for each level, requiring careful interpolation from the chart. Heights are read to 1 dm, pressure at the surface to 1 mb and temperature to 1°C.

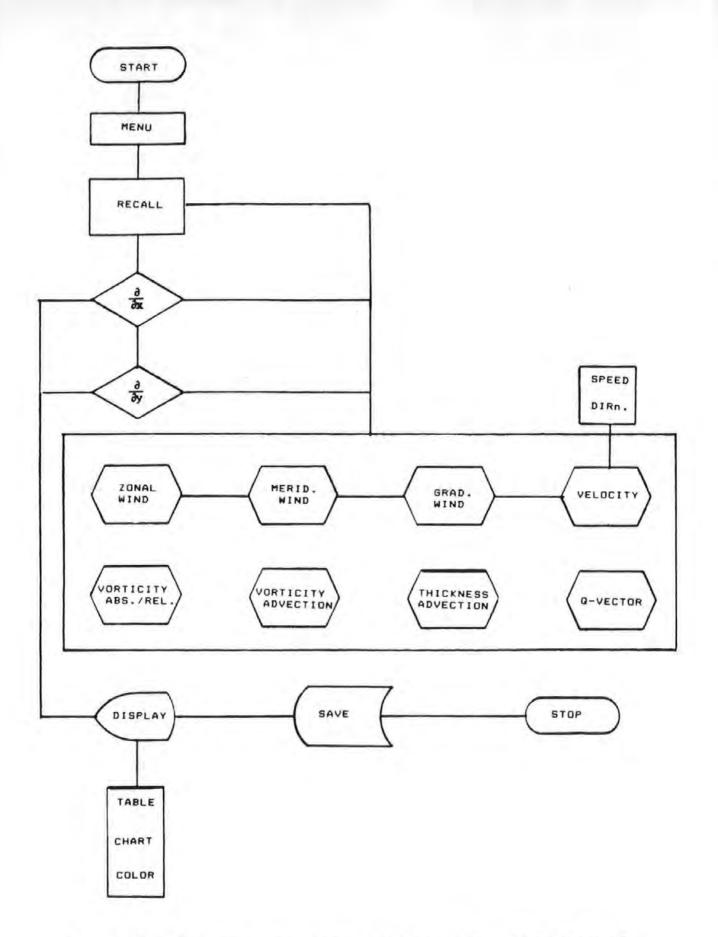
The Analysis Model employs an interactive menu technique and raw

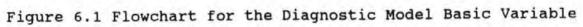
The Analysis Model employs an interactive menu technique and raw data stored through the digitising programme is recalled. This data can be displayed as a table, an array or a colour coded picture before any calculations are done so that a visual check can be made. The flowchart describing the Analysis Model is shown in Figure 6.1.

Operating the programme the following basic data for the analysis level can be obtained, stored and printed.

- (i) Raw data, Heights or thickness
- (ii) Zonal geostrophic wind
- (iii) Meridional geostrophic wind
- (iv) Geostrophic wind velocity, strength
- (v) Geostrophic wind velocity, direction
- (vi) Zonal gradient wind
- (vii) Meridional gradient wind
- (viii) Gradient wind velocity, strength
 - (ix) Gradient wind velocity, direction
 - (x) Geotrophic vorticity

The synoptic situation for 16 January 1982 is analysed and described. This is not normally required as only selected values are used in the research but are demonstrated to show the versatility of the model and aids its description. The 16 January 1982 synoptic event, although nine years old, was chosen because these data were used to test the various experimental methods tried during the model development.





The analysis is for an area in the North Atlantic Ocean for 0000Z hours on the 16th January 1982. The published data for this period, see Figures 6.2 and 6.3, shows a frontal cyclone centred, 49°N 57°W, with well marked fronts. The cyclone is shown to be decaying (occluding) with the upper air (500 mb) low centre also at 49°N 57°W. The records for this period of depression locations and central pressures are found in Table 6.1. The various outputs have been manually analysed, Figure 6.4 composite, at the 500 mb level, Figure 6.5 composite, the fields at the surface and Figure 6.6 composite, the thickness fields. The position of the fronts from the published data, Figure 6.2, are located on each picture with the input data, heights or any of the calculated parameters. These are geostrophic wind strengths, gradient wind strengths and geostrophic vorticity values. With Figures 6.4 (C), 6.4 (D), 6.5 (C) and 6.5 (D) clearly showing as expected the differences between geostrophic and gradient wind values where curvature is large. Gradient values being larger with anti-cyclonic flow but less in cyclonic flow.

Date	Position	Pressure	Tendency mb.hr ^{.1}	Movement Dir.x Spd. ™ x ms ⁻¹
15 Jan 16 Jan 17 Jan	38°N, 72°W 49°N, 57°W 53°N, 40°W	988 mb 955 mb 965 mb	-0.92	044 x 17.44

Table 6.1 Depression Characteristics

At the 500 mb, Figure 6.4(A), the maximum flow is 1110 km to the south of the low centre showing a poleward movement west of $38^{\circ}W$ with an equatorwards flow to the east of this point.

The area of maximum vorticity, Figure 6.4(B) indicates the upper occurs where the curvature and shear low centre and contributions are large. The line of zero vorticity is approximately in the same position as the core of the This suggests that the frontal maximum flow west of 45°W. zone at this level, 5.5 km, is in this position. Within the ridge vorticity is negative and to the east as flow separates. Zero vorticity isopleths are found either side of the ridge, the western most zero line coincides with the surface cold front.

Gradient wind, Figure 6.4(D), extends the 40 ms⁻¹ isotach ahead of the geostrophic wind, Figure 6.4(C), in way of the ridge but downstream at 25°W gradient strengths are less because the flow is now sub-geostrophic.

The thickness chart, Figure 6.6 (A), shows the three dimensional effects of temperature. The intrusion of warm air into the cold air is clearly seen at 45%. The thermal wind fields are maximum at 40°N 57°W and also at 55°N 45°W. Two separate flows come together in way of the ridge but the southerly arm separates from the northerly part to accommodate the preceding cold front.

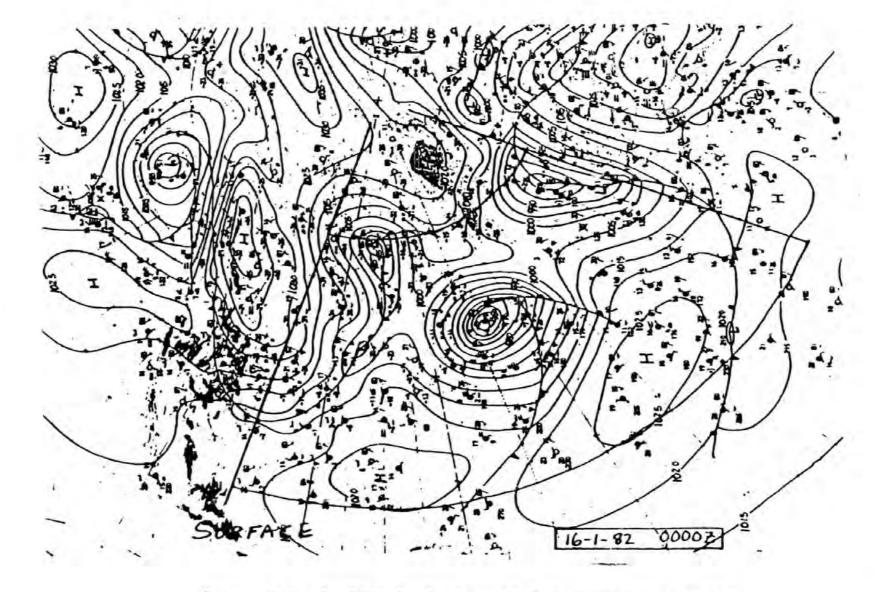


Figure 6.2 Surface Analysis : 16th January 1982, 00002 Figure Quality, see note on page 24

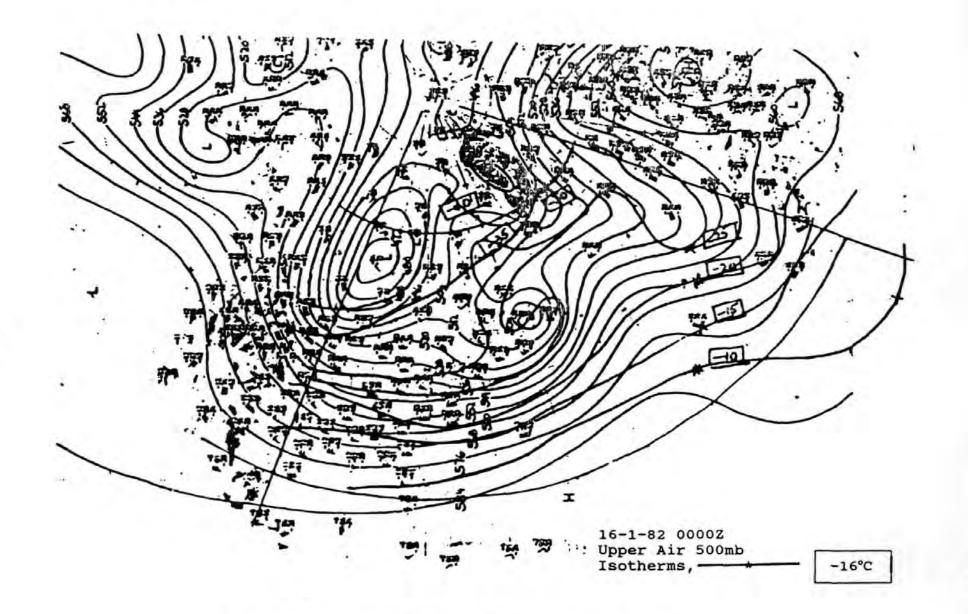


Figure 6.3 500 mb Analysis : 16th January 1982, 0000Z

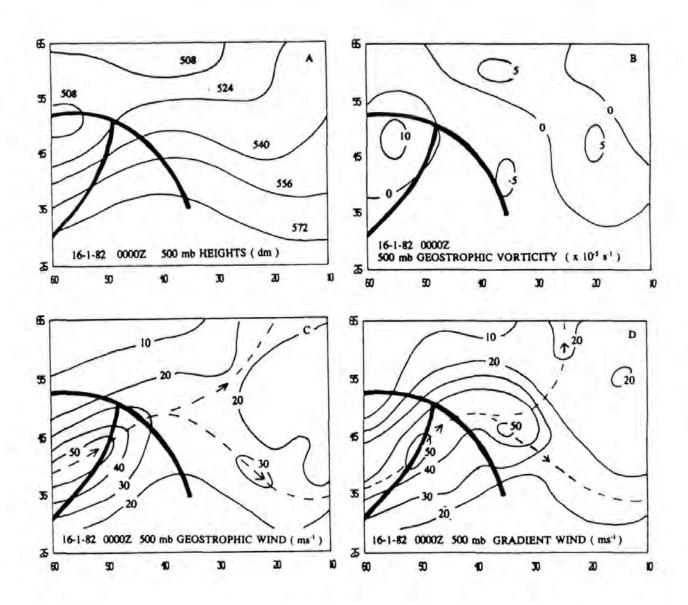
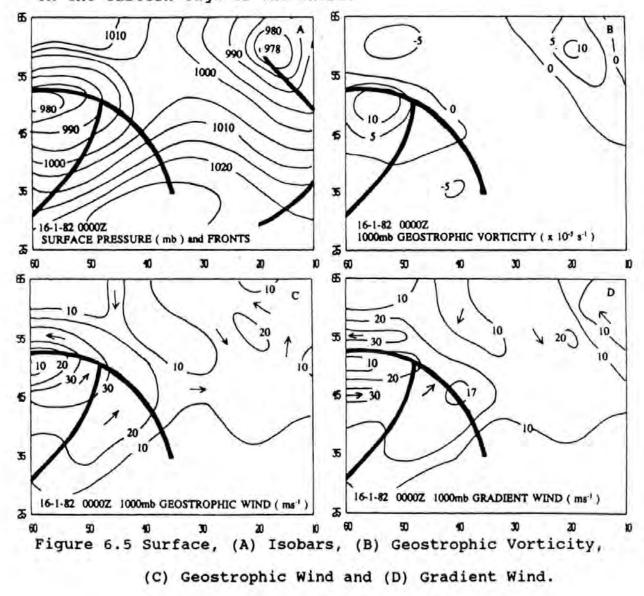
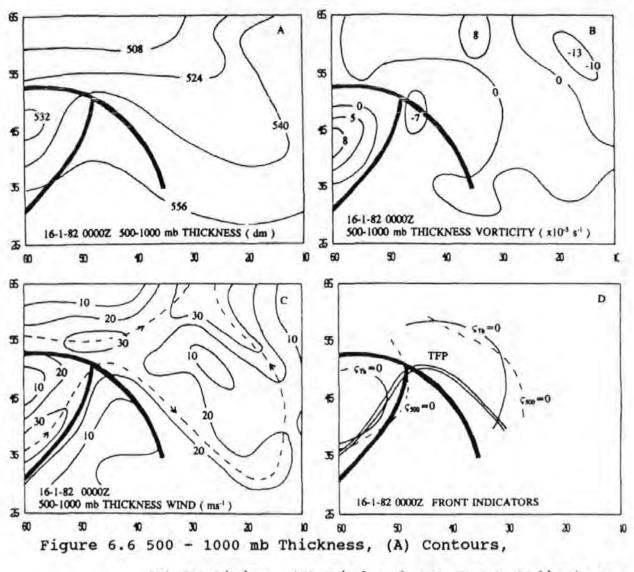


Figure 6.4 500 mb (A) Height Contours, (B) Geostrophic Vorticity, (C) Geostrophic Wind and (D) Gradient Wind.

The area of maximum thickness vorticity, Figure 6.6(B), centred near 44 $^{\circ}$ N 60 $^{\circ}$ W, is seven degrees to the south-west of the vorticity maximum at 500 mb. The surface patterns, Figure 6.5(A), identifies two low pressure areas one which has virtually occluded and shows a cold front running north/south on the eastern edge of the chart and the other centred at 50° N 59%, the system of interest, being partly occluded but with well defined warm and cold fronts. Figures 6.5(C) and (D) show the differences between the geostrophic wind and gradient wind fields. The maximum wind strengths, 30 ms⁻¹, are 900 km from the centre of the depression but the gradient winds are not so well defined. The maximum positive geostrophic vorticity, Figure 6.5(B), are located at 51°N 55°W and are also of the same value on the eastern edge of the chart.





(B) Vorticity, (C) Wind and (D) Front Indicators.

The relative positions of the various frontal indicators, Figure 6.6(D), are compared with the published surface location. All indicators locate the overall aspect of the depression. Analysis at the upper flow level locates the cold front behind the surface position, with the warm front ahead of its surface position, as the warm air overlies the cold air to the north. The Thermal Front Parameter (TFP), the line where maximum horizontal temperature contrast occurs, defined alternatively where the strongest thickness wind fields occur, mirror the surface fronts but lie 225 km to the north.

The movement of the frontal depression is obtained by transferring the three positions to a Mercator Chart and fitting a curve through each point. The direction of movement and speed at the central position can then be estimated. Table 6.2 shows various parameters for the developed cyclone which can be compared to its movement.

Table 6.2 Calculated Parameters

Date	Position	Movement	Dir.ºT x Spd.ms ^{.1}
Warm Sec	ctor at 1000	mb level	
16 Jan	40°N, 45°W	Geostrophic Wind	d Flow 056 x 24
500 mb	level		
16 Jan	45°N, 45°W	Geostrophic Wind	d 052 x 37
	45°N, 55℃W	Maximum Flow	059 x 59
Thicknes	ss (1000 - 50	0 mb)	
16 Jan	47°N, 49°W	Thermal Wind	025 x 24
	55°N, 45°W	Maximum Flow	091 x 33
	40°N, 57℃W	Maximum Flow	048 x 39
Positive	e Vorticity F	ields	· · · · · · · · · · · · · · · · · · ·
16 Jan	48°N, 55°W	500 mb Va	alue 11E-5 s ⁴
	44°N, 60°W	Thickness	8E-5
	50°N, 55°W	1000 mb	13E-5

The parameters used have been obtained from the data display and show interesting comparison with the European Weather Bulletin. Interpolation has been achieved using the Lagrange polynomial. Pressure at 0000 Z is still falling and the direction of movement of this frontal depression is more closely related to the 500 mb flow than the surface flow, however the warm sector wind strength gives a better estimate for speed. The thickness parameters on first inspection do not seem to indicate movement but clearly show warm and cold advection along the frontal zone.If the thermal wind is taken within the location of the warm sector, $45^{\circ}N$ $45^{\circ}N$, a much closer value is obtained, $057^{\circ}T \ge 11$ m s⁻¹.

6.6 Comment on the Analysis

These calculated data outputs evolved after many trial runs using various interpolating methods and with different grid sizes. With many differencing schemes boundary conditions are lost at each stage. The scheme incorporated in this model retains these boundary points and fits a number of cubic curves which are spliced together, see Chapter 5, in one direction.

The basic parameters used in this demonstration were not meant to provide indicators for depression forecasting, but to show the possibilities of using a scheme of this type to enable the structural detail of depressions to be observed.

The parameters calculated must be realistic to enable a worthwhile investigation to be made. The initial data to be digitised must represent the optimum situation, this poses the question " How accurate is a weather chart?". Numerical weather prediction models require the "best" initial conditions as input. Various schemes have been employed, <u>Lorenc, (1986)</u>, such as variational methods, splines, Kriging, optimal interpolation, successive corrections, constrained initialisation, Kalman-Bucy filters and data assimilation using adjoint models. To incorporate such schemes is beyond the scope of this project, bearing in mind this is not a prediction model but a diagnostic model.

It is assumed that the weather charts used are the best condition available, confirmed by the U.K. Meteorological Office by phone in response to my request by letter, see Appendix B.

The diagnostic model used in this project has been tested by comparing wind velocities at the 500 mb and 1000 mb levels. The following wind velocities were obtained:

- i, observations as plotted;
- ii, manually calculated geostrophic velocities from
 chart;
- iii, manually calculated gradient Velocities from
 chart;
 - iv, model geostrophic velocities;
 - v, model gradient velocities;

The method of comparison uses a vector error technique, <u>Axford</u> (1968), which shows

$$\mathbf{v}_{\mathbf{E}}^{\mathrm{c}} = \mathbf{v}_{\mathbf{F}} - \mathbf{v}_{\mathbf{A}}^{\mathrm{c}}$$

where $\mathbf{v}_{\mathbf{F}}$ is the forecast wind and $\mathbf{v}_{\mathbf{A}}$ is the actual wind. The mean vector error is given by

$$\langle \nabla_{\rm E} \rangle = \langle \nabla_{\rm F} \rangle - \langle \nabla_{\rm A} \rangle$$

Cancellation of value differences occur with $|\langle \mathbf{v}_{E} \rangle|$ so it is more appropriate to use an average of the absolute vector errors in the form $\langle |\mathbf{v}_{E}| \rangle$.

The variance, $\sigma_{\rm E}^{2}$, of the vector error distribution is given by

$$\sigma_{\rm E}^{\ 2} = \langle (\mathbf{v}_{\rm E} - \langle \mathbf{v}_{\rm E} \rangle)^2 \rangle = \langle [(\mathbf{v}_{\rm F} - \langle \mathbf{v}_{\rm F} \rangle) - (\mathbf{v}_{\rm A} - \langle \mathbf{v}_{\rm A} \rangle)]^2 \rangle$$

or $\sigma_{\rm E}^{\ 2} = \sigma_{\rm F}^{\ 2} + \sigma_{\rm A}^{\ 2} - 2 \sigma_{\rm F} \sigma_{\rm A} R$

where σ_A , σ_F are the standard vector deviations of \mathbf{V}_A and \mathbf{V}_F , with R is the stretch correlation coefficient between \mathbf{V}_A and \mathbf{V}_F .

Solutions may take the form

$$|\mathbf{\nabla}_{\mathbf{E}}|^2 = |\mathbf{\nabla}_{\mathbf{E} \text{ speed}}|^2 + |\mathbf{\nabla}_{\mathbf{E} \text{ direction}}|^2$$

where $|\mathbf{v}_{E_{speed}}|$ is a vector error in speed and $|\mathbf{v}_{E_{direction}}|$ is a magnitude error in speed due to the incorrect direction.

In this analysis speed and direction are separated to give a clearer visualisation of the errors and are shown for the 500 mb level in Table 6.3 and for the 1000 mb level in Table 6.4. The data for these tests were taken from six separate events, see Appendix C. Observations at grid points were used where available. Otherwise grid points were chosen at random and manual calculations made to estimate both geostrophic and manual calculations made to estimate both geostrophic and gradient values.

Table 6.3 500 mb Velocity Errors

Strength (ms⁻¹), Direction (°)

Comparison	No.	< v _E >	σ(mean)	< V _E >	$\sigma(average)$
<u> Obs - C geos</u>	20				
Strength	[[-3.555	8.725	5.96	5 7.293
Direction		-1.0	2.550	1.0	2.550
<u> Obs - C grad</u>	20				
Strength		-2.24	4.319	3.65	0 3.216
Direction		-1.0	2.550	1.0	2.550
<u> Obs - M qeos</u>	20				
Strength		0.25	6.916	5.25	4.510
Direction	}	10.2	21.13	18.8	14.03
<u> Obs - M qrad</u>	20				
Strength		0	6.607	5.6	3.506
Direction		7.75	21.344	17.75	14.16
<u>C geos -M geos</u>	55				
Strength		1.324	6.464	4.58	4.75
Direction		7.145	16.023	12.78	12.02
<u>C grad -M grad</u>	55		1		
Strength		0.602	7.770	5.90	0 5.088
Direction		3.981	17.741	13.40	12.90

where C:- published chart, M:- model.

The comparison between the published chart at 500 mb and the model output indicates standard deviations of 4.75 ms^{-1} for geostrophic strengths and 5.09 ms^{-1} for gradient considerations. The directional standard deviations are about 12.5°.

Surface flow shows a smaller vector error than at the upper

Table 6.4 1000 mb Velocity Errors

Strength (ms⁻¹), Direction (°)

Comparison	No.	< ∇ _E >	$\sigma(mean)$	< V _E >	σ(average)
<u> Obs - C qeos</u>	17				
Strength	1 1	-4.512	4.226	4.90	3.77
Direction		1.471	5.077	2.059	4.87
<u> Obs - C grad</u>	17			1	
Strength		-4.353	4.917	5.01	4.244
Direction		1.471	5.077	2.059	4.87
<u> Obs - M qeos</u>	17				
Strength		-5.206	4.359	5.618	3.813
Direction		-8.0	23.507	21.06	13.16
Obs - M grad	17				
Strength		-5.441	6.070	6.03	5.486
Direction		-9.47	21.552	19.12	13.74
<u>C qeos-M qeos</u>	46			1	
Strength		-0.3	3.822	2.63	2.788
Direction			18.50	15.11	11.55
<u>C grad-M grad</u>	46				
Strength		-0.022	3.186	2,239	2.267
Direction		-6.717		15.5	11.63

where C:- published chart, M:- model.

level but this must be expected when the velocities are considerably less. Directional errors are larger approximately 15°.

The model results compare favourably with the measured variables from the chart and show using the calculated wind fields further parameters can be derived, assuming the published chart is a reasonable likeness to the real atmosphere for this time. The programmes for the digitising and diagnostic packages are listed in Appendix D.

CHAPTER 7 Indicators of depression characteristics

The major concern of the mariner planning a voyage is for the vessel to maintain a prompt service, possibly keeping to a tight schedule. This must be achieved in a seamanlike manner in compliance with any international rules and to ensure that any damage to the ship and cargo is kept to a minimum. Middle to high latitude trans-ocean passages necessitate crossing the oceans where frontal depression activity is strongest. The mariner requires knowledge of how existing depressions move, where new ones form and how these low pressure areas develop or decay. The most important of these is the first, the movement characteristic. Depressions can travel at 50 knots and the generated sea wave patterns from the storm wind fields can alter the ocean wave distribution sufficiently over 24 hours to adversely affect the vessels performance. When depressions are first detected by a weather centre and placed on the chart they are generally very small, maybe 400 nm in diameter with a central pressure a little below 1010 mb. After two days the central pressure could fall to 990 mb and the storm diameter could increase to 1200 nm. Geostrophic wind velocities, Equations 6.6 and 6.7, assuming the depression was at Latitude 25° initially and later at Latitude 50°, with standard surface pressure at 1013 mb gives velocities of 14.6 ms⁻¹ for the first condition and 18.6 ms⁻¹ the latter.

This demonstrates that changes of wind speeds in depressions

are generally small even with large pressure changes over the twenty-four hour period. To appreciate the mechanisms for movement and pressure change within the depression, situations have been analysed showing the relationship between the basic variables at an instant and its characteristics.

7.1 Structure and Movement of the Frontal Depression.

Eight separate synoptic situations were selected to demonstrate the relationship between the structure of the depression, its movement and the pressure tendency.

Structural detail, in terms of the basic variables, were obtained using the diagnostic model, outputs being manually analysed. This simplified analysis for each occasion shows the location of:

- i, surface fronts;
- ii, surface low centre;
- iii, main 500mb flow with maximum wind strength;
 - iv, main 500-1000mb thickness flow with maximum wind strength;
 - v, maximium positive and negative relative vorticities.

The depression characteristics were obtained using the European Weather Bulletins. Storm locations prior and after each selected event were transferred to a navigators Mercator Chart. Direction of movement were obtained by measuring the direction of the

track curve through each point ($\pm 2^{\circ}$) and the speed estimated by interpolating along the track ($\pm 2 \text{ ms}^{-1}$). Pressure tendencies were obtained using the Lagrange Interpolating Technique, see Chapter 5, section 2.2, with time substituted for distance. The distribution of field variables and its characteristics, see Figures 7.1 and 7.2 are summarised in Table 7.1.

The eight cases demonstrated outline the difficulties in relating the basic variables within the depression to its characteristics and any similarities to other depressions. Although the maximum fall in pressure, in the cases demonstrated, occurs when the movement is greatest, it is

Takie it concluded in its popleboli chalacteristic	Table	7.1	Contingency	Table	for	Depression	Characteristics
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Question /date	14.2.89	7,2,87	16.1.82	4.3.85	21.1.87	10.4.87	18.5.87	20.3,89
Pressure change 12 hrs	-25	-13	-11	-10	-8.5	-2.5	-1	5
Direction (degs True)	65	22	55	25	90	25	35	28
Speed (m/sec)	20	8.2	8.5	10	10.8	12	10	3.8
Trough Line Cant W(ht)	Ŷ	Ŷ	Y	Y	ព	Y	Y	n
Thick Flow to N of 500	Ŷ	Ŷ	y.	Y	Ŷ	Y	У	Ŷ
500 Flow Accl:Front Apex	(-)	(-)	(-)	(-)	(-)	(+)	0	(-)
Thick Fl Accl:Front Apex	0	(-)	(+)	0	0	0	0	(-)
500/F1 Max:Front Apex	n	٥	ก	n	n	n	n	n
Thick F1 Max:Front Apex	Ŷ	ņ	n	Ŷ	Ŷ	n	Ŷ	n
500 F1 Max:Trail Cold/F	Y	Y	Y	Y	Ŷ	Y	Y	У
Thick F1 Max:Trail Cold/f	n	У	У	n	Π	Ŷ	n	У
Surf Rel Vort (1e-5)	11	7	13	24	5	8	6	12
500 Rel Vort (1e-5)	9	11	11	11	12	11	9	10
Vort Diff (1e-5)	2	-4	2	13	-5	-3	-3	2
Distance (no):+U with ht	139	351	277	300	0	362	650	-300
Thickness (dm)	515	520	530	\$27	560	531	545	520
Slope or Cant of Trough	0.020027	0.008008	0.010342	0:009495	0	0.007929	0.004532	-0.00937
Angle	1.147406	0,458849	0.592603	0.544076	0	0.454318	0.259695	-0.53685

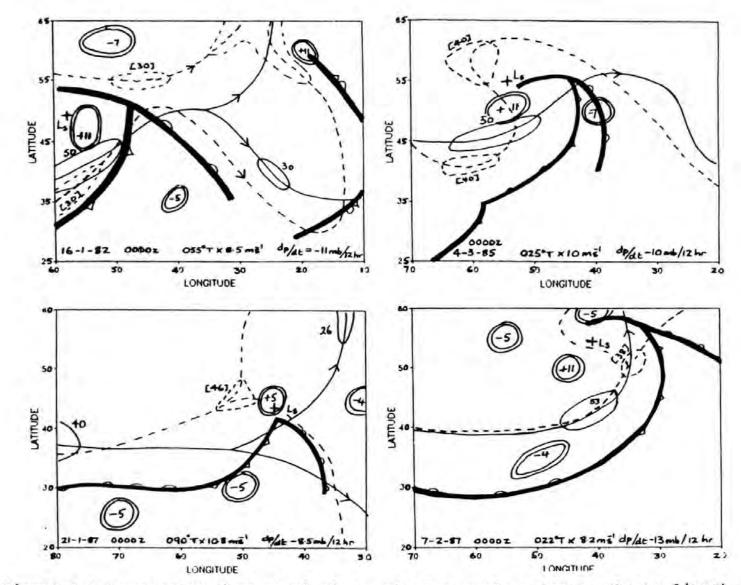


Figure 7.1 Depression Characteristics : showing surface fronts (heavy lines), 500 mb core flow (lines) with maxima and minima speeds, 1000-500 mb thickness (pecked lines) and surface relative vorticity (double lines).

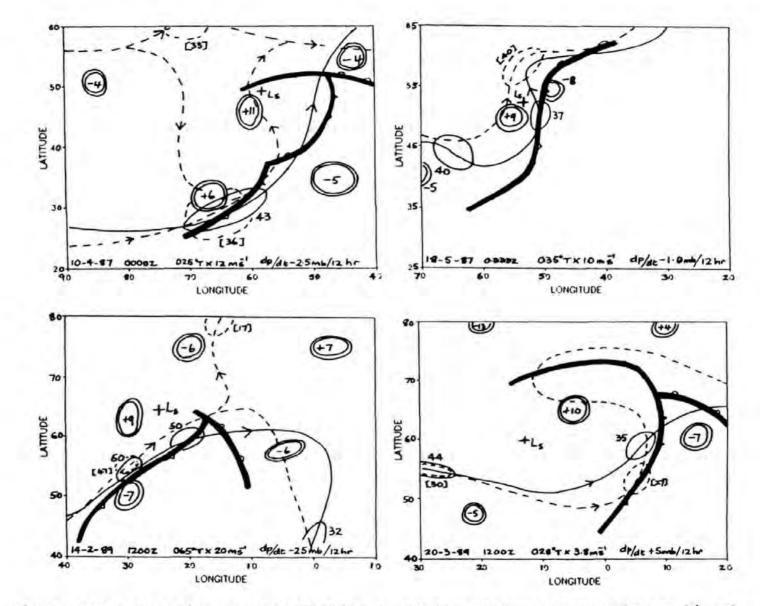


Figure 7.2 Depression Characteristics : showing surface fronts (heavy lines), 500 mb core flow (lines) with maxima and minima speeds, 1000-500 mb thickness (pecked lines) and surface relative vorticity (double lines).

not always the case. The tilt of the core of the depression with height, understood to be a good indicator of pressure change, Green, (1970), should show maximum decrease in pressure with time when the tilt is close to the horizontal in the upwind direction. The examples chosen shows maximum pressure fall of 25 mb in 12 hours with the tilt of 1.14° to the horizontal yet in four of the other examples where the pressure tendency is between 10 and 13 mb over the same time period the slope is reduced to between 0.45° and 0.59°. The occluding example, 20-3-89, does at least show a reversal in the slope where the cold air at the upper level is ahead of the surface flow. The superimposing of the upper low over the surface feature on the 21-1-87 however does not reveal that decay is imminent, another accepted indicator, as pressure is still falling. 8.5 mb in 12 hours. The patterns of relative vorticity, positive in all cases, shows that in four cases the greater values occur at the surface (50%). The greatest difference occurs on 16-1-82 when the surface relative vorticity exceeds the 500 mb value by 13E-5 s⁻¹ and the average difference of the other cases being $3E-5 s^{-1}$. This extreme case did not produce excessive pressure change, -10 mb in 12hrs or movement, 025°T at 10 ms⁻¹. The core of the thickness flow in all cases near the depression is on the cold side of the 500 mb flow. This must always be the case to satisfy the "drawing up" of the warm air within the depression. Along the trailing cold front the thickness flow is on the warm side of the 500 mb flow or even at the same position.

The crossing of these contours reflects the importance of temperature advection and baroclinic instability to the development process.

7.2 Comment

The use of basic variables did not produce any clear indicators of development and the wind fields were not sufficiently good indicators of movement bearing in mind the erratic nature for storm movement, see Chap. 2. The initial emphasis was placed on determining more appropriate movement indicators as routeing decisions are mainly based on the geographical translation of the storm, not its development.

7.3 Movement of Depressions

Sixty-five situations between the years 1981 to 1989 have been analysed to show storm movement, these data are shown in Appendix E and are categorised as three basic cases, Figure 7.3, they are:

i, fast moving depression associated with well defined straight 500 mb flow, generally on the poleward arm of the jet wave, Figure 7.3 (A);

ii, stationary or slow moving depression associated with enclosed 500 mb low or deep trough, Figure 7.3 (B);

iii, surface depression having formed on the trailing cold front of a previous occluding system running north

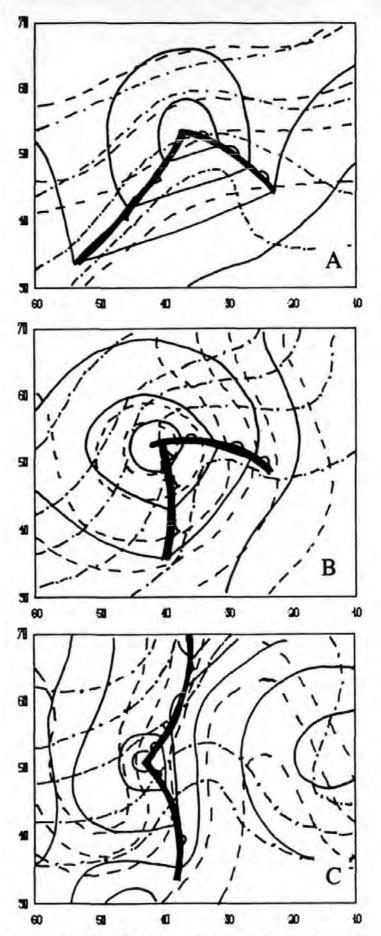


Figure 7.3 Depression Types with surface isobars (lines), 500 mb contours(pecks) and 1000-500 thickness (dash-dots).

south and is blocked from progressing eastwards by an anticyclone, Figure 7.3 (C).

The use of surface warm sector wind fields as an indicator of depression movement, bearing in mind the three cases categorised, will on many occasions either over- or underestimate speed of progression. The direction of average movement of the depression should closely follow, within 25°, the 500 mb flow and the surface warm sector isobars/wind fields when moving rapidly, greater than 15 knots, but if the depression is moving slowly or stopped the fronts will rotate in the direction of the flow. In this situation neither the 500 mb maximum wind or the surface warm sector wind will provide a good indicator. In case iii it is likely that the movement is better determined by the surrounding surface pressure pattern or the downwind "stationary" ridge at the 500 mb level. Any movement of the depression over twenty-four hours will be negligible and for routeing decisions could be assumed stationary.

An alternative indicator, termed the "TEN" indicator which utilises the average flow at the 500 mb level near the geographical surface location of the depression is tested against other indicators. Sixty-five situations were analysed and the following information were obtained:

i, location;

- ii, pressure tendency;
- iii, actual storm movement: direction & speed;
- iv, "TEN" degree distance across 500 mb pattern in way of Surface Low;

v, 500 mb flow: direction and strength;

vi, surface warm sector flow: direction and strength.

Data for the movement indicators iv, v and vi are demonstrated in Figure 7.4 were obtained as follows

TEN Degree Distance Indicator. Initially marking surface low centre on the 500 mb chart and measuring five degrees of latitude as a distance perpendicular to the flow each side of the low centre. The contour gradient over this distance gives an average geostrophic wind and the direction of movement is normal to this line.

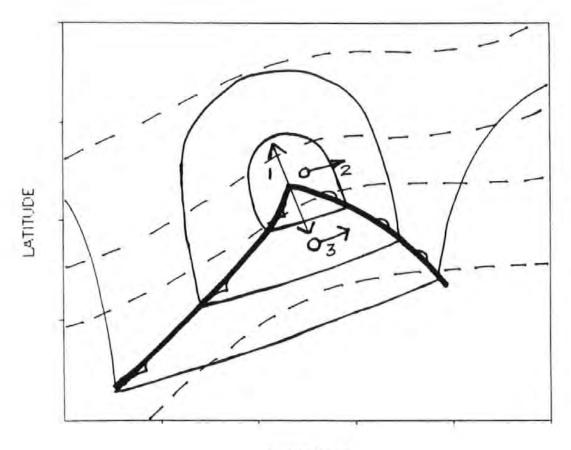
500 mb Indicator. Obtaining the geostrophic wind over the surface centre.

<u>Surface Warm Sector.</u> Obtaining the average geostrophic wind in the warm sector.

Comparison of the actual storm characteristics, direction and speed, with the three movement indicators show the "TEN" Degree Indicator a more realistic measure. The results of each regression using "Curfit-PC" Software are shown in Figure 7.5 and summarised in Table 7.2.

Three regression tests on each indicator were carried out, linear for speed and direction and a polynomial for deviation against speed.

The direction regression between the actual and the indicator shows a slightly better correlation for the "TEN" indicator although the standard error is greater than the warm sector



LONGITUDE

Figure 7.4 Movement Indicators, 1, "TEN" , 2, 500 mb Wind and 3, Warm Sector Wind

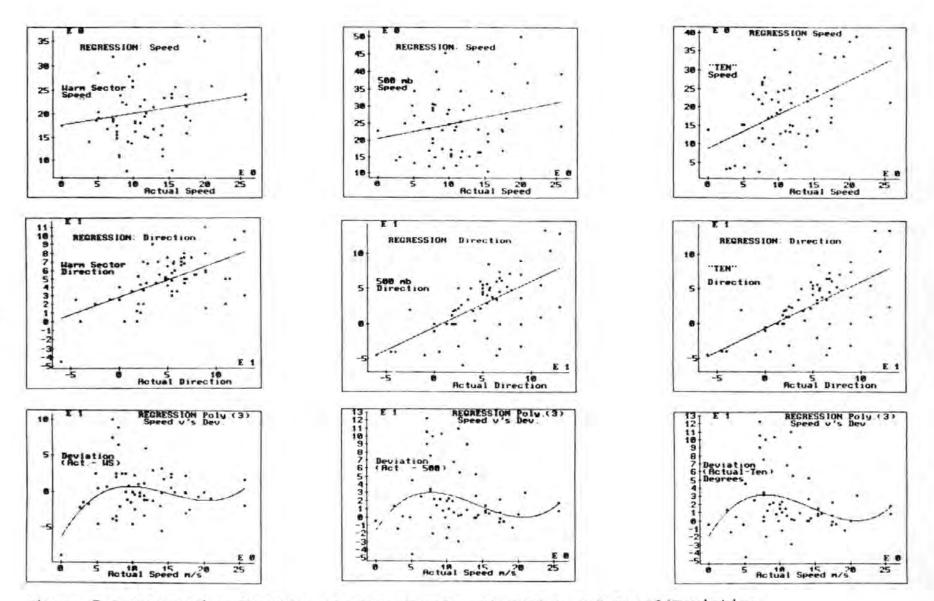


Figure 7.5 Regression Results, showing Speeds, Direction and Speed/Deviation

Table 7.2 Regression Results.

DIRECTION (°) : Linear Regression (Actual v Indicator)

Coefficients	"TEN"	500	Warm Sector
Correlation Determination	.635 .403	.615 .378	.586 .344
Stand. Error	32.9	33.6	22.26

SPEED (ms⁻¹) : Linear Regression (Actual v Indicator)

Coefficients	"TEN"	500	Warm Sector
Correlation Determination	.514 .264	.235	.211 .044
Stand. Error	7.96	9.18	5.90

SPEED (ms⁻¹) v DIRECTION DEVIATION (°): Poly.Regression (x³) (Actual Speed v Diff (Actual Dir. - Indicator Dir.))

Coefficients	"TEN"	500	Warm Sector
Correlation Determination	.316 .100	.286 .082	.335 .112
Stand. Error	34.0	35.2	32.0

indicator. The regression of speed shows that the "TEN" indicator produces the best fit. The third test, important because this shows the relationship between storm speed and the deviation of the actual direction of the storm from the indicator, reinforces the belief that slow moving storms tend to rotate, fast moving storms are carried with the 500 mb flow with little deviation yet at speeds near20 knots considerable deviation occurs. The warm sector polynomial regression however produced the best fit although the "TEN" indicator did produce a correlation coefficient which did compare favourably with the warm sector correlation.

Software was constructed to facilitate quick calculation of the "TEN" indicator to ease analysis but this could be replaced by a scale similar to the familiar Geostrophic Wind Scales so that shipboard interest would not be lost through computational difficulties.

The "TEN" Indicator Scale, see Figure 7.6 is entered as follows:

a, On the vertical scale enter the latitude of the depression,b, Enter the gradient obtained on the horizontal scale,

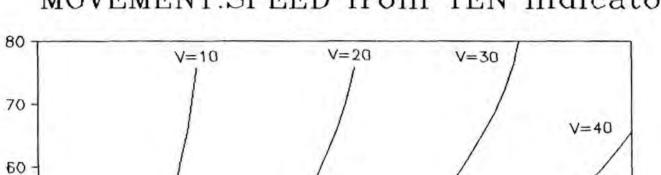
c, The intersection of these two data gives the indictor speed of depression movement.

The speed obtained is an over-estimation but can be adjusted using the equation for the line in the regression,

y = A + Bx

where the coefficients for the regression of actual speed and the "TEN" indicator are: A = 8.83 and B = 0.926. Table 7.3 shows this relationship.

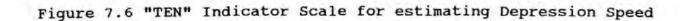
The deviation of the "TEN" indicator direction from the actual direction of movement using a cubic polynomial shows increasing deviation when speeds are greater than 10 ms⁻¹, however the quadratic polynomial over-simplifies the deviation at speeds



MOVEMENT:SPEED from TEN Indicator

V=50

V=60



TEN Indicator Separation metres

30 - 40 -

Table 7.3 "TEN" Indicator Forecast Speeds,ms¹.

"TEN"	Speed
5	-3.55
10	1.17
15	5.80
20	10.44
25	15.06
30	19.69

greater than 25 ms⁻¹ and therefore the best fit might be obtained using the mean of these two values. Table 7.3 gives the various values of deviation from the flow against speed for the two regressions with the calculated mean. Figure 7.7 shows the curve of mean deviation plotted against speed.

				-		-1
Table 7.4	Polynomial	Curve	Values	and	Means,	ms'.

Act.Speed	Poly.(2)	Poly.(3)	Mean
0	18.0	-18.8	0
2	21.0	5.6	13.3
3	22.5	14.5	18.5
4	23.7	21.3	22.5
5	24.6	26.3	25.5
10	25.5	29.7	27.6
1.5	20.8	13.5	17.1
20	10.6	0	5.3
25	- 5.8	11.5	3.1
			L

7.4 Movement Indicators : Summary

The analysis shows that forecasting the movement of the depression can be obtained using the "TEN" Indicator. Speed being derived by using a spacing of 300 nm perpendicular each side of the surface storm centre at the 500 mb level. Analysis using a different distance might produce a better fit but this was not pursued, the "TEN" distance was thought more practical and easier for the mariner to use.

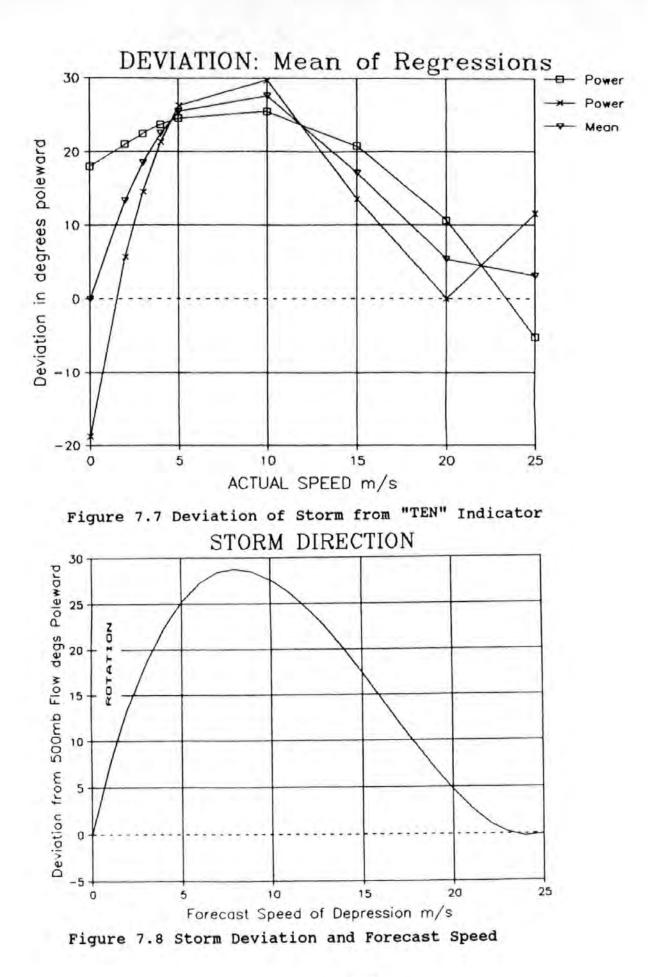
Direction of depression movement using the "TEN" Indicator, Figure 7.8, reveals rotation of the depression is maximum when the storm is stationary, and rotation is minimal at 5 ms⁻¹ as movement increases. Maximum deviation, approx. 30° , from the 500 mb flow occurs at 8 ms⁻¹ and decreases to 20 ms⁻¹ when the depression can be assumed to move closely with this flow.

7.5 Indicators of Storm Development

Diagnostic modelling of storm development have been based mainly on the Momentum Equations. The following have contributed to the theory of development:

- i, Sutcliffe, 1939;
- ii, Petterssen, 1956;
- iii, Krishnamarti, 1968;
- iv, Hoskins, 1978.

The Diagnostic Model incorporates the following development equations, these are described and tested.



The results of each method are compared.

The theories of development by Sutcliffe and Petterssen use the Vorticity Equation.

$$\frac{D}{Dt} (\zeta + f) = -f \nabla_h \cdot \Psi$$
 7.1

which shows the relationship between forcing from the divergence term (R.H.S.) and the total derivative of absolute vorticity. This equation is obtained by differentiating the components of the Momentum Equation in terms of the co-ordinate at 90° from the component as follows:

$$\frac{\partial}{\partial y} \left(\begin{array}{c} \underline{Du} \\ \underline{Dt} \end{array} = \dots \right)$$

$$\frac{\partial}{\partial x} \left(\begin{array}{c} \underline{Dv} \\ \underline{Dt} \end{array} = \dots \right)$$

subtracting gives

...

$$\frac{D}{Dt} \zeta = \frac{D}{Dt} \left(\frac{\partial v}{\partial x} - \frac{\partial u}{\partial y} \right)$$

The Vorticity Equation shows the relationship between the horizontal divergence and the rate of change in absolute vorticity at a level.

When the divergence approaches zero, absolute vorticity is conserved and balance is maintained between the Coriolis term and relative vorticity. Conservation can occur:

- a, at the level of non-divergence, usually considered between the 500 and 600 mb levels, about half depth between the jet core near the Tropopause and MSL;
- b, where development is non-existent.

Using Quasi-Geostrophic theory, which implies the wind velocity remains in approximate balance with the pressure gradient, geostrophic wind velocities can be substituted for vorticity values but not for divergence.

When development is non-existent the equation can be reduced

$$\frac{\partial}{\partial t} \zeta = -\underline{V} \cdot \nabla (\zeta + f)$$
 7.2

The local derivative of vorticity is replaced in the Sutcliffe development by

$$\frac{\partial}{\partial t} \zeta = \frac{g}{f} \left(\frac{\partial}{\partial t}\right) \nabla^2 z \qquad 7.3$$

The development theory was not considered at a level but between two levels. Hence the three dimensional structure could be analysed. The method could describe development in terms of the thickness, the Sutcliffe approach or in terms of the boundary conditions as adopted by Petterssen. Important relationships between any two levels are

GeostrophicVelocity	Σ _{upper}	-	\underline{V}_{lower}	=	Υ _τ
Divergence	Dupper	-	D _{lower}	=	D _T
Rel.Vorticity	$\boldsymbol{\zeta}_{ ext{upper}}$	-	ζ_{lower}	=	ζ_{T}

For simplicity, as the upper level is 500 mb no subscript is used. The subscript 0 is used instead of lower and means 1000 mb level.

The difference between two levels

$$\mathbf{f} \nabla_{\mathbf{h}} \cdot \underline{\mathbf{Y}}_{\mathbf{T}} = -\frac{\partial}{\partial t} \boldsymbol{\zeta}_{\mathbf{T}} - \underline{\mathbf{Y}} \cdot \nabla \left(\boldsymbol{\zeta} + \mathbf{f} \right) + \underline{\mathbf{Y}}_{\mathbf{o}} \cdot \nabla \left(\boldsymbol{\zeta}_{\mathbf{o}} + \mathbf{f} \right) \qquad 7.4$$

Sutcliffe replaces the local derivative using Eq.7.3

$$\frac{\partial}{\partial t}\zeta_{T} = \frac{g}{T} \left(\frac{\partial}{\partial t}\right) \nabla^{2} \left(Z - Z_{o}\right) = \left(\underline{Y}_{o}, \nabla\right)\zeta - \left(\underline{Y}, \nabla\right)\zeta_{o}$$

The normal form of the Sutcliffe Development Equation is

$$\mathbf{f} \nabla_{\mathbf{h}} \cdot \underline{\mathbf{Y}}_{\mathbf{T}} = - \left(\underline{\mathbf{Y}}_{\mathbf{T}}, \nabla \right) \left(\boldsymbol{\zeta}_{\mathbf{T}} + 2 \boldsymbol{\zeta}_{\mathbf{o}} + \mathbf{f} \right)$$
 7.5

The Diagnostic Model uses Equation 7.5 in the form

$$\nabla_{h} \cdot f \underline{V}_{T} = -(\underline{V}_{T} \cdot \nabla) (\zeta_{T} + 2 \zeta_{o})$$
 7.6

The Petterssen Development Equation uses the Vorticity Equation at the level of non-divergence and substitutes thickness and surface vorticity in the local derivative

$$\frac{\partial}{\partial t} \left[\left(\zeta_{o} + f \right) + \left(\zeta_{T} + f \right) \right] + \underline{V} \cdot \nabla \left(\zeta + f \right) = 0 \qquad 7.7$$

with manipulation the total derivative of surface absolute vorticity can be expressed

$$\frac{D}{Dt} (\zeta_{o} + f) = -\frac{\partial}{\partial t} (\zeta_{T} + f) + \underline{V}_{o} \cdot \nabla (\zeta_{o} + f) - \underline{V} \cdot \nabla (\zeta + f)$$
7.8

This development replaces the local derivative with the Laplacian of the thickness advection

$$-\frac{\partial}{\partial t} \left(\zeta_{T} + f\right) = -\frac{R}{f} \nabla^{2} \left(-\frac{g}{R} \Upsilon_{o} \cdot \nabla Z_{T}\right)$$

The Diagnostic Model incorporates the Petterssen Development Equation in the form

$$\frac{D}{Dt}(\boldsymbol{\zeta}_{\circ} + f) = -\frac{R}{f} \nabla^{2}(-\frac{g}{R} \underline{Y}_{\circ}, \nabla Z_{T}) + \underline{Y}_{\circ}, \nabla(\boldsymbol{\zeta}_{\circ} + f) - \underline{Y}, \nabla(\boldsymbol{\zeta} + f)$$
7.9

Hoskins Development Theory, the Q-Vector, is in the form of the Omega Equation, Krishnamarti, but simplifies the input variables to horizontal geostrophic wind components and potential temperature fields.

$$N^{2} \nabla_{h}^{2} w + f^{2} \left(\frac{\partial^{2} w}{\partial z^{2}} \right) = 2 \left(\frac{g}{\theta_{o}} \right) \nabla Q$$

where the Brunt-Vaisala frequency

ŀ L

$$N = \left(\frac{g}{\theta} \frac{\partial \theta}{\partial z} \right)^{\frac{1}{2}}$$

The sign of Q is an important aspect in diagnosis, upward motion occurs when the sign is negative, convergence, and downward motion when divergent. The sense of the circulation is with Q pointing in the direction of the low-level ageostrophic motion and towards the rising air. Application of Q-Vector theory by <u>Hoskins & Pedder, (1980)</u>, <u>Thorpe,(1985)</u> and others have studied particular storms. Temperature fields were obtained from 1000-500 mb thickness values, these are assumed to reflect the temperature structure at 700/750 mb, are transformed to potential temperature values. Charts at 700 mb level are used to provide geostrophic wind velocities. The gradient of these two variables were used to find the Q-Vector at this level.

Potential Temperature, θ , is replaced in Equation 7.10 with temperature, T, as the European Weather Bulletins shows plotted temperature detail at 500 mb. By hand analysing this information the temperature structure can be obtained for this level. The Q-Vector has two components

$$Q = (Q_x, Q_y)$$

$$= 2 \frac{g}{T_o} \left(-\frac{\partial u_g}{\partial x} \frac{\partial T}{\partial x} - \frac{\partial v_g}{\partial x} \frac{\partial T}{\partial y} \right),$$

$$- \frac{\partial u_g}{\partial y} \frac{\partial T}{\partial x} - \frac{\partial v_g}{\partial y} \frac{\partial T}{\partial y} \right)$$
7.11

The R.H.S. of Equation 7.10 can be written in the form

$$2\left(\frac{g}{T_{o}}\right)\nabla_{\cdot}\underline{O}=2\left(\frac{g}{T_{o}}\right)\left(\frac{\partial Q_{x}}{\partial x}+\frac{\partial Q_{y}}{\partial Y}\right)$$

The Diagnostic Model incorporates the Q-Vector, separation of each term is maintained as follows

$$Q_{1} = - \frac{\partial u_{g}}{\partial x} \frac{\partial T}{\partial x}$$
$$Q_{2} = - \frac{\partial v_{g}}{\partial x} \frac{\partial T}{\partial y}$$
$$Q_{3} = - \frac{\partial u_{g}}{\partial y} \frac{\partial T}{\partial x}$$
$$Q_{4} = - \frac{\partial v_{g}}{\partial y} \frac{\partial T}{\partial y}$$

$$Q_{5} = \frac{\partial Q_{1}}{\partial x}$$

$$Q_{6} = \frac{\partial Q_{2}}{\partial x}$$

$$Q_{7} = \frac{\partial Q_{3}}{\partial x}$$

$$Q_{8} = \frac{\partial Q_{4}}{\partial x}$$

The model resolves for the divergence of Q

$$\nabla_{.Q} = 2 \left(\frac{g}{T_0} \right) \left(Q_5 + Q_6 + Q_7 + Q_8 \right)$$
 7.12

7.6 Model Results

The three theories, section 7.4, were used to analyse development, four occasions are selected, these have been hand

analysed and are shown in this section.

The basic vorticity equation is used with gradient wind velocities to find divergence, with reduction for friction at the 1000 mb level.

Each method is effectively a measure of vertical motion. Well established depressions showing larger values of "ascent" than smaller storms which may be forming rapidly. A measure of this ascent to the surrounding condition is necessary so that strength of development can be ascertained. The model can compare the central grid point field value to the four grid point values around this point, as follows

Strength Factor =
$$\frac{F(i,j)}{\overline{F}}$$

This method must be adjusted to cater for negative development indicators, as follows

 i, If all values are negative :- change to positive values
 ii, With both positive and negative values a constant is introduced to make all values positive with the largest indicating maximum ascent fields and takes the form

Strength Factor =
$$\frac{C + F(i,j)}{C + F}$$

The following occasions were used to demonstrate development at a frontal depression, they are

16 - 1 - 82, Figures 7.9A and 7.9B

4 - 3 - 85, Figures 7.10A and 7.10B 21 - 1 - 87, Figures 7.11A and 7.11B 18 - 5 - 87, Figures 7.12A and 7.12B

Five diagrams are constructed for each occasion and show the following fields

Sutcliffe Petterssen Q - Vector 500 mb Vorticity Equation 1000 mb Vorticity Equation

Calculated data using various substitutions in these equations generated many data files. The 16-1-82 occasion produced sufficient data to fill fifteen 5 1/4" floppy discs, although single sided, something like 15 x 20 kbytes of space.

Typical data calculated but not demonstrated includes

- 1, 200 mb wind velocities, vorticity and vorticity advection
- 2, 200-500 mb thickness, winds and vorticity etc.
- 3, 200 mb Q-Vector fields
- 4, Petterssen development at 500 mb using 200-500 mb layer
- 5, Vorticity equation at 700 mb
- 6, 750 mb thermal structure
- 7, 700 mb Q-Vector fields
- 8, Potential Vorticity

<u>16 - 1 -82</u>

This event shows a well established frontal depression partly occluded. The surface analysis suggests that the depression is the first in a new family as it is separated by a relatively high pressure area from the previous sequence seen on the eastern side of the chart, Figures 7.9A. The characteristics of this storm, see Table 7.1, shows pressure falling 11 mb in 12 hours and movement 055°T at 8.5 ms⁻¹.

Figure 7.9A shows strong similarities between the three recognised methods. Both the Sutcliffe and Petterssen methods are easily comparable, strong ascent, negative values for Sutcliffe, occur at the front apex and also ahead of the warm front. Q-Vector differences although much smaller also show clearly ascent associated with the frontal zones.

Figure 7.9B show rates of change in vorticity at the 500 mb and 1000 mb. Ascent indicated by positive values occurs along the warm front and partly along the cold front at the 500 mb level, whilst at 1000 mb positive vorticity change occurs at the apex or meeting point of the fronts. The Strength Factor charts for these fields show positive values in all the diagrams associated with the meeting point of the fronts. Areas of positive Strength Factor values are found along the cold front in all diagrams except the 1000 mb Vorticity Equation, this implies that 500 mb vorticity advection contributes largely to subsequent development. The area of positive values visually appear greater than the negative values and this would confirm that this storm is still deepening.

4 - 3 - 85

This surface analysis for this event indicates a depression nearly fully occluded with a wave on the trailing cold front. Characteristics, again see Table 7.1, show pressure falling at 10 mb in 12 hours and movement 025°T at 10 ms⁻¹. Figures 7.10A and 7.10B show areas of ascent again occurs in advance of the warm front and at the apex of the fronts or top of the occluded front. The wave on the trailing cold front does show increases in the Strength Factor this is clearly marked on the Q-Vector and 500 mb Vorticity Equation charts. Positive Strength Factor areas outweigh areas of negative values within the ciculation of the main depression agreeing with the pressure tendency.

<u>21 - 1 - 87</u>

This storm is moving more to east than the previous two events, 090°T at 10.8 ms⁻¹ with pressure falling 8.5 mb in 12 hours. The surface analysis shows a mature depression with a trailing cold front extending westward with a small wave to the left hand side of the chart. Ascent is found in Figure 7.11A on all charts slightly in advance of the warm front close to the apex. Figure 7.11B shows positive values of vorticity behind the apex of the fronts yet the Strength Factor charts shows some ascent in advance of the surface warm front at the 500 mb level yet at the 1000 mb positive values agree with Figure 7.11A. This development apparently does not depend upon the 500 mb vorticity advection as in the 16-1-82 and 4-3-85 events as flow is more zonal but splits in advance of the surface system.

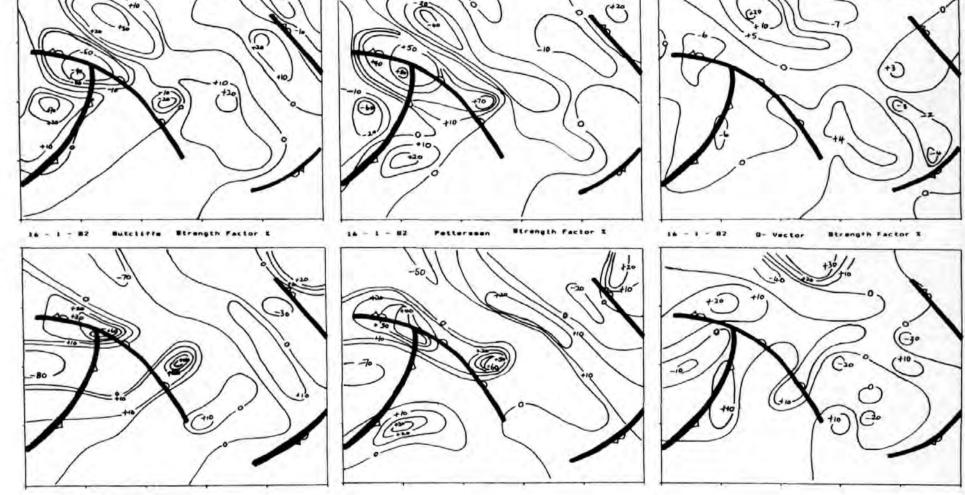


Figure 7.9A 16-1-82: Development using Sutcliffe, Petterssen and Q-Vector techniques, top magnitudes and bottom strength factor %.

16 - 1 - 82 Butcliffe units # le-10

16 - 1 - 02 Petterson units a le-10

16 - 1 - 02 0- Vector units + 1e-16

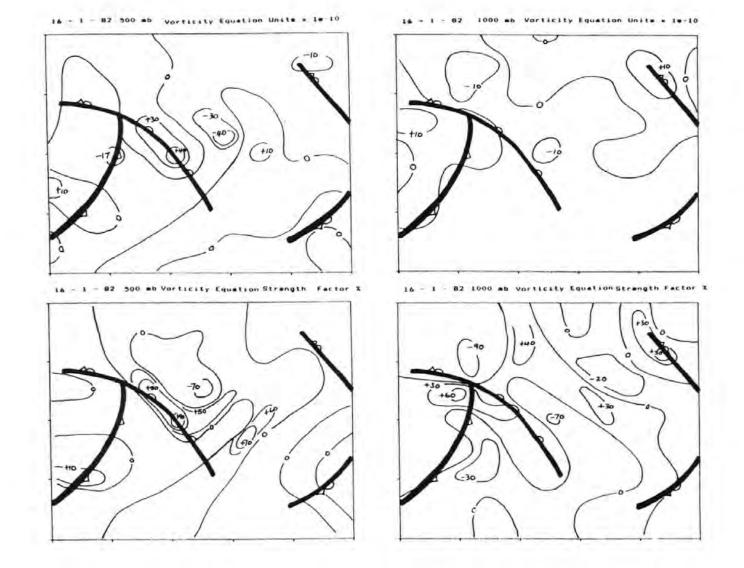


Figure 7.9B 16-1-82: Development using the Vorticity Equation, top magnitudes and bottom strength factor %.

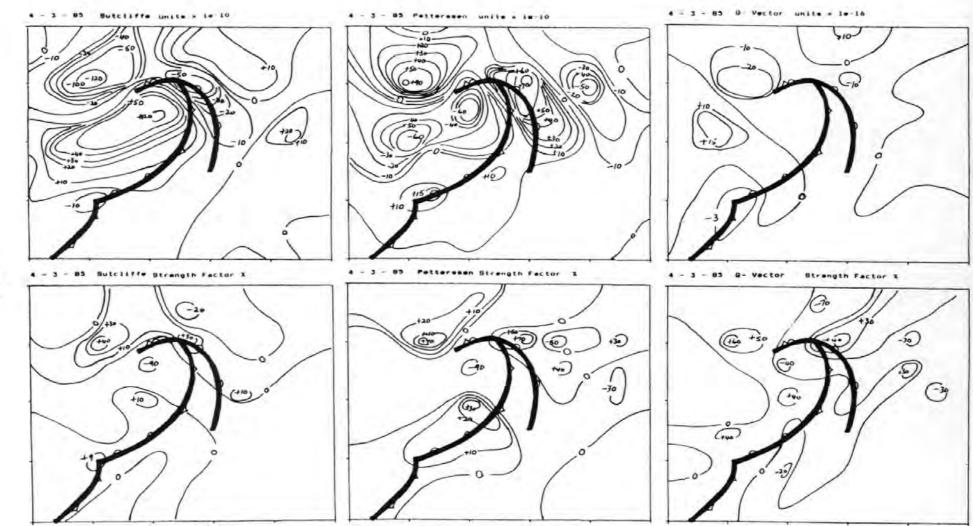


Figure 7.10A 4-3-85: Development using Sutcliffe, Petterssen and Q-Vector techniques, top magnitudes and bottom strength factor %.

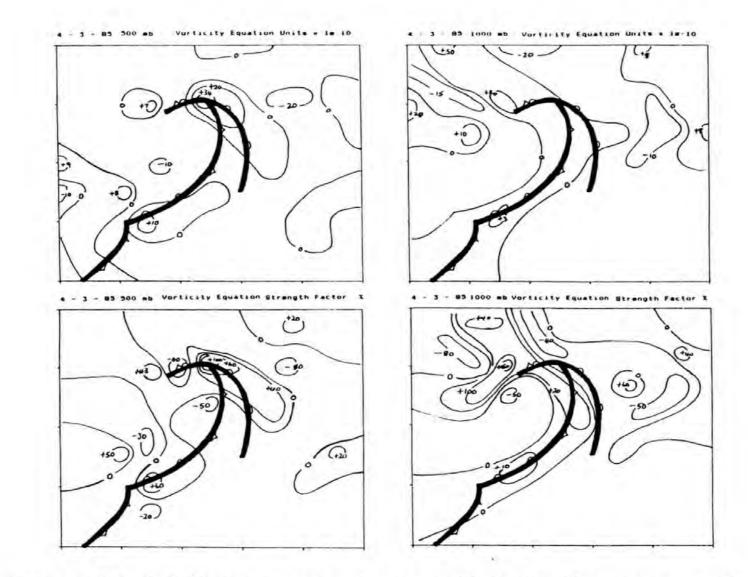


Figure 7.10B 4-3-85: Development using the Vorticity Equation, top magnitudes and bottom strength factor %.

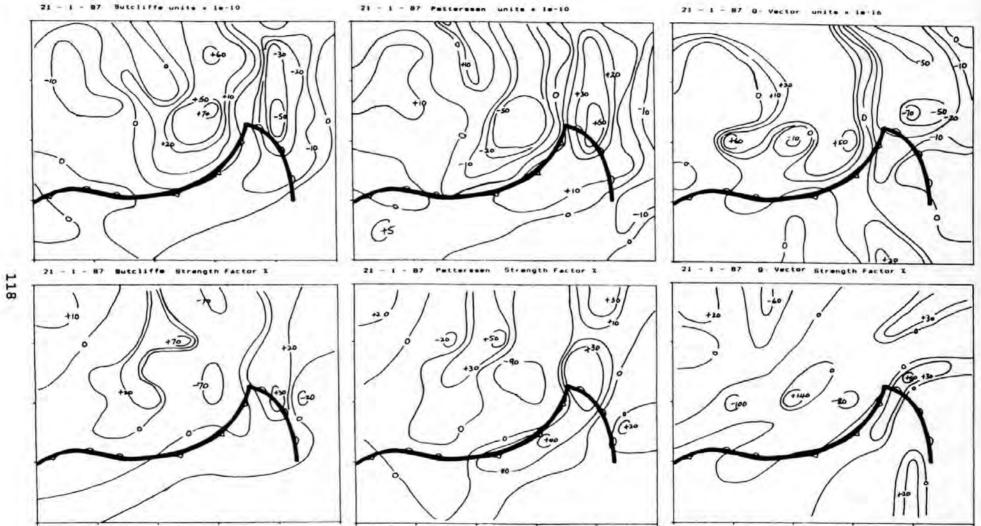


Figure 7.11A 21-1-87: Development using Sutcliffe, Petterssen and Q-Vector techniques, top magnitudes and bottom strength factor %.

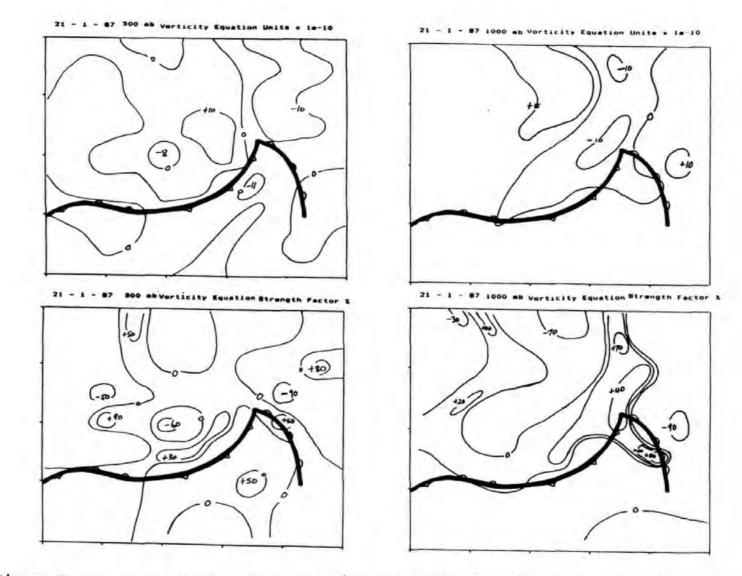


Figure 7.11B 21-1-87: Development using the Vorticity Equation, top magnitudes and bottom strength factor %.

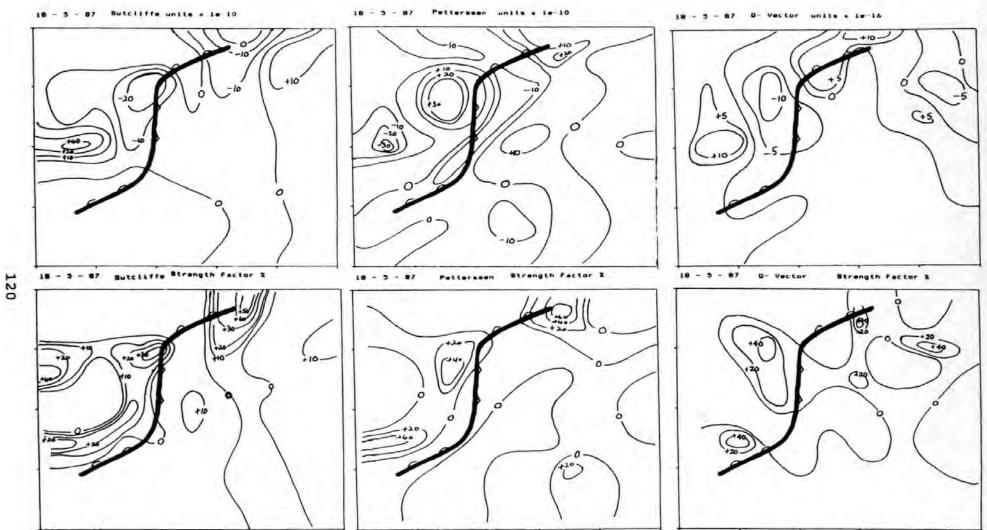


Figure 7.12A 18-5-87: Development using Sutcliffe, Petterssen and Q-Vector techniques, top magnitudes and bottom strength factor %.

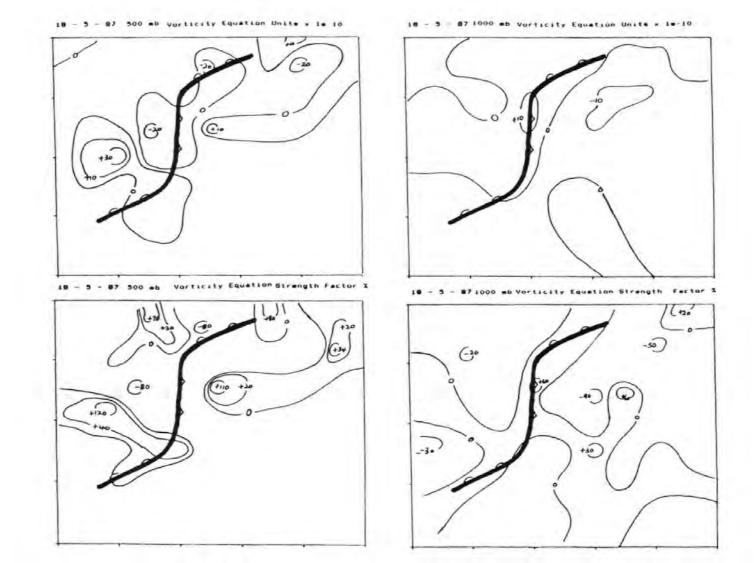


Figure 7.12B 18-5-87: Development using the Vorticity Equation, top magnitudes and bottom strength factor %.

18 - 5 - 87

This event shows a storm with fronts appearing as a wave with little or no pressure change, -1 mb in 12 hours, and moving 035°T at 10 ms⁻¹. Ascent can be seen on Figures 7.12A and 7.12B with the exception of the 500 mb Vorticity Equation. The Strength Factor diagrams show strong ascent along the frontal zone in all diagrams, except with the 500 mb Vorticity Equation. This large region of sinking air may indicate why the pressure tendency is negligible.

General Comment

The four occasions demonstrated show that a small memory personal computer can be used to study the complex diagnostic structure of storms along the baroclinic zone. The five tests used show surprising similarity, the Vorticity Equation reinforces the existing development algorithms and shows the contribution made by the following terms

i, 500 mb Vorticity Advection

ii, 1000 mb Divergence.

The contribution to development in the events illustrated are

16 - 1 - 82 mainly 500 mb vorticity advection
4 - 3 - 85 mainly 500 mb vorticity advection
21 - 1 - 87 mainly 1000 mb divergence

18 - 5 - 87 probably 1000 mb divergence

In all cases demonstrated the systems were developing although one event showed only a small pressure change over 12 hours. Generally the Strength Factor diagrams show that ascent

(positive values) are greater than descent values over the extent of the depression.

The latter two events show that 1000 mb divergence contributes to the development, both having a straight 500 mb flow pattern extending over hundreds of miles. The first two studies when the Index Cycle is low, 500 mb pattern globally producing three troughs and ridges, contribution is from the 500 mb vorticity advection.

Further studies are required to extend these ideas, however at this stage it was thought to be unrealistic through time restraints.

In the next chapter a case study is conducted. Using the "Ten" movement indicator the mariner can test the shore based routeing instructions sent to the ship and question course orders accordingly.

Chapter 8 A Case Study

Oceanroutes Ltd. are undertaking a research project in conjunction with the Institute of Maritime Studies, PSW, under the supervision of Prof. R. Motte. The research team was able to obtain digitised ocean environmental data from Oceanroutes (USA), California. These data are commercially available from the Meteorological Forecasting Services in America unlike the U.K. Oceanroutes have kindly provided data to cover the period 24-4-91 to 14-5-91, which has allowed model performance to be monitored and the "TEN" movement indicator applied to a route west-bound across the Atlantic, using performance data from an existing vessel.

Data are stored on floppy discs for ease of transfer and were brought from America etc. Each day of data are held in three files, surface fields, surface pressures and 500 mb heights.

The surface fields contain the following information:

- a, Wind Direction;
- b, Wind Speed;
- c, Primary Wave Direction;
- d, Primary Wave Height;
- e, Primary Wave Period;
- f, Secondary Wave Direction;
- g, Secondary Wave Height;
- i, Secondary Wave Period.

Each daily file contains analysis and forecast data, differences occurring through grid point spacing, forecasting period and data availability. Data are available for a 2.5 by 2.5 degree or 2.5 by 5 degree grid, and forecasting periods extending to 240 hours with data at 12 hour intervals.

The wealth of data supplied has allowed the surface winds calculated by the diagnostic model to be compared to "real values" as produced by a national forecasting centre for marine operations.

8.1 Diagnostic Model Performance

The digitised surface wind detail was compared to the calculated geostrophic, gradient and friction reduced winds.

Results show that the model works well for surface wind values, this suggests as surface spatial changes are larger than the spatial height differences at 500 mb, a better correlation would be obtained at this level. Results are shown in Table 8.1 using all 198 grid point surface wind velocities. The removal of wind velocities of less than 2.5 ms⁻¹, reduces the number of data points by forty-seven but considerably improves the fit for wind direction.

Surface wind values for the 4-5-91, using all 99 grid points, were compared to the model calculations of various wind types the results are shown in Table 8.2. These results compare

favourably with earlier tests on model performance, see Chapter 6. The tests comparing model wind values to the surface wind values in the European Daily Weather Bulletins (EDWB) gave an average speed errors of 2.63 ms⁻¹ and direction 15.11°. Average speed errors being smaller using the digitised data, but with direction the reverse is true.

Table 8.1 (Geostrophic	Wind	Velocity	Comparison	and	Errors
-------------	-------------	------	----------	------------	-----	--------

Correlation	198 Points	151 Points
Speed Direction	0.69 0.89	0.68 0.95
Speed Error	m per s	m per s
Avg. Diff. Stan. Dev.	2.49 1.88	2.33
Dir. Error	degs.	degs.
Avg. Diff. Stan. Dev.	33.27 32.60	24.00 19.40

This is probably due to the source information being different. Pressure and 500 mb Height data is down loaded from the National Meteorology Center (NMC) and the surface calculated fields from the Fleet Numerical Oceanographic Center (FNOC). Any differences between the data FNOC uses for the field calculations and NMC data might be sufficient to produce these errors.

Digitising the surface weather chart from the European Weather

Bulletin of 4-5-91 0000Z and comparing the FNOC data for the same occasion, gives

Largest Pressure Difference	4	mb
Average Difference	1.26	mb
Standard Deviation	1.12	mb
Correlation Coeff.	0.977	,

Reasonable care was taken in digitising EDWB data, reading to 1 mb. The analysis from EDWB locates the depression near 45°N,60°W, four degrees of longitude further to the east than the American analysis. These differences although not pursued in this project could cause considerable errors in wind velocities and the fields calculated from them.

Table 8.2 Model Wind Correlations and Errors

Correlation	Geostrophic	Gradient	Friction
Speed	0.72	0.73	0.73
Direction	0.88	0.88	
Speed Error	m per s	m per s	m per s
Avg. Diff.	3.45 2.68	3.14	1.42
Stan.Dev.		2.23	1.07
Dir.Error	deg	deg	deg
Avg. Diff.	31.21	31.29	28.84
Stan. Dev.	30.37	30.35	31.24

8.2 Ship Routeing: A Case Study

The practical use of the "TEN" movement indicator, outlined in Chapter 7, is demonstrated. The data obtained through Oceanroutes California were used for a hypothetical routeing exercise using an operational routeing model, <u>Calvert,(1990)</u>. One run was made using the forecast data at the 1st May 1991 and another uses the analysed data from the 1st May to the 4th May.

The ASTOR, 20,606 GRT a multi-purpose cruise liner having a design speed of 19.5 knots uses 70 tonnes of fuel a day from a power unit of 11,765 kW. Ship performance is given by the standard operational data algorithms, <u>Evans, et al.(1992)</u>.

The route, which may seem unusual, was from the North Norwegian coast and returning to the Gulf of Mexico for further cruise duties. The passage with passengers aboard was intended to be pleasant and comfortable as possible with the vessel skirting the iceberg box, Figure 8.1, calling at Bermuda prior to Nassau in the Bahamas were the passengers will dis-embark. The route is from 59°N,15°W to 40°N,45°W a great circle distance of 1611 nautical miles.

The weather in the Atlantic at this time, 1-5-91 to 4-5-91, see Figures 8.2 to 8.9, was dominated by a blocking high centred at 57°N 15°W which moves south to 50°N 23°W by the end of the

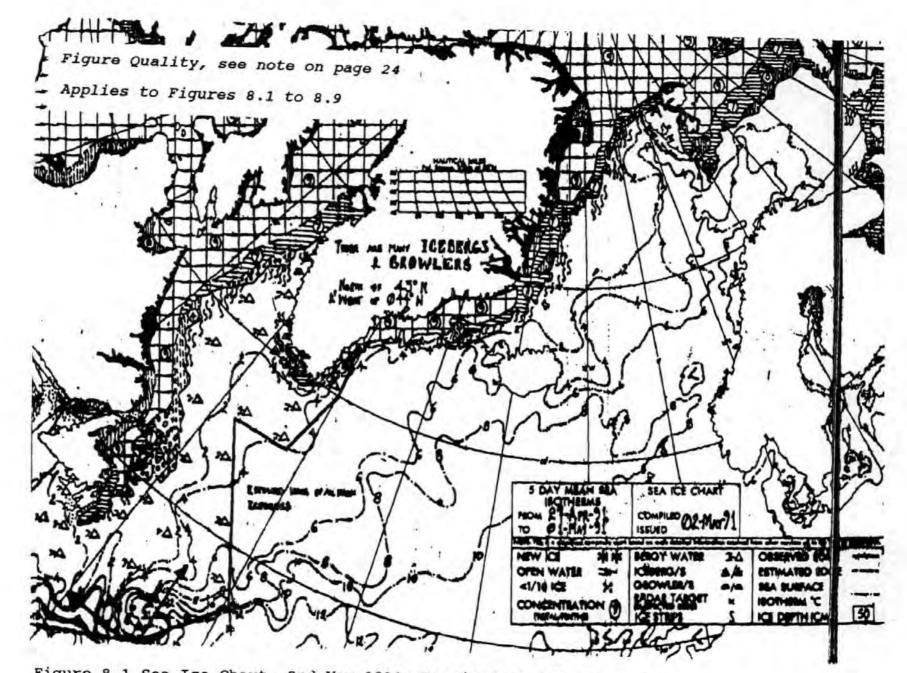


Figure 8.1 Sea Ice Chart, 2nd May 1991: Received at IMS Met.Station

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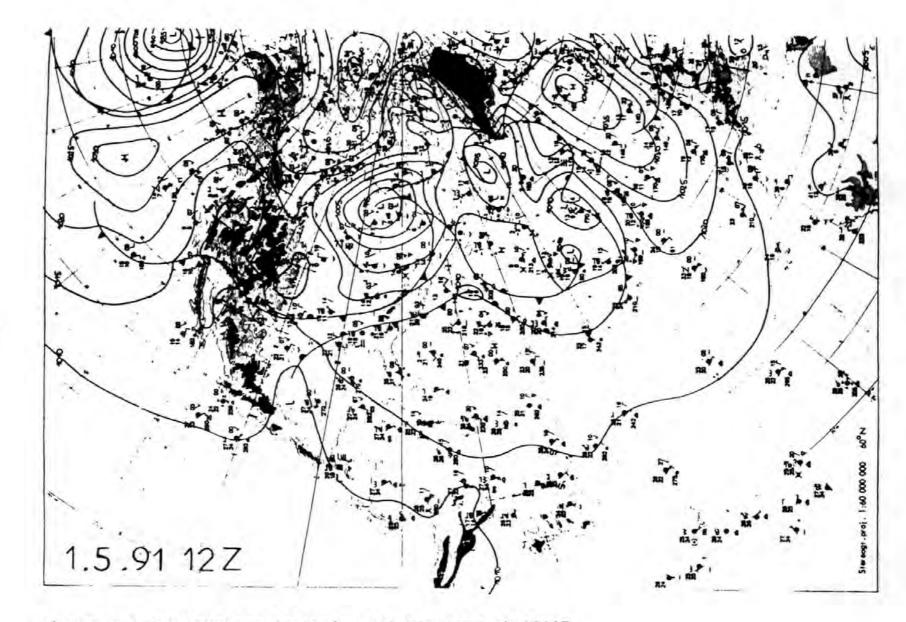


Figure 8.2 EDWB Surface Analysis, 1st May 1991 at 1200Z

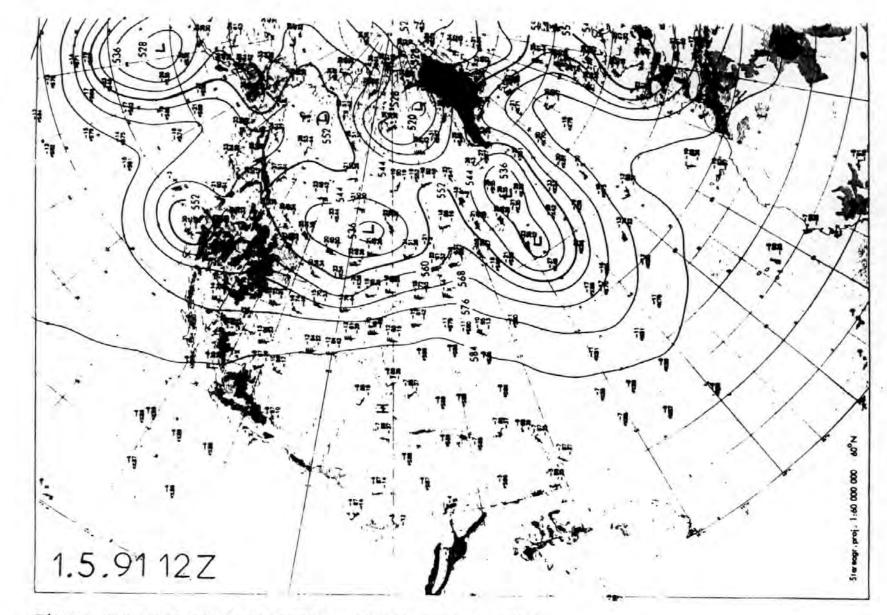


Figure 8.3 EDWB 500mb Analysis, 1st May 1991 at 1200Z

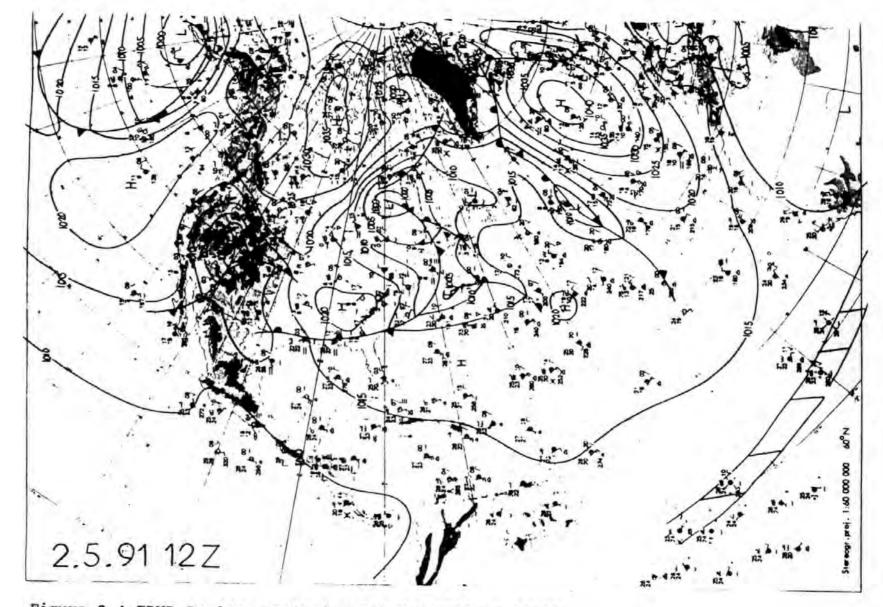


Figure 8.4 EDWB Surface Analysis, 2nd May 1991 at 1200Z

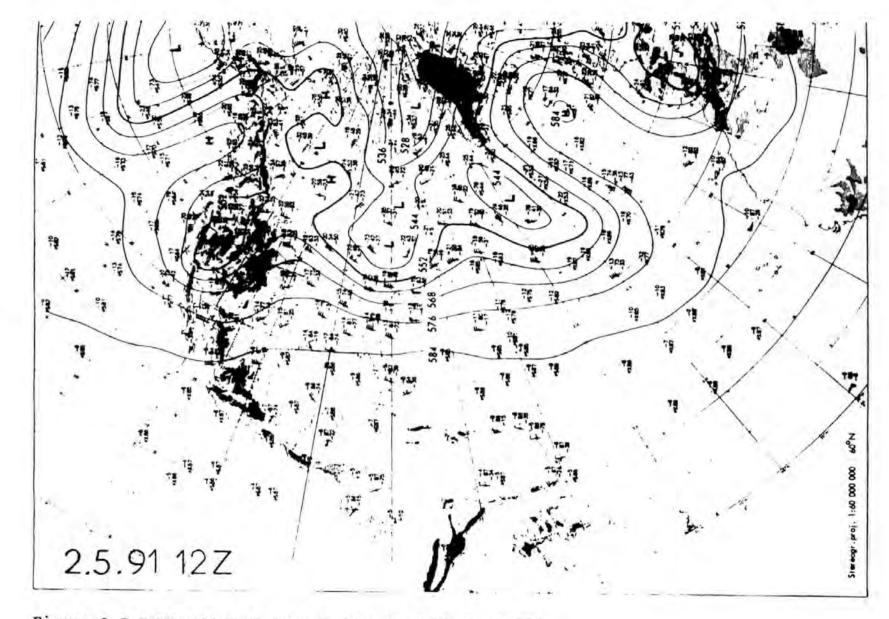


Figure 8.5 EDWB 500mb Analysis, 2nd May 1991 at 1200Z

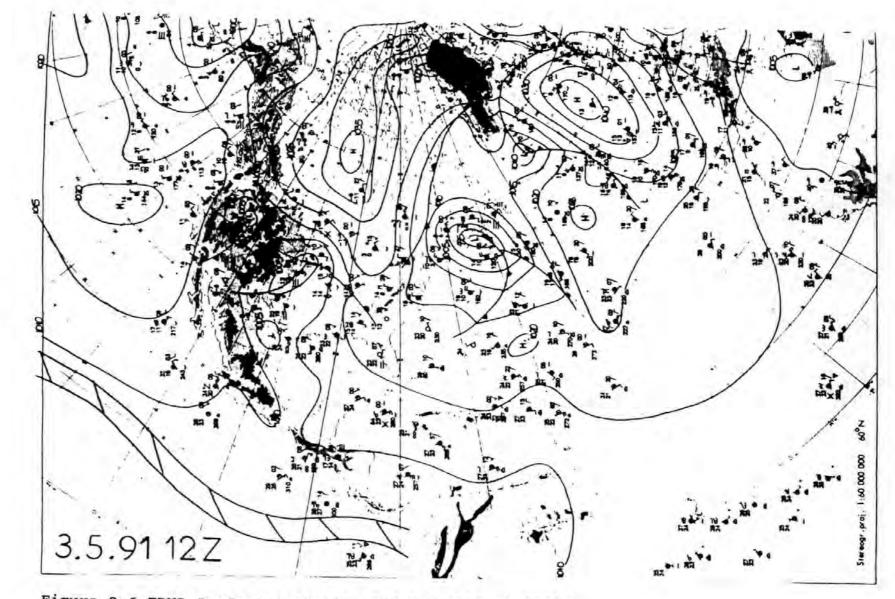


Figure 8.6 EDWB Surface Analysis, 3rd May 1991 at 12002

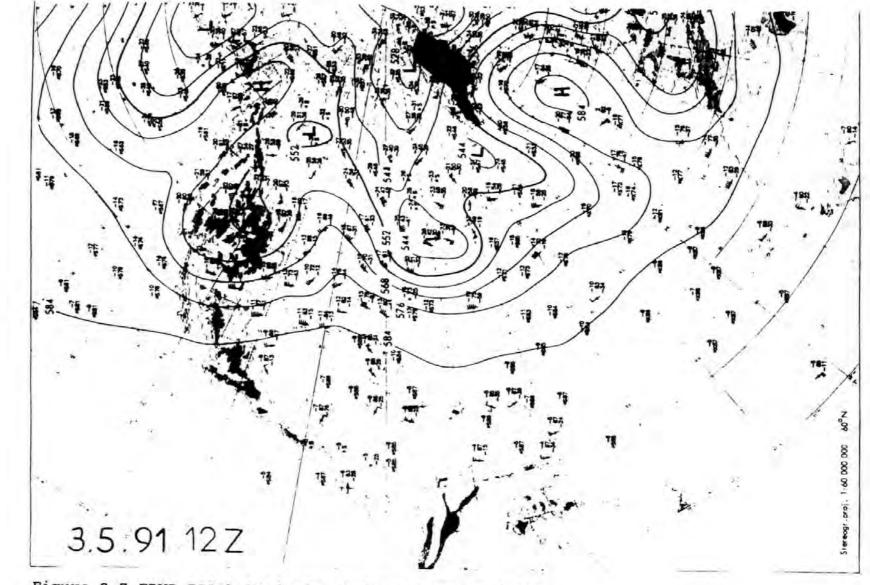


Figure 8.7 EDWB 500mb Analysis, 3rd May 1991 at 1200Z

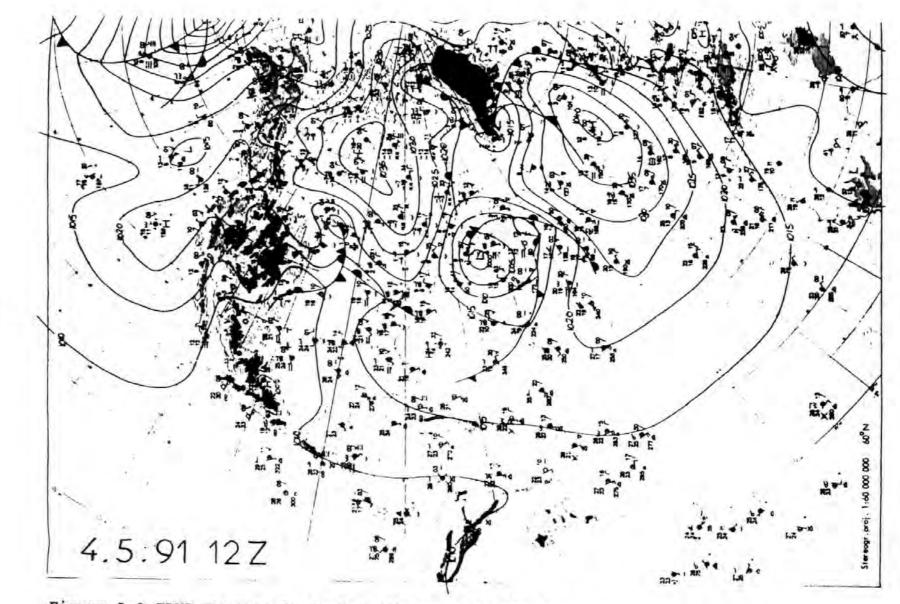


Figure 8.8 EDWB Surface Analysis, 4th May 1991 at 1200Z

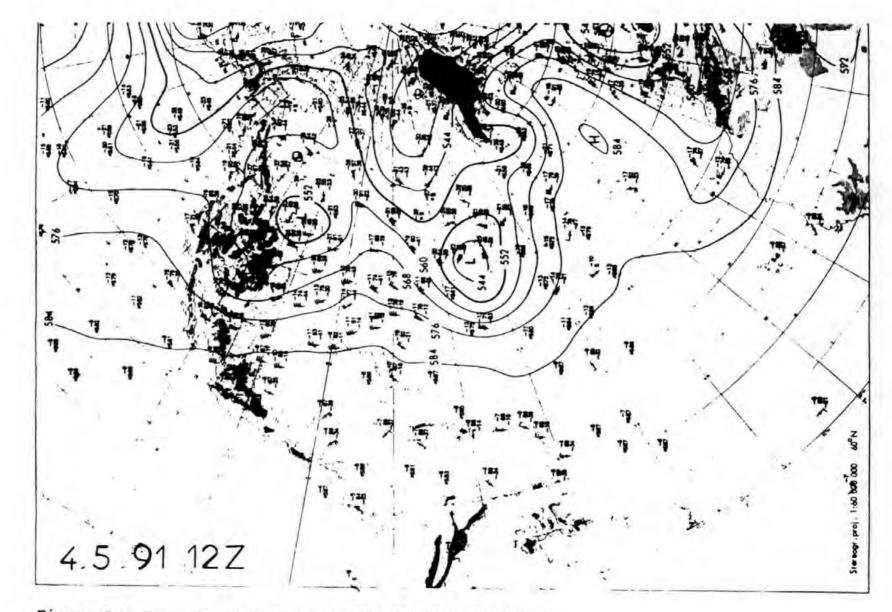


Figure 8.9 EDWB 500mb Analysis, 4th May 1991 at 1200Z

period. West of this blocking feature, from 35°W to 50°W, the isobaric pattern was meridional with a frontal zone north/south with a number of waves. By 4-5-91 the frontal zone has weakened sufficiently to allow the depression south of Nova Scotia, 43°N 63°W, to push eastwards increasing the isobaric gradient at 45°W as the high pressure resists this eastward progression. The 500 mb chart also reveals this change as the poleward arm of the jet weakens at the end of the sequence. Winds at the destination also show these changes as they back to the southwest and increase in strength to 26 knots.

Using the forecast data the routes obtained by the model, Figure 8.10 and Appendix G, was to the east of the great circle or least distance track (LTD) as the maximum fields coincide with the direct route. Between forty and seventy hours run time the maximum fields occur to the east of the direct route and coincide with the chosen route and the ships course is altered to the west to avoid these adverse fields returning to the LDT.

The analysis data does not indicate the fields intensifying to the extent suggested by the forecast data and the route produced by the model was between the forecast route and the least distance route. Both surface winds and significant wave heights are plotted, Figures 8.11 and 8.12, for each section of the voyage. These composite diagrams show analysis data and forecast data, in brackets, appropriate for each day and possible ship position. At the destination, 40°N 45°W, on the 4-5-91, analysis

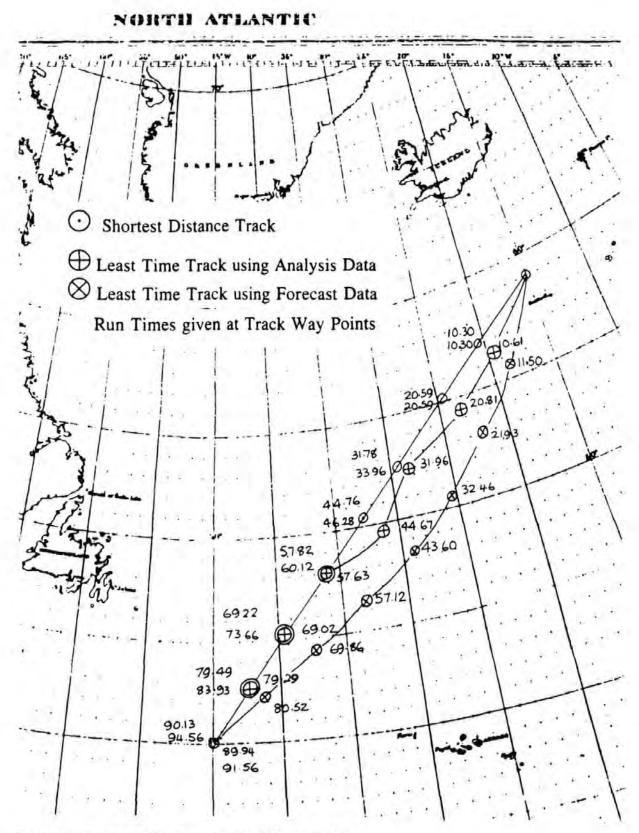


Figure 8.10 Ship Route Model Results

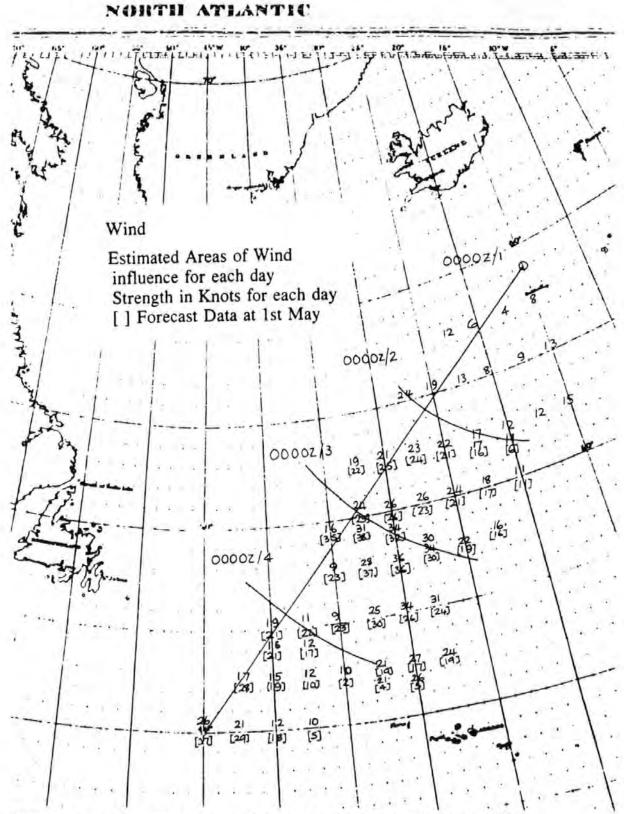
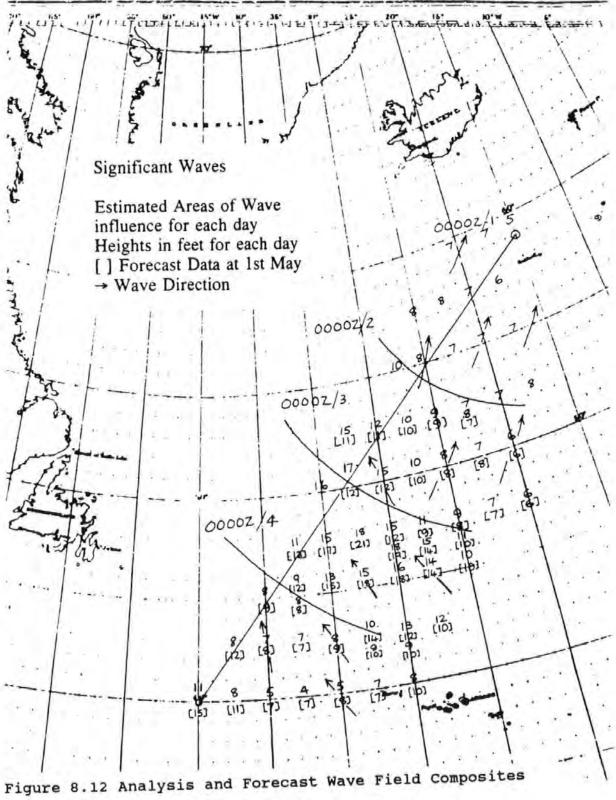


Figure 8.11 Analysis and Forecast Wind Field Composites

NORTH ATLANTIC



indicates strongest wind and wave fields and these weaken towards the east. Table 8.3 shows wind data from the EDWB surface charts and both analysis and forecast digitised data at selected positions near the route over the four day period.

The routeing model uses 12 hour information commencing at 0000 hrs. The "TEN" indicator has been used on the 1200Z EDWB analysis and 500 mb charts, Figures 8.2 to 8.9, which reflects the mean flow over the 24 hours. These charts are assumed similar to the weather data available to the mariner through the worldwide facsimile service.

The route is divided into four legs, representing each day of the voyage and the "TEN" indicator was applied to the appropriate depressions effecting each section with comments as follows:

<u>1st Leg : Time interval 0 - 24 hours.</u>

The dominating feature is the blocking anticyclone, $56^{\circ}N$ $15^{\circ}W$, to the south of the vessel and two depressions to the west and south.

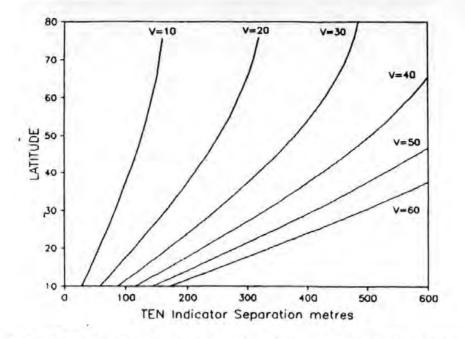
Speed and Direction adjustments are obtained using Figures 8.13, 8.14 and 8.15.

Actual depression movement was measured using successive EDWB surface charts. The location of each system was assumed accurate

Table 8.3 Wind and Wave data: Comparison between EDWB observations,

FNOC analyses and forecasts

Dirn.	Ht.
216	6
216	9
204	9
156	13
156	20
156	14
192	9
	216 204 156 156 156



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Figure 8.13 "TEN" Indicator Scale for estimating Depression Speed

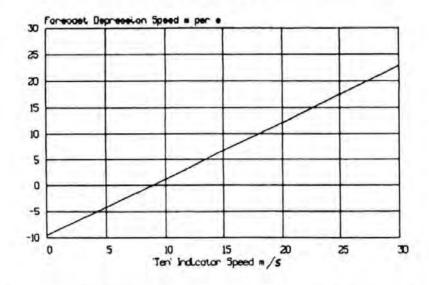


Figure 8.14 Forecast Speed using "TEN" indicator

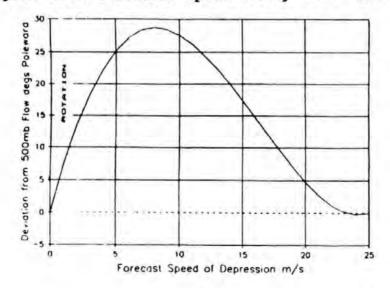


Figure 8.15 Storm Deviation using forecast speed

to 60 nm and the distance calculated between these positions, error 1 nm, was obtained using plane sailing, a standard navigational technique. Over a twenty-four hour time interval the distance error would be a maximum of 120 nm and the speed error of 5 knots, the calculated distance error being minimal.

The depression, 50°N 42°W, on 30-4-91 at 1200Z, pressure 999 mb, moves as follows

10 degree gradient290m gives23 ms⁻¹Speed after reduct.gives13 ms⁻¹ or 26 knots500 mb Direction335°TDirection Adjust.20°Depression Direct.315°T

Actual Depression Movement from successive charts Speed 14.5 ms⁻¹ or 29 knots Direction 302°T

The wave depression, 44°N 40°W, on 1-5-91 at 1200Z using the same method above gives

"TEN" 005°T * 40 knots Actual 006°T * 35 knots

The mariner would interpret this information as follows: Northern Depression moves to the west thus easing the present gradient if the anticyclone to the east is stationary. At this stage this appears likely as the 500 mb ridge is well established in this area and would mean weakening winds and sea state. The wave depression to the south as it progresses rapidly poleward would tighten the isobaric spacing thus increasing wind and wave fields at the end of the period. Wind fields near the LDT indicates 24 knots.

2nd Leg 24 - 48 hours.

The EDWB surface chart for the 2-5-91 1200Z shows the blocking high at 53°N 17°W maintaining its dominance with southerly winds on its western side. The route which passes through this region is influenced by the north/south trailing frontal zone on which a number of waves and wave depressions were found during the early part of the voyage. The routeing instructions were based on the assumption that the strong wind and wave fields along the LDT are maintained but weaker to the east. The wave at 57°N 40°W on the 2-5-91 1200Z using the "TEN" indicator gave a movement 330°T at 30 Knots and suggests a weakening pressure gradient as it moves west. The mariner rightly interprets an easing of the wind fields along the LDT.

The FNOC analysis shows this detail with the wind along the LDT at 21 knots, 4 knots less than the forecast, and to the east the wind fields are maintained. The wave depression, with enclosed contours, at 41°N 37°W was much stronger than the wave to the north and would influence the route later after 36 hours have elapsed.

The movement characterics are

"TEN" 325°T * 24 knots Actual 350°T * 25 knots

At the end of this leg wind strengths increase to 34 knots to the east of the LDT, 100 nm, backing slightly and are encountered until 60 hours have elapsed, but near the LDT the values are less.

<u>3rd Leg 48 - 72 hours</u>

The EDWB surface chart for 0000Z on the 3-5-91 locates the wave depression at 46°N 37°W, on the LDT about 300 nm from the ship, but within its circulation. The mariner notes this rapid movement to the north west and with the reception of the 1200Z surface chart sees the depression is well to the north of the LDT at 54°N 41°W, with the following movement detail

"TEN" 350°T * 48 knots

Actual 347°T * 41 knots

The "TEN" indicator apparently over-emphasises the speed but over the twenty-four hours speed has increased from 24 knots and the actual speed is measured over the last twelve hours. With the wave depression well to the north with a weakening frontal zone the chart shows a weak high pressure at 40°N 40°W. Winds and waves in this area would decrease over the next 24 hours from the LDT eastwards. The FNOC data shows a general easing of both the wind and wave fields, winds drop 5 knots on average.

The experienced mariner at this point of time, would expect the weather pattern to change, the weakening of the trailing frontal zone to the west of the dominating blocking high may be the precursor of the winds veering to the west indicating eastward progression of frontal depressions on the east coast of America. The EDWB 500 mb charts over the three days show a weakening of the trough and the poleward arm as flow at this level becomes more zonal.

The chart shows at 46°N 62°W, south of Nova Scotia, a frontal depression, pressure 995 mb, its movement indicators are

"TEN" $320^{\circ}T + 6$ knots Actual $314^{\circ}T + 7$ knots

The depression at this stage would not influence the winds and waves over the third leg and passage would progress with wind and sea conditions improving.

4th Leg 72 - 96 hours

After an elapsed time of 84 hours the EDWB for 1200Z on the 4-5-91 shows a warm front at the destination. In advance of this feature the winds are S*E at 30 knots and cover a large area between 35°N 45°W to 50°N 40°W. Behind the warm front winds are much weaker, 10 knots, and have veered to the SW. The FNOC data at 0000Z 4-5-91 suggests a general easing of the winds along the LDT, a reduction of 4 knots on average, whereas the forecast data shows the fields maintaining or even

strengthening. To the east of the LDT the winds weaken considerably and at a distance of 200 nmiles a strength of 10 knots was indicated. After 90 hours elapsed time and near the ships destination the winds increase in strength to 26 knots, an increase over the twenty-four hours of 19 knots, the forecast shows 37 knots. The shore router would be aware of this change from the previous days analysis and 24 hour forecast but the mariner may not be aware. The mariner on receipt of the 1200Z surface chart would check the movement of the depression to the west and would note that it has started to occlude. The present weather over the last twelve hours to mid-day along the LDT has been winds southerly at 17 knots, cloud thickening with rain at times becoming more continuous. He would appreciate an increase is likely if the depression moves east or if the fronts rotate which seems more likely. From the charts received it is apparent that the depression has not moved over twenty-four hours, however the wave shown on the cold front would indicate any rotation.

Applying the "TEN" indicator to this feature gives

"TEN" 005°T * 31 knots

Actual 000°T * 25 knots

This rapid movement north of the warm front would be apparent to the mariner and would be sufficient for him to realise that a more eastward route to Bermuda would allow a more pleasant passage missing the worst of the weather at the destination. However, the criteria for the way points were nominated at the outset and for these reasons the vessel is directed through the heavy seas to reach its destination.

8.3 Comments on the routeing case study

These data were not selected, they were the only available data at the time that Oceanroutes could obtain. These data were not ideal to test the effectiveness of the "TEN" movement indicator but the results are encouraging. The "TEN" indicator would provide better results when depressions progress eastward across the ocean, unlike this situation when the 500 mb level shows a cut-off situation which implies a surface blocking high pressure to the east.

The "TEN" indicator would be useful to the mariner as it could provide

- i, movement detail of depressions when not being routed
- ii, reinforce or provide a check for the mariner on the instructed route.

The relative change in winds over each leg of the voyage are demonstrated in Table 8.4 and shows both analysis and forecast detail. The results of using the "TEN" movement indicator are compared to actual system movement along each leg and are summarised in Table 8.5. The largest differences were 25° in direction and in strength 7 knots.

The case study showed slight differences in surface data from different sources, this is to be expected as it is more than likely the routeing model would be based on digitised data, such as FNOC. The mariner is unable to receive this at present

only the data available through facsimile transmissions, but even these might be slightly different as forecasters each side of the ocean construct their charts independently with their own interpretation. The use of different shipboard data from the shore based routeing agency as in this case study would reflect normal practice.

The study used demonstrates to the mariner and the routeing agencies the benefits of the "TEN" indicator especially when the weather pattern changes. It would allow on board modification to the route, which is the masters prerogative, as in this case when a route further to the east at the destination location would be beneficial. Table 8.4 Summary of Average Relative Winds from FNOC Data for each Leg of

passage showing changes for Analyses and Forecasts (Bracketed)

LEG/Date	e May 1	May 2	May 3	May 4
ONE	0	Stronger (Stronger)	Stronger (Weaker)	Weaker (Stronger)
TWO	0	Weaker (Weaker)	Stronger (Stronger)	Weaker (Weaker)
THREE	0	Stronger (Stronger)	Stronger (Stronger)	Weaker (Weaker)
FOUR	0			Stronger (Stronger)

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Table 8.5 Summary of "TEN" Indicator Performance versus Actual Movement:

location given with type of system

	LEG 1	LEG 2	LEG 3		LEG 4
	50N 42W Dep.	41N 37W Wave Dep.	54N 41W Wave Dep.	46N 62W Dep.	40N 53W Wave Dep.
TEN	315T * 26 knots	325T * 24 knots	350T * 48 knots	320T * 6 knots	005T * 31 knots
ACTUAL	302T * 29 knots	350T * 25 knots	347T * 41 knots	314T * 7 knots	000T * 25 knots

Chapter 9 Conclusions and Recommendations

The Graphical Model developed allows for the construction and storage of composite weather pictures. Software permits the rapid recall and playback of this data as an animated film. The initial construction of sequences shows the intricate evolution of the frontal depressions and the upper air flow over the N.Atlantic. The knowledge and interest gained from these loops naturally led into the design of a diagnostic model to analyse fields appertaining to the movement and development of these systems.

The construction and operation of a diagnostic model using a limited memory desk top computer has enabled the study of synoptic scale phenomena, namely mid-latitude frontal depressions within the baroclinic zone, to be accomplished successfully. This research has been carried out within the limits of the capability of the technology prevailing in the early to mid nineteen eighties.

The Apple II computer has a limited memory of 64K, was programmed to facilitate:

- i, the digitising of real time weather data;
- ii, the computation of relevant field variables using the Basic programming language;
- iii, the illustration of flow fields using colour graphics
 which could be recorded on video (compatibility

between computer and VCR is not always easy or feasible).

The initial research involved the time consuming construction of a multi-purpose yet flexible software package to enable field variables to be calculated, stored and retrieved as required. A cubic spline technique is adopted to obtain gradients at each grid point of any variable, whether real or synthetic, this prevents boundary data loss, optimises computing time and produces reasonable results.

Velocity errors at the 500 mb level, see Chapter 6, were: Observed v calculated geostrophic wind

Speed \pm 5.97 ms⁻¹, Direction \pm 1.0° Observed v model geostrophic wind Speed \pm 5.25 ms⁻¹, Direction \pm 18.8°

The objectives of this research is to update the criteria for forecasting storm characteristics so that the mariner or other users are able to follow the evolution of any storm, whether forecast charts were available or not. The "TEN" indicator, requiring both the surface and the 500 mb level data, gives a more realistic guide to storm progression. It is obtained by measuring the difference in height fields at the 500 mb level over ten degrees of latitude perpendicular to the flow, but centred about the storms surface location.

The method the mariner currently uses depends on the warm sector

wind fields, which means that if there is a wind the storm must be moving. The sole use of the 500 mb chart also presents practical problems with regard to the location that best reflects the storm movement. The method developed, the "TEN" indicator, does allow for strong winds to be found in stationary systems. Sutcliffe development theory suggests that storm characteristics are controlled to a certain extent by the thickness pattern, namely the thermal wind. If the surface feature lies within an enclosed upper trough then the thickness fields tend to rotate the surface low in an anticyclonic direction as the winds on the western side of the trough are N'ly, at the trough W'ly and on the eastern side S'ly. The "TEN" indicator encompasses this element and this is reflected in the results obtained. When the upper air flow becomes more zonal surface storms are steered along the jet stream. This research shows that as depression progression increases from zero, the rotation decreases and the deviation from the 500 mb flow also increases. This deviation is maximum, 28°, to the cold side of the flow when the speed of movement is approximately 8 ms^{1} , this gradually decreases to zero deviation as speed increases to 23 ms⁻¹. The research shows that the "TEN" movement indicator produces a better approximation to depression speed, correlation against actual speed 0.54, than either the warm sector method 0.21 or the 500 mb wind fields 0.235. The direction correlation also shows a similar trend although all the correlation coefficients are of the order 0.6.

The provision of digitised data from the USA, kindly obtained

through Oceanroutes Ltd., allows the diagnostic model wind fields to be compared with Fleet Numerical Oceanagraphic Center (FNOC) outputs. Using the surface pressure fields from the National Meteorology Center (NMC) as the source data ,the diagnostic model produced wind fields compare favourably with the FNOC data, also the same source data, producing the following correlations, speed 0.68 and direction 0.95. Speed errors were 2.33 ms⁻¹ and the direction errors 24°.

The case study is conducted with the benefit of additional information from Oceanroutes Ltd. whose Plymouth research department were willing to run, using their operational ship routeing software and their recently designed ship performance algorithms, a number of sequences with both analysis and forecast data. The routes obtained are analysed in relationship to the weather movement, and the "TEN" indicator is used to explain the differences between the forecast and analysed tracks.

The use of the "TEN" indicator in the case study shows how this indicator would aid the mariner. Over the four days of this case study the mariner is able to forecast or readily appreciate the movement of the five low pressure systems which affect his chosen route. The accuracy of these forecasts give a maximum error of 25° in direction and 7 knots in speed. Bearing in mind that over the period of the case study three of the systems were wave depressions on the trailing cold front of the primary depression, these errors are acceptable. The forecast of the two

depressions over this period gives a directional error of 13° and a speed error of 3 knots. Errors in direction are greatest at low speeds whilst speed errors are greatest at speeds greater than 40 knots. Using these errors the depression moving at a speed of 10 knots could be 104 nm from its forecast position after 24 hours whilst a depression moving at a speed greater than 40 knots may be 170 nm ahead of its forecast position. Storms which are mature have a diameter of 1000 nm so these errors are not significant.

Whilst the search for better development indicators is not so rewarding as the search for better movement indicators the versatility of the diagnostic model is demonstrated. The four cases illustrated show three existing theories of development, Sutcliffe, Petterssen and the Q-Vector. These use geostrophic winds and the results show that ascent is greatest just in front of the warm sector towards the centre of the depression at the meeting point of the fronts in all cases where pressure is falling. The 18-5-87 diagrams shew an area of ascent behind the frontal apex and in this case pressure is steady.

The vorticity equation which uses gradient wind approximations also show regions of marked ascent at the 500 mb level close to but in advance of the warm front near the frontal apex in the three cases where pressure is falling. The 18-5-87 case where pressure is steady does not show any ascent near the frontal apex. Similar results are found at the 1000 mb level, gradient wind values are adjusted for surface friction, show ascent near

the frontal apex or just behind it where pressure is falling. Again the 18-5-87 case does not show such a definite pattern as the others.

Vertical motion in the three cases where pressure is falling are summarised in Figure 9.1 and shows the relationship between ascent and descent in terms of the strength factor. The average depression characteristics shows pressure falling at 10 \pm 1.5 mb in 12 hours, speed 10 \pm 1.5 ms⁻¹ and direction 050 \pm 25°. Maximum development using the Sutcliffe, Petterssen and

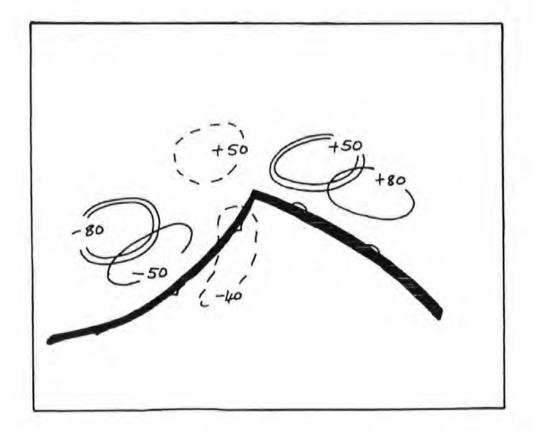


Figure 9.1 Average Depression Development showing vertical motion expressed as a percentage, double lines from Sutcliffe,Petterssen and Q-Vector, single 500 mb and pecked 1000 mb Vorticity Equation. Q - Vector theories, marked as double lines, show the average strength factor as a percentage, positive values indicating ascent stronger than the surrounding flow and negative values descent. Single lines indicate ascent and descent using gradient wind values in the Vorticity Equation at 500 mb level, which agree with the recognised theories, and pecked lines the areas of ascent and descent at 1000 mb level.

The vertical motion in a developing depression shows a uniform pattern of ascent fields, these are modified when the system starts to occlude. More research is needed to relate these field changes to pressure tendency and storm movement, which is outside this brief.

The movement indicator produced by this research provides the mariner or sea user with some additional insight into the complexities of storm movement. It is believed that this type of indicator could be improved, using the same approach, with further studies incorporating storm size. The storm's behaviour must be related to its size and pressure tendency, thus by varying the distance over which the 500 mb gradient is measured, say the diameter of the 1000 mb isobar a better fit might obtain.

Prior to any further work into the study of depression behaviour the designed diagnostic model should be modified to reduce computing time. The first essential is to convert the software so that it could be used on IBM compatible machines and to use

a more efficient language, such as 'C', this will allow the incorporation of both the digitising and analysing software into a single package. The possible adoption of a technique to produce the gradient of any variable more effectively than the time consuming method currently employed will speed up any further studies.

The modified diagnostic model will then be ideal for use as a teaching aid as well as a research tool. Its interactive features will allow users to comprehensively investigate the structure of depressions within the baroclinic zone using simple or even the more complicated parameters as outlined in this project. Further research should be conducted into the dynamics of frontal activity and storm evolution making more use of digitised data as it becomes more accessible. Multi-level diagnostic analysis of storm structure and the continuous analysis every six hours over the storms life might provide some of the indicators for development that this research has started to investigate. The model could also be easily modified to include tropical storm features and sea wave mechanics.

The sea user or mariner will benefit from any study into storm indicators but only if these are of a practical nature, easy to use and visualise. Currently the weather charts for the North Atlantic Ocean can be obtained through WMO facsimile transmissions and appropriately include surface analysis, 500 mb analysis together with thickness information. Forecast information at these levels are available for various periods

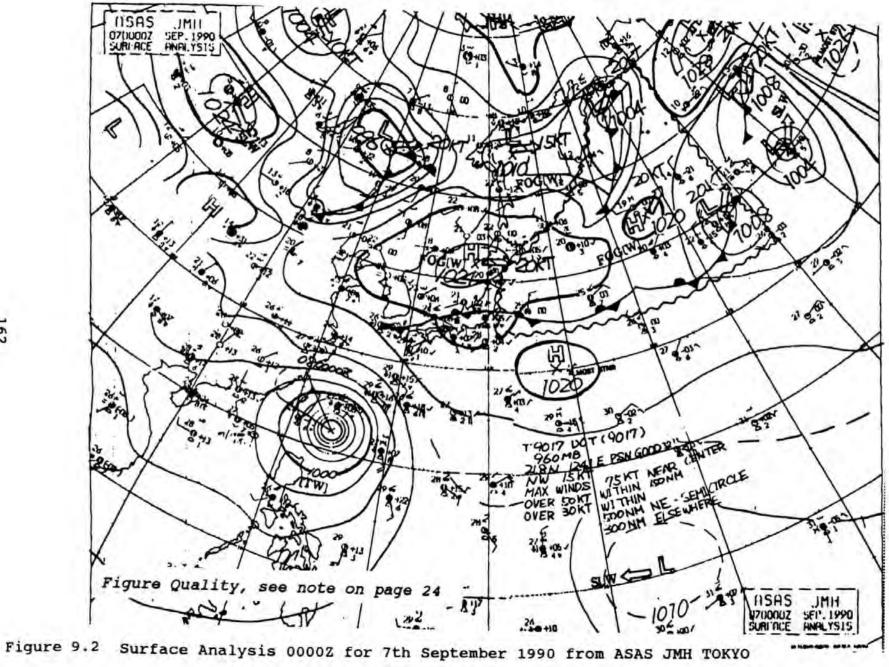
up to 120 hours. These charts are transmitted at various times during the day and the task of receiving these data places an undue burden on the ships crew, especially with the practice of reduced manning.

For example the United Kingdom Meteorological Office station Bracknell (GFA) transmit 0000Z data for areas A and F as follows

Surface Analysis	0341 hrs
24 hr Prognosis	0431 hrs
500/1000-500 mb Anal.	0438 hrs
24 hr Prognosis	0630 hrs

Forecasts for greater periods, 48 and 72 hr., are available only for the Eastern North Atlantic.

To receive these data alone means considerable inconvenience, however, bearing in mind these data are for one synoptic period, the receipt of any additional data do indeed put considerable strain on the watchkeeper. The transmitting centre could provide information of system evolution on a composite chart utilising both movement and development indicators, this will reduce the data needed for the mariner to make his pertinent routeing decisions. The Japanese marine broadcast transmitted via Tokyo does utilise some of these ideas on their surface charts, Figure 9.2, showing the movement of all pressure systems over the North Pacific Ocean. Movement is indicated by an arrow in the direction of travel, unlike the UK Met.Off. which mark the track of some fast moving storms, also the speed is indicated alongside in knots. Even stationary systems are



indicated as such. If an indication of tendency could also be included, it makes the mariners decision making process easier. The Japanese also provide simple indications of fog, ice and heavy seas, and in tropical regions always show tropical storms, typhoons, with danger areas. Additionally there are simple notes about the characteristics of each storm, which include tendency, strongest winds and heavy seas.

The search for better storm characteristics, both movement and development, and their inclusion through the marine weather facsimile service will be of great benefit to the mariner, optimise data transmission efficiency, improve the shipboard understanding of shore routeing decisions, cultivate better shipboard choice of route and thereby reduce time at sea, damage to ship and cargo etc.

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APPENDICES

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Appendix A

The output data using the programme "Depression" monitors the performance of a vessel passing through the centre of a stationary depression.

The vessel departs from Lat. 42° 50'N, Long. 39° 34'W on a course of 250°T with a smooth water speed of 18 knots. The run time of forty-eight hours is used and vessels speed with the sea state are indicated for each hour.

			DEPRESSION STATIONARY				
TimeShip			Course	Speed	DIST	Wave HT	Dirn
0	42.85	39.56	250	17	0	2.50	330
	42.76		250	17	17	2.60	330
	42.66		250	17	33	2.70	330
	42.57		250	17	50	2.80	330
	42.47		250	16	66	2.90	330
	42.38		250	16	83	3.00	330
	42.29		250	16	99	3.10	330
	42.20		250	16	115	3.20	330
	42.10			16	131	3.40	330
	42.01		250	16	147	3.50	330
	41.92		250	16	163	3.70	330
	41.84			15	179	3.80	330
	41.75		250	15	194	4.00	330
	41.66		250	15	209	4.10	330
	41.58		250	15	224	4.30	330
	41.49		250	15	239	4.50	330
	41.41		250	14	254	4.70	330
	41.33		250	14	268	4.90	330
	41.25		250	14	282	5.10	330
	41.17		250	13	296	5.30	330
	41.10		250	13	309	5.50	330
	41.02		250	13	322	5.70	330
	40.95		250	13	335	5.80	330
	40.88		250	12	348	5.90	330
	40.81		250	12	360	6.00	330
	40.74		250	12	372	6.00	330
	40.67		250	13	384	5.80	329
	40.60		250	13	397	5.50	329
	40.52		250	14	410	4.80	329
	40.44		250	16	424	3.60	329
	40.36	48.78	250	17	440	1.80	329
	40.26		250	18	457	.20	329
	40.16		250	18	475	.00	328
	40.05		250	18	493	.00	321
	39.95		250	18	511	.00	155
	39.85		250	18	529	.00	152
	39.75		250	18	547	.50	151
	39.65		250	17	565	2.40	151
	39.55		250	15	581	4.20	151
	39.47	51.97	250	13	596	5.20	151
	39.40		250	12	609	5.70	151
	39.33		250	12	. 621	5.90	151
	39.26		250	12	632	6.00	151
	39.20		250	12	644	6.00	150
	39.13		250	12	656	5.90	150
	39.06		250	12	667	5.80	150
	39.00		250	12	679	5.60	150
	38.93		250	13	692	5.50	150
	38.86		0	0	704	5.30	150

Appendix B

Paper read at the International Conference on Computer Applications at the Royal Institution of Naval Architects, 19-20 November 1985, London.



INTERNATIONAL CONFERENCE

in association with THE NAUTICAL INSTITUTE and THE INSTITUTE OF MARINE ENGINEERS

COMPUTER APPLICATIONS In the OPERATION & MANAGEMENT of SHIPS & CARGOES

19-20 NOVEMBER 1985 LONDON VOL. I

THE ROYAL INSTITUTION OF NAVAL ARCHITECTS 10 UPPER BELGRAVE STREET, LONDON, SW1X 8BQ. Telephone: 01-235 4622 DIAGNOSTIC AND DYNAMICAL MODELLING FOR WEATHER ROUTEING OF SHIPS USING ON-BOARD MICROCOMPUTERS

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1. INTRODUCTION

There would be no problem in precisely weather routeing a vessel across an ocean if it was possible to forecast with total accuracy the actual sea state existing for the duration of a voyage, making the assumption that the performance of that vessel throughout a range of sea conditions may be quantified. Such an ideal circumstance is not, as yet, possible. Depending upon the general synoptic situation existing for the period, it is fair to make the assumption that the actual accuracy of a weather forecast deteriorates as time progresses. This is, of course, in spite of the massive strides made in technology and considerable contribution in learning of the various forecasting agencies over the recent past decade. The new forecasting techniques of dynamical models, housed in massive computers, have made it possible to extend, with some confidence, the forecast period. Mariners may receive, on board, through the machinery of a standard marine facsimile device surface forecasts of sea state for forty-eight hours ahead and general lower atmosphere steering indicators for up to one week shead of the analysis time. The latter give, in certain circumstances, an indication of the future movement of middle latitude depressions or cyclones1.

The environmental information may be matched to ship performance data by using a microcomputer on board ship or, indeed, on shore. Dynamical programming techniques may then be used to generate optimum routes and a diagnosis of individual storms assist in voyage planning.

2. SHIP DAMAGE AND LOSS

A ship may be damaged or delayed by the action of sea waves on her hull, structure or cargo. Paradoxically, the recent rapid transfer of freight to the through transport mode of containerisation has highlighted this. The flimsy container, (flimsy, that is, in comparison with the hull of a conventional freighter) often bears the brunt of a breaking sea with disastrous consequences. The relatively poorer sea keeping characteristics and higher potential speed of these vessels, allied to the requirement

to maintain a schedule as part of a multimodel system, may cause ship operators to take a harder look at the advantages a system of weather routeing has to offer. Much of the recent effort to reduce ship damage and loss by applications of technology has not been directed to loss due to environmental causes. Radar and navigational instrumentation are directed towards reducing collisions and modern inertial gas systems reduce the risk of explosion and fire in tankers. Little has been done in the application of new understandings and/or new technologies towards minimising the effects of stress of weather leading to damage or foundering and abondonment.

The Table I indicates that some 0.3 of all ship losses are as a direct result of press of weather and this relates to approximately half a million tonnes of shipping each year. Consideration should be given in attempting to reduce this alarming statistic.

Not surprisingly the main areas of ship loss are in the middle latitudes of the North Atlantic and North Pacific Oceans. By far the greatest number of losses due to nonsustainable extremes of weather occur in these areas . Of course these are the densest trade routes but that is not the complete answer. It is, coincidentally, the home of middle latitude, extra tropical, depressions, which sweep across this baroclinic zone. They dominate the weather in these areas, covering great areas of ocean with uninterrupted wind fields of long duration, which, in their turn, build up wide and fully developed ses states. On some routes as much as 30% extra fuel is consumed, and an equivalent ratio of time added to voyage lengths, because of their effects². They also cause damage to vest effects². They also cause damage to vessel and cargo. One North Atlantic operator has calculated an annual service cost of \$800,000, as directly attributable to these storms3. The depressions travel in an approximately easterly or north of east direction at various speeds, which over the open ocean may be meaned to some thirty or forty knots. Vessels are most "at risk" on westbound passages when they are closing these systems at a relative fifty or sixty knots (for a twenty knot vessel). The consideration must be to minimise this The

system effect by judiciously planning a course through least wind and sea effects".

3. HODELLING

The meteorological services use world wide data collection methods and the largest computers ever devised in a multi-million pound operation. Weather patterns are forecast for days shead using complex and intricate, multi layer prognosis models. The numerical models now in use, for example in the British Meteorological Office, incorporate physical principles such as wave growth, interaction and dissipation, the advection of swell energy, refraction and friction. The basis of the model is a discrete directional rave energy spectrum, (14 frequencies and 16 directions) which is determined by the surface wind fields forecast by the numerical weather prognosis model. Information on wave height and period can then be obtained by calculating the appropriate statistical moment of the energy spectrum⁵. The current ocean wave forecast are run on the huge CDC Cyber 205 computer, producing open ocean forecasts up to forty-eight hours ahead for areas of the North Atlantic and North Pacific Oceans north of 18°N.

The authors do not intend to compete with the vast resources or complexities of these Prognostic models. Rather, as it is recognised by most seafarers that middle latitude cyclones are "the enemy", an attempt is made to understand the structure, development and future movement of each potential storm with a view to avoiding their ability to adversely affect a voyage.

It is suggested that storm avoidance may be practiced either by diagnostic modelling of each storm and/or by dynamic programming, whereby the criteria of time, fuel economy and cargo damage may be considered for optimisation procedures. The data input is as provided by the meteorological services through standard marine facsimile channels. The modelling relies entirely on this input.

4. GRAPHICAL DIAGNOSTIC MODELLING

A boosted micro-computer may be used to produce instructive information on weather Using a drawing tablet, charts systems. may be reproduced showing pertinent weather festures. For example, fronts of middle latitude depressions may be superimposed on the 500 mb upper air flow. By viewing a continuous sequence of successive overlays, a study of evolving events is made. This facilitates analysis as the observer can more readily visualise the complete pattern, thus movement and development is easier to comprehend. Thus in general the movements of frontal depressions are related, in the western part of the ocean, directly to the jet flow field, and on the eastern wide they generally tend to escape poleward from the jet flow, to follow preferred spin patterns at the entrance and exit regions of the jet complex⁷.

Figs 1 and 2 show a typical winter sequence of overlay charts for the period 1st to 10th January 1982 over the North Atlantic Ocean. Contours, representing the height of the 500 mb pressure level, are drawn at 5760, 5600, 5440

1	(1) 9 ((r= = =1	(1) TOTALS (from all campas)		ESS OF WEATHER,	hills
			anti-r af	afilian grees Lamo	···/.
978	110	м			1
n	279	1.1		6.61	.34
	20	1.4		0.42	.39
# 1	349	1.7	74	8.41	. 30
-	136	1.44	41	8.40	.17
#3	101	1.25	n	0.29	.12
	113				40

TABLE 1 VESSEL LOSS STATISTICS

- (i) TOTALS AND
- (ii) LOSS DUE TO STRESS OF WEATHER, FOUNDERING AND ABANDONGENT

and 5280 metres, with their associated polewards pressure gradient. The surface fronts are indicated by thick shaded lines.

The general flow indicates a stationary trough at 500 mb over the east coast of America. The flow trends poleward lessening in strength as the gradient decreases. Over the ten day period the exist region undergoes considerable change. Mid-way through the sequence the flow south of Greenland bifurcates but towards the end of the period the flow strengthens with a resumption of the continuous jet.

North Atlantic depressions form within this flow, generally in the poleward moving air downwind of the trough, close to Florida. They are advected and intensify as they move across the Atlantic contained within the "control" of the strong upper air flow. The depression over Newfoundland on the 5th January is carried toward Greenland as the upper air flow weakens. It has moved poleward and is over the west coast of Greenland on the 7th and 8th January. increasing seasonal temperature values by some 25°c. By the and of the c. By the end of the sequence, the depressions are again constrained by the upper air and move across the Atlantic Ocean into N.W.Europe.

This particular sequence outlines some of the difficulties involved in synoptic forecasting over the oceans in middle latitudes, which may be summarised and categorised as follows:

- ۸. Initial depression formation and growth (cyclogenesis).
- R. Movement and development related to strong upper air jet patterns.
- C. Movement and development related to weak upper air jet patterns.

Strategic ship routeing involves avoiding the worst effects of frontal depressions and the generated sea wave patterns, or traversing them on the "favourable" side. If the weather situation relates to case B, with each depression forming on the trailing cold front of the preceding depression and crossing the ocean within the control of the narrow zone of the upper air jet the process of ship routeing is reasonably straightforward. However, when this sequence is broken, new depressions may form well away from the preceding family. If the situation is typical of C, the depressions may escape from the weak jet or become stationary. An early awareness of these subtle changes, areas of development and undue deviations in the flow, can assist in route planning. A specific analysis of available data will afford the mariner or routeing officer a clearer indication of the evolving weather pattern.

5. SPECIFIC ANALYSIS

A set of equations expressing the physical coupling and energetics of weather systems will assist in their diagnosis.

5.1 Standard Equations

Momentum

$$\frac{Du}{Dt} - fv + \frac{1}{9} \frac{\partial p}{\partial x} = 0 \qquad 5.1$$

$$\frac{Dv}{Dt} + fu + \frac{1}{\rho} \frac{\partial p}{\partial y} = 0 \qquad 5.2$$

$$+\frac{1}{2}\frac{3p}{2}=0$$
 5.3

Continuity

$$\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} + \frac{\partial u}{\partial z} = 0 \qquad 5.4$$

where:

'D/Dt is the total derivative following a fluid particle u, v, w are the wind components along the cartesian co-ordinates x, y, z.

f coriolis parameter

p pressure

o sir density

E gravity

5.2 Pressure - Height transformation

Upper air charts show height changes of the relevant constant pressure surface. In Equations 5.1 and 5.2 the terms containing pressure may be replaced using the hydrostatic relationship:

$$\frac{1}{\rho} \frac{\partial p}{\partial x} = g \frac{\partial z}{\partial x} \quad , \quad \frac{1}{\rho} \frac{\partial p}{\partial y} = g \frac{\partial z}{\partial y} \, .$$

5.3 Estimation of Diagnostic Components

The geostrophic velocities up and vg to a first approximation, are obtained from Equations 5.1 and 5.2 by assuming the total derivative, D/Dt, is small. The geostrophic velocities are:

$$u_g = -(g/f) (\partial z/\partial y), v_g = (g/f) (\partial z/\partial x) \qquad 5.5$$

The thermal wind V, the difference between geostrophic velocities at two levels, is represented:

$$v_{t} = v_{0} - v_{L}$$
 5.6

L are upper and lower levels. · where υ.

$$\partial u_{g} = - (g/f) \partial/\partial y (Z_{u} - Z_{L}) ,$$

$$\partial v_{g} = (g/f) \partial/\partial x (Z_{u} - Z_{L}) , \qquad 5.7$$

The depth of air between two pressure levels, ZU - ZL, is a convenient way of determining the thermal structure. This relationship may be obtained from the Integrated Hydrostatic Equation.

$$\Delta z = z_{U} - z_{L} = (RT/g) \ln (P_{U}/P_{L})$$

174

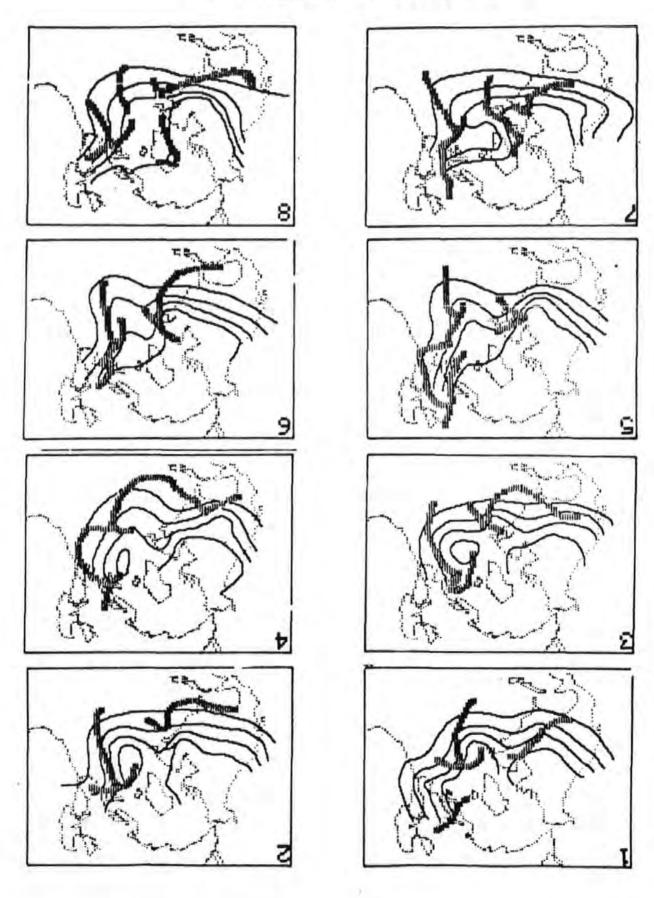


Fig 1. Picture Sequence, lat to 8th January, contours at 500 mb and sea level fronts.

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The usual thickness chart, $P_L = 1000 \text{ mb}$ and $P_U = 500 \text{ mb}$, shows the three dimensional movement of the lower half of the troposphere, containing both near surface and upper level data. Surface to 1000 mb level adjustment, using the hydrostatic equation and assuming a mean density, is necessary.

The geostrophic vertical component of relative vorticity, (a measure of fluid spin), ξ_g , as $\frac{\partial v_g}{\partial x} - \frac{\partial u_g}{\partial y}$ can be represented:

$$\zeta_{a} = (g/f) (\nabla^{2} z)$$
 5.9

where the Laplacian, V2z, indicates

The more complex diagnostic relationships, omega and Q vectors⁹ are not attempted in this paper diagnosis using the latter method for a cold front model outlining the structure etc, has been successfully attempted¹⁰. The intention is to show the basic ideas of diagnostic modelling utilising a micro-computer and its application to weather routeing of ships.

5.4 Availability of Data

Facsimile networks transmit charts¹¹ showing circulations at various levels of the atmosphere. Various scales and projections are used, creating difficulties in comparison. To minimise this effect a geographical grid is employed rather than a regular rectangular grid. Using latitude and longitude dats are digitised and filed, using array techniques. Finite difference methods are employed to estimate values of variables used in diagnosis.

5.5 Finite Difference Methods

The solution of geostrophic wind velocities, equations 5.8, are:

$$u_{s_{i,j}} = -(g/f_{i,j})(z_{i,j+1} - z_{i,j-1})/(2d)$$

$$v_{s_{i,j}} = (g/f_{i,j})(z_{i+1,j} - z_{i-1,j})/(2d \cos \theta)$$

The distance, d, between the geographical grid points in the north/south, j, direction are the same everywhere. The east/west distance between grid points, i, is constant for the same latitude, but varies with latitude, d cos 0, see fig 3.

The resultant geostrophic wind can be obtained from the relationship

$$\mathbf{v}_{\mathbf{g}_{i,j}} = \left[u_{\mathbf{g}_{i,j}}^{2} + v_{\mathbf{g}_{i,j}}^{2} \right]^{1/2}$$

The solution for gradient wind values can be obtained from Eqns 5.1 and 5.2 by including the ageostrophic contribution with its geostrophic effect.

The finite difference solution for relative geostrophic vorticity, equation 5.9, is:

$$s_{i,j} = (4/g/f_{i,j}) (d \cos \theta_j)^{-2} [\bar{z} - z_{i,j}]$$

where Z is the mean height of four points equal distance from the central point, Z_{i,j}, in a cross pattern. Using the east/west grid points to obtain distance, d cos 0 interpolated values for the north and south grid points can be calculated.

$$Z_{N}^{*} = Z_{i,j} \pm \cos \theta_{j} (Z_{i,j+1} - Z_{i,j})$$

$$Z_{S}^{*} = Z_{i,j} \pm \cos \theta_{j} (Z_{i,j} - Z_{i,j-1})$$

where Z_N^* and Z_S^* are the interpolated north and south grid point values.

$$z = (z_N^* + z_{i+1,j} + z_S^* + z_{i-1,j})/4.$$

Finite differencing will always effectively reduce the size of the grid, each application loses the boundary values and therefore the number of grid points must be chosen with this in mind. The distance between grid points using units of 5 degrees for latitude and longitude spacing gives:

Distance between latitude grid points... 560 km.

- Distance between longitude grid points at Latitude 20° ... 522 km.
- Distance between longitude grid points at Latitude 60° ... 278 km.

5.6 Input Procedures

Surface and SOOmb charts are digitised using developed software. The following fields can be calculated and displayed.

Surface
 Adjustment to 1000 mb level
 Geostrophic wind and components
 Gradient wind and components
 Geostrophic relative vorticity

b, 500 mb Geostrophic wind and components Gradient wind and components Geostrophic relative vorticity

c, Thickness (using 500 - 1000 mb levels mb levels) Thickness Thermal wind and components Thickness geostrophic relative vorticity Mean geostrophic vorticity.

Display of any of these features is possible either showing a tabular display or a colour coded image.

5.7 Indicators

The main indicators¹², for front row tion are:

a, Thermal Front Parameter (TFP). Fronts are located where the change in horizonatal temperature structure is maximum, i.e. indicated by the proximity of the temperature contours.

b. Zero line of relative vorticity at the 500 mb level.

c, Zero line of relative vorticity of the 500 - 1000 mb thickness values.

d. Zero line of the mean relative vorticity of the 500 - 1000 mb thickness.

The movement of systems may be related to the thickness flow and intensification to the slope of core of the low with height⁶, measured by the change in the position of the maximum positive relative vorticity field with height and by comparing the positive vorticity advection fields.

6. Observation

The example for diagnosis is for an area in the North Atlantic Ocean bounded by latitudes 30 and 60 degrees and longitudes 75 to 20 degrees for the 16th January 1982.

The surface chart, Fig 4, shows a depression centred, 49° N 57° W. with well established fronts. The depression is decaying (occluding) and the fields of positive relative vorticity, not shown, are coincident with the isobars.

At the 500 mb level an upper level low is centred at 59° N 58° W, Fig 5, with the maximum flow 110 km to the south showing poleward movement west of 38° W and an equatorwards component to the east. The area of maximum positive relative vorticity, 48°N 55° W, is between these two features where curvature and shear are a maximum. The line of zero vorticity is approximately in the same position as the core of the maximum flow west of 45° W. This suggests that the frontal zone (at this level, 5.5 km), is in this position. Additional indicators show positive vorticity advection within this area. East of 45° W near the ridge the zero vorticity line and the line of maximum flow separates.

The thickness chart, Fig 6s, shows the effects of the surface disturbance on the 500 mb flow as a distinct northward wedge of warm air embedded in the cold flow. The thermal wind parameter is maximum at 35° N 70° W and splits into two parts new 35° N 70° W and splits into two parts near the wedge of warm air, 40° N 52° W. The area of maximum mean relative vorticity, 50° N 58° W, is situated at the apex of the warm air wedge. The zero line of mean relative vorticity is coincident with maximum thermal winds west of the split and lies between the two thermal wind indicators to the east. Fig 6b also shows thickness but with additional indicators. These separate charts are produced for clarity. On this chart the thermal front parameter and the zero line of thermal relative vorticity indicate the boundary of the warm air within the wedge. The position of maximum positive thermal vorticity is located close to the cold front, 45° N 55° W.

Fig 7 gives the relative positions of the various frontal indicators, these can be compared with the surface analysis location. All the indicators locate the overall aspect of the depression. Higher level analysis locates the cold front behind the surface position and the warm front ahead of its surface position, as the warm air overlies the cold air to the north.

The movement of the depression is shown on Figs 4 and 6 (b), as mark 0, for the following and previous days. The lines of constant thickness tend to steer the depression and speed is related to the thermal wind, see Table II.

Pressure change over the period is also shown in Table II., Pressure falls over the period 15th and 16th January with a subsequent rise over the last twenty-four hours. This weakening of the depression was shown on the surface chart, Fig 4, and is to be expected as the indicators show little or no slope between the surface and upper level relative vorticity maxims. The upper vorticity field is 110 km to the south and 140 km to the east and ahead of the surface low.

7. Application to weather routeing

It is the middle latitude depression which in general causes the damage to ships over the main high density shipping routes. It is surely necessary for mariners to elicit full knowledge of each particular storm to assist in their management decision; making for the safety and economic benefit of the voyage.

177

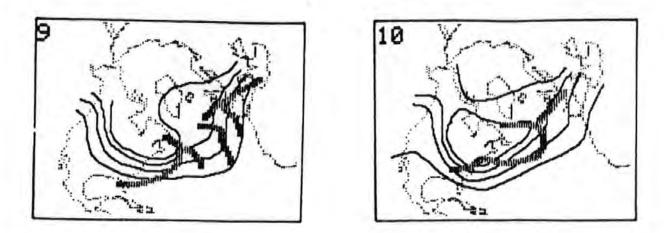


Fig 2. Picture Sequence continued, 9th and 10th January 1982

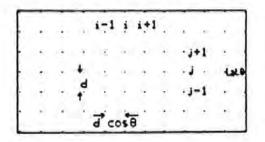


Fig 3. Finite Difference grid

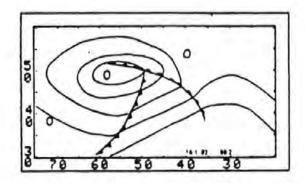


Fig 4. Surface, indicating isobars, fronts and storm movement

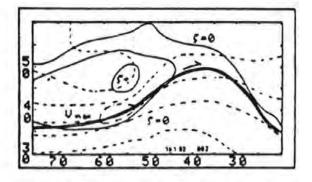


Fig 5. 500 mb level, height pecked lines

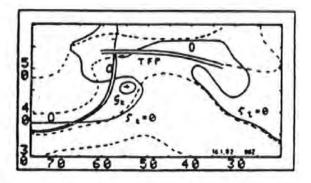


Fig 6b. 500/1000 mb Thickness pecked lines

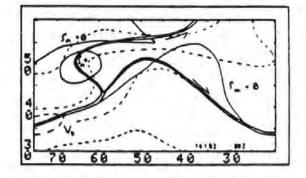
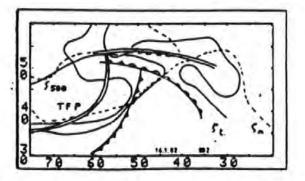


Fig 6a. 500/1000 mb Thickness pecked lines



17 Pis 7. Front Indicators

Diagnostic modelling allows for 'on the spot' analysis using simple indicators. The example chosen indicates the basic features important for voyage planning. It indicates the position of the depression; frontal location and movement with associated pressure change. Although this information is generally available on the appropriate synoptic and forecast charts for an existing depression; the diagnostic model may be used to determine the likelihood of the next depression forming, either on the trailing cold front of the last depression in the sequence or elsewhere. The use of cold front thermal diagnosis and development using vorticity fields will provide further information for the mariner. There is little point in planning to avoid a potential storm if, by the time a vessel is due in the vicinity, it has diminished to an acceptable level.

- 8. DYNAMIC PROGRAMMING
- Application of Micro-computers for weather routeing

A micro-computer may be used to generate a route or a selection of routes at the start of a voyage and, utilising current weather information.

The approach employed to the problem involves the application of Dynamic Programming to obtain an optimum route and Diagnostic modelling to obtain the longer term weather information required by the model. The criteria for optimisation initially used is minimum time. Future development will include optimisation of such factors as fuel consumption and cargo and ship safety.

It is important that the <u>relative</u> response characteristics are accurately catalogued. This is the difference in behaviour of the vessel in various sea conditions. For the purpose of model development typical performance curves have been estimated and are outlined in Figs 8A and 8. Absolute performance criteria are unimportant on relative response characteristics.

Dynamic Programming Theory applied to ship weather routeing

Dynamic Programming is a mathematical technique that can be used to make a sequence of inter-related decisions to produce an optimum result. It was developed in the 1950's by Richard Bellman and is based on his principle of optimality which stages: "An optimum policy has the property that, whatever the initial state and initial decisions are, the remaining decisions must constitute an optimum policy with regard to the stage resulting from the first decision"

To apply Dynamic Programming to weather routeing consider a grid of points in the

TABLE II DEPRES

DEPRESSION INFORMATION

Bete -82	Pasition	Pressure	Speed	*
	¥* ., 77* .	988 m	2.140	
	49" #, 54" v	955 m	31 a.s."	23 4.4
1718 40	53" =. 40" v	965 m	18.5	v"

ocean between the origin P_0 and the destination P_d .

1:19.1	Stage 2	Stage 3	Stage 6	Stage 5	
		·*21			
		."12			
	.* 22	·*33			
."12	-: 13	*74	.***	.*57	
	. 24	*35	***	*51	
	.* 15	***			
		*37			

The grid is chosen to cover the portion of ocean that is likely to contain the optimum route. In computing the optimum route the paths from each point at Stage i to every point at Stage i + 1 are considered.

Suppose the vessel leaves the origin Po at time t = 0. Its three possible courses lead If the sea condition to P11, P12 and P13. over these paths are known, then the ship speed for each of these paths can be computed from the ship performance characteristics, and the earliest times t11, t12 and t13 at which the ship can arrive at the points P11. P12 and P13 can be computed. Then consider the 15 possible courses from each point at Stage 1 to each point at Stage 2, again given the relevant sea conditions and ship performance characteristics, times for these paths can be calculated. To calculate the earliest time of arrival at each point Poy at Stage 2 the following is applied:

$$t_{2k} = \min_{j=1,2,3} \left\{ t_{ij} + T(P_{1j}, P_{2k}) \right\}$$
 8.1

That is the earliest time to get to P_{2k} is the minimum over all possible predecessor points P_{1j} of the sum of the earliest time t_{1j} to get to P_{1j} plus the time to go from P_{1j} to P_{2k} . In computing t_{2k} , the j that 179 gives the minimum indicates to point at Stage 1 which is before P2k on the shortest

route to P_{2k}. This route segment (P_{ij},P_{2k}) is recorded for use later in reconstructing the overall optimum route.

Having calculated t_{2k} for k = 1, ... 5 the 35 possible route segments from each point at stage 2 can be considered. Repeating the above procedure gives:

$$t_{3k} = \min_{j=1 \dots j} \left\{ t_{2j} + T(P_{2j}, P_{3k}) \right\} = 0.2$$

Also the route segments (P_{2j}, P_{3k}) for each of the seven points

 P_{3k} for k = 1 ... 7 are recorded. This procedure is then repeated until at the last stage the earliest time the ship can arrive at the destination is

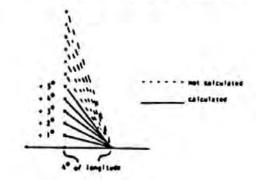
$$t_d = \min_{j=1,2,3} \left\{ t_{5j} + T(P_{5j}, P_d) \right\}$$
 8.3

Then the optimal route which achieves this minimal time can be found by working backwards through the network of points using the pairs (P_{ij}, P_i + 1, k) previously recorded at each stage.

8.3 Application to weather routeing in the North Atlantic

Dynamic Programming has been applied to ship routeing for a number of years, using a mainframe computer on shore, permitting the use of very large grids and arrays14. To implement a Dynamic Programming model on a micro-computer requires that a balance is obtained between grid size and computing capability. Development of this model has been pursued initially on a mainframe computer to enable an assessment of the data storage and handling capacity required. The model considers west bound passages in the North Atlantic¹³. defining a grid with North Atlantic¹³. defining a grid with extreme limits of 25°N to 60°N and other limits defined by the land masses. Typically a grid size of 1° of latitude by 4° of longitude has been found to be useful. For a route from the Channel Approaches to New York this implies a model with 17 stages and a maximum of 35 points on each stage. For each stage. times taken between grid points are calculated as a function of distance, forecast sea state and the ships performance. As large changes from the rhumh line between the two

points are not practical only a limited number of alternatives need be evaluated.



Taking points - 5° either side of the rhum line gives a maximum possible course divergence at each stage of approximately 55°.

An initial Dynamic Programming run is then made to find an optimal route using this rather coarse grid. Having obtained a route a second finer grid is constructed around this route, covering a divergence from the original route of up to 21° of latitude. Investigations into the optimum grid size are continuing but typically a grid size of 1/4° of latitude by 2° of longitude appears to be satisfactory. For the Channel Approaches to New York route this implies a model of 33 stages and a maximum of 21 points at each stage. Times taken between points are again calculated and a second 'fine tuning' Dynamic Programming run is made.

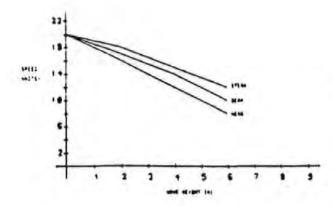
The weather information used in the model consists of two types. For the succeeding 48 hours a detailed wave height and direction information can be used provided through the standard marine facsimile channels. For longer term weather information it is proposed to employ the information given by the long term forecast 500 mb charts to predict ses areas to be avoided and it is hoped that for each sea ares a speed reduction factor can be assessed. This method of obtaining the long term weather data required by the model should provide a more realistic input than merely using seasonal averages which can frequently produce incorrect information and can never show extremes.

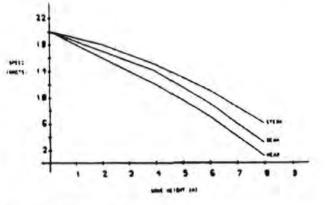
8.4 Software

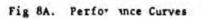
The model has been written in STANDARD PASCAL¹⁵ as this is an efficient structured language with compilers available for most microcomputers. An outline of the structure is given in Fig 11. The five modules are at present separate programs linked with data files. The modules perform the following tasks:

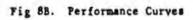
GTR - Defines the grid between departure and arrival points.

180 Calculates the grid shift vector at









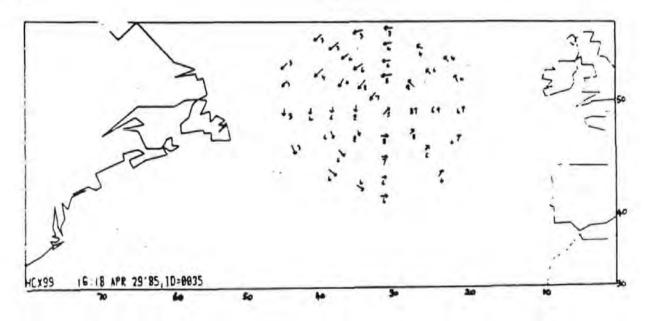


Fig 9. Simulated Sea Pattern

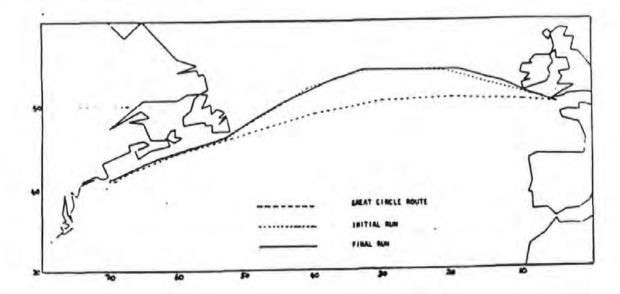


Fig 10. Optimum Route

each stage. Calculates the times required to cross between grid points.

- GDP Using the Dynamic Programming algorithm calculates a least time route.
- GTF Defines a finer grid around the route calculated by GDP. Calculates new grid shift vectors. Calculates the times required to cross between grid points.
- FGDP Using the Dynamic Programming algorithm calculates a least time route on the fine grid.
- GRA Produces a graphical output (illustrated in Fig 10)

Initial software development has taken place on a mainframe computer to give an indication of the memory and speed required from a micro-computer. Initial estimates of the software in its present configuration indicated that some 32k bytes of memory were needed for application programs and data.

The software was then transferred to a BBC micro with a TORCH extension providing 2 floppy disc drives and a second processor with 64k bytes and a CP/M operating system, providing adequate memory and suitable speed of operation.

8.5 Illustrative example

For ease of illustration, and due to editorial constraints, an idealised and limited version is given. The model has been run using an input simulated sea state pattern (Fig 9) and results compared using two representative sets of ship performance curves (Figs 8A and B).

The sea state pattern is a simplistic representation of the expected conditions resulting from a deep stationary depression centred on a latitude of 50°N and longitude 30°W. The sea crossing is from the Channel Approaches to New York, the great circle route is incorporated Fig 10.

- The following results obtained:
- Using ships performance characteristics

 (A)
 Voyage time using great circle route
 158.2hrs
 Voyage time using recommended weather route
 route
 148.1 hrs.
 Time saving = 10.1 hrs.
- (ii) Using ships performance characteristics
 (B)

Voyage time using great circle route 196.3 hrs.. Voyage time using recommended weather route = 148.1 hrs. Time saving = 48.2 hrs.

The optimum routes produced are shown Fig 10 and are the same for both sets of performance characteristics. The optimum route diverts north of the storm thus avoiding the severe head seas existing to the south of the storm .

The results demonstrate the sensitivity of the model to the ships performance in various sea states. Further research will incorporate accurate performance chara~reristics for specific vessels.

9. LI VE LOPMENT

The authors are convinced that microcomputers properly programmed and used can be invaluable in both assisting in the understanding and future development of storm activity and in route planning. This exercise can take place either on board or, assuming a suitable communications network such as TELEX, from on shore giving advice to the Ship Master.

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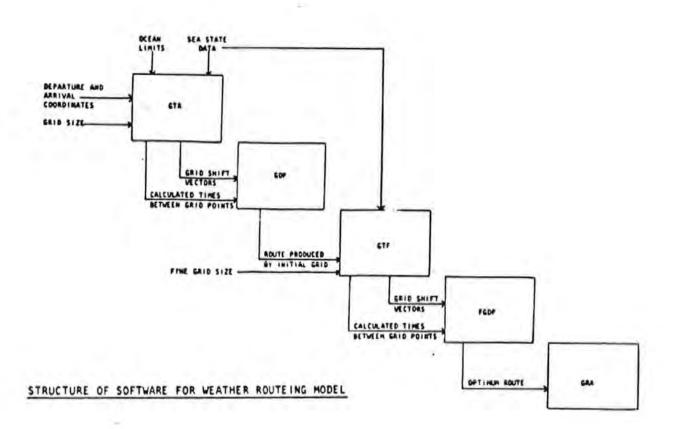


Fig 11.

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Appendix C

Communication to the UK Meteorological Office regarding the accuracy of wind fields.



POLYTECHNIC SOUTH WEST

Plymouth

Institute of Marine Studies

Department of Marine Science and Technology, Drake Circus, Plymouth, Devon PL4 8AA, United Kingdom Telephone: 0752 232410 Fax: 0752 23293 Telez: 45423 PSWAS G

The Advisory Service, Meteorological Office, Bracknell, Berhshire. 23 rd. May 1989.

Dear Sir;

I recently telephoned your office with a query regarding the accuracy of published weather charts against published balloon details or plotted observed data and it was suggested I put in writing the problem.

My interest in this area results from the construction of a diagnostic model to investigate frontal depression characteristics over the oceans. I have employed a cubic spline technique to prevent loss of boundary values and to reduce smoothing effects when using a five degree grid spacing. However in testing the performance of the model, at this stage only at the 500 mb level, certain problems have arisen in checking the wind fields (both geostrophic and gradient velocities).

I have used Met. Office fax. charts with balloon ascent data for a number of coastal stations for N.W.Europe comparing the observed values with i, individually calculated geostrophic and gradient values, ii, model geostrophic and gradient values. I have also carried out the same exercise using the European Meteorological Bulletin (German) data, these charts carry a number of plotted data models. Three cases were used such that the jet exit was cyclonic, straight and anticyclonic over N.W. Europe.

These results are summarised. Correlation coefficients for wind strength at the stations are as follows;

Chart source			Met. Office (40)	E.M.B. (25)
Cal. geostrophic	V'S	Obs.	.78	.96
Cal. gradient	¥'5	Obs	.74	.81
Cal. geos.	v's	Mode1	.80	.88
Cal. grad.	Y's	Model	.79	.76

Head of Department: Professor Roger H Motte, E.C., MS., PhD, DIC, MCIT, FRMMS



cases, producing correlation coefficients;

Cal. geostrophic v's model .94 Cal. gradient v's model .93

The differences between calculated and model output seem to be normally distributed.

I fully understand that during the construction of any chart other inputs are made, such as, satellite, aircraft, ship, buoys, plus numerical data both past and present to establish the best likely picture, this could be borne out in the results I have obtained.

My query is to ascertain whether I can obtain better basic data than the information currently available. Also whether the correlation coefficients obtained are reasonable bearing in mind the number of cases measured as I cannot find any information (MWR,Met.Mag.,QJ etc. 1963>) regarding chart verification or error analysis appertaining to this matter.

I hope you can help me,

Many thanks,

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manhon

B.J.Manhire, Senior Lecturer, Dept., Marine Science and Technology.

Appendix D

The following data were used to obtain surface and 500 mb wind errors.

Data were obtained as follows:

- i, Plotted wind fields assumed as observed data
- ii, Manual calculation of geostrophic and gradient velocities using the contours as drawn
- iii, Model output of geostrophic and gradient wind fields using digitised height and pressure fields.

The type of flow is indicated as follows:

- i, 0 straight or geostrophic flow
- ii, 1 sub-geostrophic or cyclonic flow
- iii, 2 super-geostrophic or anticyclonic flow

				Obset		Chart			1	lode:	1		
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	2011	3		Dir	F	Dir	F	Dir		Dir	F	Dir	F
4	5	45	2		•	295			31.4				
		35	ĩ						18.0				22.0
		25	2						18.1				12.0
		45	ĩ				37.8				36.0		29.0
		45	2				10.8		12.6				12.0
		45	2			140			10.8		8.0		10.
		60	ī			110		110		130	7.0		8.
		60	2			326		326	13.9				4.
		60	2			335	7.3	335		330			6.
		60	2			325		325	11.4				
		70	2			215		215		240			4.
		60	0			355		355		340	7.0		6.
		50	1				19.0		15.9			347	15.
		40	1			280	20.2	280	14.5	290		279	21.
		55	1			255		255			35.0	270	31.
		45	0			233	23.4	233			25.0	239	20.
		35	1			and the second se	15.2		25.7		19.0		23.
		25	0			310			14.0		14.0		15.
		35	0			70	3.0	70	3.1	80	5.0	80	6.
		35	2					245	16.7	242	10.0	251	10.
		35	2			215	10.2	215	12.1	251	11.0	254	16.
		65	1			294	7.1	294	6.2	314	10.0	313	8.
4	0	55	2			270	7.8	270	10.1	248	6.0	250	7.
4	5	45	0			180	14.0	180	14.0	177	11.0	166	12.
3	0	35	2			154	12.5	154	13.6	158	14.0	160	14.
4	0	40	1			300		300		297	7.0	302	5.
4	5	40	1						10.6		10.0		9.
4	5	40	2						14.1		13.0	177	16.
4	5	40	2				12.4		12.9		9.0		9.
4	5	45	2			157							21.
3	0	35				250							
4	0	35	2			140							
5	0	65	1			265							
6	0	60	1			275							
4	5	55	2			180							6.
		35	2			90			13.9		9.0		11.
		35	1			210							33.
4	5	65	1			335							
3	0	40	1			260							15.
4	0	40	1			250							21.
		55	0			320							18.
6		55	1	270		270							
5	0	45	1		20.0	205							
5	5	55		190		190		190			16.0		
4		25	2	315		315							
4	0	35	1	340	9.5	340	9.0	340	0.0	360	11.0	378	12.

si	tion	ND	ypo	bsei	rvatio	Chart	t i			lode.			
at	Long		-			GEOS		GRAD		SEOS		GRAD	
				Dir	F	Dir	F	Dir	F	Dir	F	Dir	F
4	5 6	5	1	10.77			44.3			304	40.0	308	52.
4		5	1			245	22.9			242	28.0	242	16.
4		5	1				20.2		18.1		20.0		
4		5	2			180	12.1		13.5		10.0		10.
3		ō	1				16.2		14.6				15.
4		õ	ī			193			11.8	200		200	7.
5		õ	2				19.8		27.4		18.0		
6		ŏ	2			225			30.7		33.0		
4		5	1			238			36.3				
4		5	ō						46.0				
									37.0				
4		5	2			292							25.
4		5	2			310	32.7		38.3				
3		5	1				13.9		13.1		13.0		13.
4		5	2				19.4		23.5		21.0		24.
5		5	2			283		100 100 100 100	50.7		28.0		33.
6		5	1			255	9.4		8.4	241			11.
4		0	1				17.2		14.2				
4	5 5	0	1						25.0				
4	5 4	0	1						35.4				
3	5 6	0	1			260	30.3	260	27.5				
5	5 6	0	2			295	8.5	295			10.0		
2	5 6	0	2			255			16.0				
4	5 4	5	1			224	42.9	224	36.5	220	47.0	230	39.
4		5	2			252	17.2	252	25.0	250	22.0	250	24.
4		5	2				31.2		37.3	310	29.0	330	31.
5		5	0			195	28.3		28.3		33.0		
3		5	2			215	18.8		20.7		14.0		
3		5	ō			200	6.1			220	8.0		8.
4		5	õ			268	37.8	268	37.8		34.0		
4		5	õ			282		1 million (1 mill			33.0		36.
4		5	1			265			22.3				
2		0	2			325	9.6		10.5			351	8.
		0				280	32 6		28.7				
3			1			200	22.0	283	17.1	272	24 0	281	19
4		0	1						18.8				
5		0	1	-	25	240	22.0	240	33.0	234	24.0	274	51
4		0	2	295									
3		5	2	320			18.3		22.0				
5		5	2		17.5				29.8		6.0		8.
5		0	1	185					24.7				
6		5	2	270					32.1				
5		5	1		15	315	14.1	315	12.2				
3		0		260					13.7				
4	5 5	5	1	235					35.0				
3	5 3	0	2	335					15.7				
3	5 1	5	1	270					22.7				
3		5		260	20	260	19.4	260	20.0	251	18.0	250	17.

Appendix E

The following Basic programmes were used in this project:

i, programme for data input and manipulation

ii, programme for field estimation - the diagnostic model

DATA INPUT PROGRAMME

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18 REN DOTO
 14 CALL - 936: UTAB 16: PRINT "PROBRON FOR DATA INPUT"
 16 FOR HT - O TO 39: PRINT "." HENT HT
 18 FOR HT - @ TO LODO: NEXT HT
 28 Ds = CHR$ (13) + CHR$ (4)
 29 DIM HK 13.11 > DIM T(11.9)
 20
    01H Z(11.9).P(11.9).HP(11.9).TH(11.9)
 31 DIM (K 11.9): DIM (K 11.9): DIM HOK 11.9)
 32 DIH HHK 11.9)
 14 GOTO 100
 35 PRINT DE . CATRLOS" I BET AS
 36 CALL - 936: VTAB & PRINT "CHORT NONE"
 37 PRINT & INPUT HS
 38 PRINT : PRINT : PRINT "CHART DATE ": PRINT : PRINT : INPUT D
 39 04 . STRS (D):CS . HS + OS: CALL - 936
 48 PRINT DS. "OPEN" .C.
    PRINT "LORDING "INS
 41
    PRINT DO, "READ" .CS
 42
    INPUT HE
 47
    INPUT JY: INPUT IX: INPUT SP
 48
    INPUT JI: INPUT II: INPUT J2: INPUT 12
 SO FOR J = JI TO J2
 50 FOR I = [] TO 12
 75 INPUT H(1.J)
 77 GOSUB 178
    NEXT II NEXT J
 88
 90
    PRINT DS . "CLOSE" .CS
 91 RETURN
 92 CALL - 936: PRINT : PRINT DE, "CATALOS": GET AS
 93 CALL - 936: PRINT "LOCATION OF BOTTOM LEFT GRID POINT"
 94 PRINT "LAT "I INPUT JV
 95 PRINT "LONG "I INPUT IX
 96 J = 0:1 = 0:5P = 5
97 Y = SP + J + JYIX = 1X - SP + 1
 98 JI = 0:11 = 0:J2 = 8:12 = 10
99 RETURN
100 CALL - 936: UTAB 4: PRINT "HENU"
181 FOR HT = 8 TO 39: PRINT "-" JI NEXT HT
182 PRINT : PRINT "1...NEN": PRINT : PRINT "2.. ALTER": PRINT : PRINT "3...O
     ISPLAY"
183 PRINT : PRINT "4., RECALL DATR": PRINT : PRINT "5., SAVE DATA": PRINT :
      PRINT "6... ADD DATA"
184 PRINT & PRINT "7 ... SURFACE ADJUSTMENT"
    PRINT : PRINT "8.. WARTOUS"
105
100 PRINT : PRINT "9.. OUIT"
109 PRINT : PRINT : INPUT A: CALL - 936
110 IF A . 6 THEN GOTO 200
111 IF A = 1 THEN GOTO 898
112 IF A . 3 THEN
                   60T0 388
114 IF A = 4 THEN
                   60SUB 35
116 IF A . 7 THEN
                   60T0 988
117 IF A . 8 THEN
                   80T0 1088
118 IF A = 5 THEN GOSLIB 488
119 IF A = 9 THEN GOTO 999
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128 IF A = 2 THEN GOTO 124 121 60TO 188 124 PRINT "WHAT POSITION" 125 PRINT : PRINT 130 INPUT Y.X 148 J = (Y - N) / SPII = (IX - X) / SP 142 CALL - 936: PRINT "VALUE STORED IN FILE" 143 PRINT : PRINT : PRINT "LAT", "LONG", "HE" 145 PRINT : PRINT Y.X.HKI.J) 150 PRINT : PRINT : PRINT Y.X. PRINT : PRINT 155 INPUT H(L.J) 168 GOTO 108 170 IF NO = "HEIGHTS" THEN Z(I.J) = H(I.J) 171 IF HI = "PRESSURE" THEN P(1,J) = H(1,J) 172 IF HE - "THICKNESS" THEN THE I.J) - HEL.J) 173 IF NS - "THOUS" THEN HP(1.J) = H(1.J) 174 IF NE . "TEMP" THEN T(1,J) . H(1,J) 176 IF HE = "HINDU" THEN UK I.J) = HK I.J) 177 IF NO . "HINDU" THEN U(1,J) = H(1,J) 178 IF HE - "DIRECTION" THEN HOLL,J) - HEL.J) 100 IF TE = "FIRST TERM" THEN T(1.1) = H(1.1) 182 IF TO . "SECOND TERH" THEN P(1.) . W(1.) 184 IF HE . "THY" THEN T(I,J) - H(I,J) 186 IF HS = "THOR" THEN T(I,J) = H(I,J) 190 RETURN 200 CALL - 936: PRINT "WHAT POSITION": PRINT : PRINT : PRINT : 218 INPUT Y.XI CALL - 936 228 JJ = (Y - JV) / SPIII = (IX - X) / SP 225 FOR J = JJ TO J2: FOR I = II TO 12 230 IF I . 12 THEN II . 0 241 Y = SP + J + JN1X = IX - SP + I 245 CALL - 9361 PRINT "LAT ".Y." LONG "JX 250 PRINT : PRINT : INPUT H(1.J) 255 IF H(1,J) = 9999 THEN H(1,J) = 0 258 IF HKI.J) - 8 THEN 60TO 108 260 NEXT II NEXT J 270 GOTO 100 3330 CALL - 936: VTRE 6: PRINT "DISPLAY FORMAT" 382 FOR HT . O TO 391 PRINT "-" II NEXT HT 385 PRINT : PRINT "1.. TABLE": PRINT : PRINT "2. CHART" PRINT : PRINT "3. COLOR CHART" FOR HT = 0 TO 39: PRINT "-" IT HEXT HT PRINT "CHORT HOME "INSI" DATE "ID 307 308 PRINT "NONTH AND YEAR "INS 389 PRINT I PRINT "LEFT BOTTON CORNER " . NI" "ITX 310 PRINT : PRINT : INPUT B 311 CALL - 936: IF 8 - 1 THEN 60TO 315 312 IF B = 2 THEN GOTO 600 313 IF 8 = 3 THEN 80TO 588 315 PRINT & PRINT & PRINT *DISPLAY SPEED** PRINT & PRINT & PRINT & IMPUT HHT: CALL - 936 318 PRINT I PRINT I PRINT "LAT". "LONG" .NS 320 FOR J = J1 TO 12 325 PRINT : FOR HT = 8 TO HHT: HEXT HT

338 FOR 1 - 11 TO 12 340 PRINT SP + J + JW.IX - SP + [.H(1.J) 345 FOR HT = 0 TO HHT: NEXT HT 350 NEXT II NEXT J 398 60TO 168 400 CALL - 936: UTAB 6: PRINT " SAVE DATA" 405 INPUT "HONE "INS 418 PRINT : IMPUT "DATE "ID 428 PRINT : INPUT "HONTH AND YEAR 448 Q4 = STR\$ (0):C8 = H8 + D8 445 PRINT "SAVING "INS 459 PRINT DS+"OPEN".CS 460 PRINT DS;"HRITE",CS 478 PRINT HS 472 PRINT JVI PRINT IXI PRINT SP 474 PRINT JII PRINT ILI PRINT JZI PRINT 12 475 FOR J = J1 TO J2 476 FOR 1 = 11 TO 12 477 PRINT HK [.J) 478 NEXT II NEXT J 498 PRINT DA, "CLOSE",CO 498 RETURN 500 CALL - 936 PRINT "INPUT RANGE": INPUT OO 510 528 PRINT : PRINT "INPUT GRADUATION": INPUT O 532 68 534 FOR J = 36 TO 4 STEP - 4 FOR I - . TO 30 STEP 3 536 538 CC = - HKI / 3.(J - 4) / 4) + 00 540 C = INT (CC / 0) 550 COLOR= C PLOT 1,36 - JI PLOT 1 + 1,36 - JI PLOT 1 + 2,36 - J 552 554 PLOT 1.37 - J: PLOT I + 1.37 - J: PLOT I + 2.37 - J PLOT 1.38 - JI PLOT I + 1.38 - JI PLOT I + 2.38 - J 556 558 PLOT 1.39 - J: PLOT 1 + 1.39 - J: PLOT 1 + 2.39 - J 560 NEXT II NEXT J 565 FOR SC = 0 TO 15 578 COLOR- SCR 575 PLOT SCA + 4.39: NEXT SCA 5.99 PRINT "POSITIVE NEGATIVE" 597 GET AR: CALL - 936: TEXT : GOTO 199 600 CALL - 936 SIO PRINT "NOME "ING." DATE "ID 615 PRINT : PRINT HS 619 FOR I . II TO 12 620 TP = 1X - SP = 1 625 IF TP > = 100 THEN TP = TP - 90 638 PRINT " TPA 640 NEXT I 650 FOR J = J2 TO J1 STEP - 1 678 PRINT : PRINT 688 FOR I - I1 TO 12 682 DIS(1,J) = H(1,J)

682 015(1,J) = H(1,J) 685 IF H(I,J) > = 188 THEN 015(I,J) = H(I,J) - (100 + INT (H(I,J) / 100 587 IF H(1,J) (- - 100 THEN DIS(1,J) = H(1,J) - (100 + INT ((H(1,J) + 100) / 100)) 690 IF DIS(1.J) > = 10 THEN 700 692 IF DIS(1,J) > = 0 THEN 704 693 IF DIS(1,J) (= - 18 THEN 708 694 IF DIS(1,J) (= 0 THEN 786 PRINT * "+DIS(1+J)++ 60TO 745 796 PRINT . "JOIS(I.J)J GOTO 745 704 PRINT - "+015(1+J)+1 60T0 745 706 788 PRINT DIS(1.J) .. GOTO 745 745 NEXT II HEXT J GET ASI CALL - 936: 6010 100 750 768 CALL - 936: PRINT : PRINT 765 PRINT "NUMBER OF HOR. GRID POINTS" 778 PRINT I INPUT NH PRINT "NUMBER OF VERT. GRID POINTS" 773 790 PRINT : INPUT NU PRINT : PRINT "DIFF. IN LONG BETWEEN GRID POINTS": INPUT O 798 GOTO 100 795 PRINT " TO CONSTRUCT A NEW CHART DATA IS INSERTED AT ORID POINTS ON P 666 ROMPT, THERE ARE 11 IN THE EAST HEST SPACED AT 5 DEGREE INTERNALS AND 9 FOR LATITUDE ALSO SPACED AT 5 DEGREES." 818 PRINT I PRINT "ENTER STARTING POINTS FOR THE CHART, AT THE BOTTOM LEFT HAND CORNER , LATITUDE THEN LONGITUDE .. 840 FOR HT = 8 TO 10000: NEXT HT: CALL - 936 844 PRINT I PRINT I PRINT "HAME OF CHART"I INPUT HS 946 PRINT I PRINT I PRINT "CHART DATE": INPUT DI CALL - 936 852 PRINT "HHAT LATITUDE ?" INPUT N 854 PRINT : PRINT "WHAT LONGITUDE ?" INPUT IX 856 PRINT : PRINT : PRINT "INPUT HEIGHT HALVES ON PROMPT" 858 SP = 51.11 = 0111 = 01.12 = 8:12 = 10 960 FOR J = J1 TO J2 962 FOR I . II TO 12 864 V = SP = J + JVIX = IX - SP = I 866 PRINT "LAT" Y' LONG" X 968 INPUT HK [, J) 872 IF HK [, J) = 9999 THEN GOTO 882 898 NEXT I: NEXT J 982 FOR J = J1 TO J2: FOR 1 = 11 TO 12 884 IF HK [, J) = 9999 THEN HK [, J) = 0 886 IF H(1.J) = 1 THEN H(1.J) = H(1 - 1.1) 998 NEXT 1: NEXT J: 6010 108 998 CALL - 936 918 PRINT "1 SURFACE ADJUSTMENT" 928 PRINT : PRINT "2 THICKNESS" INPUT 6 930 935 IF 6 - 2 THEN GOTO 988 940 FOR J = JI TO J21 FOR I = 11 TO 12 945 HP(1,J) = 100 + (P(1,J) - 1000) / (9.81 + 1.25) 960 NEXT II NEXT J

962 FOR J = JI TO J2: FOR I = 11 TO 12 964 H(I.J) = INT (HP(I.J)) / 10 967 NEXT II NEXT J 979 6010 109 900 CALL - 936 982 FOR J = J1 TO J2: FOR I = 11 TO 12 985 THK 1.J) = Z(1.J) - HP(1.J) 990 NEXT II NEXT J 992 FOR 1 = J1 TO J2: FOR 1 = 11 TO 12 994 H(1,J) = INT (TH(1,J) + 0.5) 998 NEXT I: NEXT J: 6010 100 999 END 1000 CALL - 936 1001 PRINT "7 ... OU-DZ ETC" 1002 PRINT "1 ... TEMP FROM THICKNESS" 1883 PRINT "2... SURFACE FRICTION ALLON " 1004 PRINT "3 ... 3HAV HEAN " 1005 PRINT "4 ... NATH FUNCTIONS " 1006 PRINT "S...NET DIVERG" 1007 PRINT "6 ... NOME CHONGE" I INPUT HI 1008 IF HI = 2 THEN 8010 1838 1989 IF HI = 3 THEN 60TO 1588 1010 IF HI = 4 THEN GOTO 1400 1011 IF HI = 5 THEN 00TO 1350 1812 IF HI = 6 THEN 00TO 1720 1013 IF HI = 7 THEN 60TO 1889 1014 H(1,J) = .49313 + H(1,J) 1015 FOR J = J1 TO J21 FOR I = 11 TO 12 1018 H(1,J) = .49313 + H(1,J) 1020 NEXT IN NEXT J 1025 6010 100 1030 REN FRICTION 1034 PRINT "RECALL SURFACE HINDOS" 1035 INPUT " DATE "+0 1848 HS = "HINDU": 805UB 39 1842 N# = "HINDU": 605UB 39 1944 NS = "DIRECTION": 605UB 39 1060 FOR J = J1 TO J2 1961 FOR I . II TO 12 1062 IF HO(1.J) = 100 THEN HO(1.J) = 360 1063 IF HO(1,J) > 100 THEN HO(1,J) = HO(1,J) - 100 1964 IF HO(1,J) (180 THEN HO(1,J) = HO(1,J) + 180 1965 H(L.J) = HD(L.J) - 10 1066 IF HO(1,J) > 368 THEN HO(1,J) = HO(1,J) - 368 1067 IF HOX [, J) (0 THEN HOX [, J) = HOX [, J) + 368 1079 H(I.J) = HD(I.J) - 10 1072 NEXT II NEXT J 1875 0 = 0 + 0.01 1080 FOR J = J1 TO J2 1081 FOR I = I1 TO 12 1090 R90 = 57.31895 H([,J) = (2 + U(1,J) + SIN ((HO(1,J) - 18) / RAD)) / (3 + SIN ((HO(1. J) / RAD))) 1100 NEXT L: NEXT J

1105 N# = "HINOU": GOSUB 440 1130 FOR J = JI TO J2 1132 FOR I . II TO 12 1134 890 = 57.3 1150 H(1,J) = (2 + U(1,J) + COS ((HO(1,J) - 10) / R00)) / (3 + COS ((HO(1.J) / RAD))) 1160 NEXT LI NEXT J 1180 N# = "HINOU": 605UB 440 1199 6070 108 1280 REM HIND RECALL 1205 INPUT "SURFACE WIND DATE "10 1287 H# = "HIHOU": 605U8 39 1210 INPUT "SOO HIND DATE "ID 1215 N# = "WINDU": 805UB 39 1228 FOR J = J1 TO J21 FOR I = 11 TO 12 1222 V = N + (SP + J) 1223 RAD = 57.3:F = (44 + SIN (V / RAD)) / (7 + 24 + 3680) 1225 H(1.J) = - U(1.J) + U(1.J) 1227 H(1.J) . F . H(1.J) 1230 NEXT I: NEXT J 1235 NE = "C+1": INPUT "DATE "JD: GOSUE 448 1250 IMPUT "SURFACE HIND DATE "+D 1255 N# - "HINOU": 605U8 39 1268 INPUT "SOO HIND DATE "JD 1265 Hs - "HINDU": 805U8 39 1298 FOR J = J1 TO J21 FOR I = 11 TO 12 1282 V . JV + (SP . J) 1283 RAD = 57.31F = (44 + SIN (Y / RAD)) / (7 + 24 + 3680) 1285 H(I.J) = U(I.J) + U(I.J) 1287 H(1.J) = F + H(1.J) 1298 NEXT II NEXT J 1295 N# = "C+2": INPUT "DATE "ID: GOSUB 448 1299 60TO 100 1300 REM RECALL TERMS 1382 PRINT "FORMAT FIRST-SEC OR FIRST/SECOND" 1385 INPUT "FIRST TERM "INS 1306 TE = "FIRST TERM" 1387 INPUT "FIRST TERM DATE "+D 1388 60508 39 1310 INPUT "SECOND TERM "INS 1311 IF NS . "CONSTRNT" THEN GOTO 1316 1312 TA . "SECOND TERM" 1314 INPUT "SECOND TERM DATE "ID 1315 GOSUB 391 GOTO 1340 1316 INPUT "CONSTRANT "IC2 1317 FOR J = J1 TO J2: FOR I = 11 TO 12 1318 P(1,J) = C2 1320 NEXT I: NEXT J 1348 RETURN 1350 REM NET DIV 1355 60SUB 1398 1368 FOR J = J1 TO J2: FOR I = 11 TO 12 1362 H(1,J) = T(1,J) + P(1,J) 1365 IF T(1,J) > 0 AND P(1,J) > 0 THEN LET H(1,J) = (T(1,J) + P(1,J)) / 2

(370 IF T(1, J) (0 AND P(1, J) (0 THEN LET H(1, J) = (T(1, J) + P(1, J)) / 1592 IF I = 0 THEN GOTO 1685 2 1300 MEXT II NEXT J 1398 8070 1468 1408 CALL - 936 1401 PRINT "3... HEAN" 1402 PRINT " 4 ... 900 " 1403 PRINT - 5... SUBTRACT 1404 PRINT " 6 ... MULTIPLY" 1405 PRINT * 7 ... DIVIDE" 1486 INPUT HI 1409 INPUT "HINUS YAN "JFS 1418 60508 1388 1428 FOR J = J1 TO J2: FOR I = 11 TO 12 1425 IF HI = 4 THEN HK [. J) = T(1, J) + P(1, J) IF HI = 5 THEN HKI.J) = T(I.J) - P(L.J) 1430 1432 IF HL = 6 THEN HK (....) = T(1...) = P(1...) 1436 IF HI = 7 THEN H(1,J) = T(1,J) / P(1,J) 1448 IF HI = 3 THEN H(1,J) = (T(1,J) + P(1,J)) / 2 1445 IF FE = "Y" THEN H(1,J) = - H(1,J) 1458 PRINT J.I 1460 PRINT P(1,J),T(1,J); PRINT H(1,J) 1470 NEXT II NEXT J 1480 INPUT "CHART NAME "INS 1498 PRINT NE: INPUT "DATE ":D 1495 GOSUB 448 1499 60TO 100 REN HEAN 1580 INPUT "CHART NAME "INS 1510 INPUT "CHART DATE "10 1520 60SU8 39 1530 1535 UR1 = HK8.8> 1537 FOR J = J1 TO J2: FOR I = 11 TO 12 1540 IF H(I,J) (URI THEN URI = H(I,J) 1542 PRINT URL 1545 NEXT II NEXT J 1550 INPUT "REQ CONSTRAT" JURI 1555 FOR J = JI TO J2 1557 FOR 1 - 11 TO 12 IF J = 0 THEN GOTO 1696 1558 1559 IF J . 8 THEN GOTO 1696 1568 IF I = 8 THEN 60TO 1696 1561 IF I = 18 THEN 80TO 1696 1564 6070 1688 1565 H(11,J) = H(0,J):H(12,J) = H(10,J) 1578 H(1,9) = H(1,0)(H(1,10) = H(1.8) IF J = 0 AND I = 0 THEN 90TO 1655 1500 1592 IF J . O AND I . O THEN GOTO 1660 IF J . 8 AND I . 8 THEN 60TO 1665 1584 IF J = 8 AND I = 10 THEN 60TO 1678 1586 IF J . @ THEN GOTO 1675 1588 1598 IF J . 8 THEN GOTO 1698

1594 IF I = 10 THEN GOTO 1698 1600 PRINT 1640 TTTT + H(1 - 1.J) + H(1 + 1.J) + H(1.J + 1) + H(1.J - 1) 1645 PRINT TTTT.HK [....) 1652 T(1,J) = (UAA + H(1,J)) / (HAA + (TTTT / 4)) 1653 T(1.J) = 100 + T(1.J): PRINT T(1.J) 1654 6010 1698 1655 TTTT = ((H(11.J) + H(1 + 1.J) + H(1.J + 1) + H(1.9)) / 4) 1656 T(1.J) = (H(1.J) - TTTT) / TTTT 1657 GOTO 1698 1668 TTTT = ((HK I - 1.J) + HK 12.J) + HK 1.J + 1) + HK 1.9)) / 4) 1661 T(1.J) = (H(1.J) - TTTT) / TTTT 1662 6010 1698 1665 TTTT = ((H(11.J) + H(1 + 1.J) + H(1.18) + H(1.J - 1)) / 4) 1666 T(1,J) = (H(1,J) - TTTT) / TTTT 1667 GOTO 1698 1670 TTTT = ((H(1 - 1.J) + H(12.J) + H(1.10) + H(1.J - 1)) / 4) 1671 T(1,J) + (H(1,J) - TTTT) / TTTT 1672 GOTO 1690 1675 TTTT = ((H(I - 1.J) + H(I + 1.J) + H(I.J + 1) + H(1.9)) / 4) 1676 T(1,J) . (H(1,J) - TTTT) / TTTT 1677 GOTO 1698 1680 TTTT = ((H(1 - 1,J) + H(1 + 1,J) + H(1,10) + H(1,J - 1)) / 4) 1681 T(1.J) . (H(1.J) - TTTT) / TTTT 1682 GOTO 1698 1685 TTTT = ((#(11,J) + #(1 + 1,J) + #(1,J + 1) + #(1,J - 1)) / 4) 1686 T(1,J) . (H(1,J) - TTTT) / TTTT 1687 6010 1698 1690 TTTT = ((H(1 - 1.)) + H(12.) + H(1.) + 1) + H(1.) - 1)) / 4) 1592 T(1.J) = (H(1.J) - TTTT) / TTTT 1696 T(1,J) = 0 1690 NEXT II NEXT J 1699 FOR J = JI TO J2: FOR I = 11 TO 12:14 (.J) = T(1.J): HEAT I: HEAT J INPUT "HAME" INSI INPUT "DATE" ID: GOSUB 448 1700 1785 60T0 189 INPUT " CHART NAME "INS 1720 INPUT " CHART DATE "+D 1730 60508 39 1740 1750 INPUT . NEW NAME "INS INPUT " DATE "JD 1760 60SU8 448 1770 6010 100 1790 REH DU/DZ 1000 CALL - 936 1805 INPUT "THICK HANE "JHS 1810 INPUT "CHART DATE "+0 1820 60SU8 39 1830 INPUT "THICK IN Y "INS 1840 INPUT "CHART DATE "10 1050 60SUB 39 1860 FOR J = J1 TO J2 1865 1870 FOR 1 = 11 TO 12

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1865 FOR J = J1 TO J2
1870 FOR 1 - 11 TO 12
1000 V . SP . J . JVIX . IX - SP . I
1882 ROD = 630 / 11
1884 8 = 9.81
1896 F = 4 + 22 + SIN (Y / RRD) / (7 + 24 + 68 + 68)
1090 UZ = - (6 + T(1,J)) / (F + TH(1,J))
1895 H( I.J) = UZ / 18
1900 NEXT II NEXT J
1905 HS = "UZ"
1918 GOSUB 448
1920 INPUT "THICK IN X "INS
1930 INPUT "CHART DATE "ID
1935 GOSUB 39
1940 FOR J = J1 TO J2
1945 FOR I - I1 TO 12
1950 Y = SP + J + JVIX = IX - SP + 1
1952 RRD = 630 / 11
1954 6 . 9.81
1556 F = 4 + 22 + SIN (V / MAD) / (7 + 24 + 68 + 68)
1968 UZ = (6 . T(1,J)) / (F . TH(1,J))
1978 HK 1.J) - UZ / 10
1990 HEXT II NEXT J
1985 HE - "UZ"
1998 60908 448
2000 0010 100
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x

DIAGNOSTIC MODEL PROGRAMME

5 PRINT "DATE 161... 16TH. SECT 1. 500" 6 PRINT "DATE 161.1.16TH.SECT 1.1000" 98 RETURN 7 PRINT "DATE 161.2.16TH.SECT 1.THICK" 99 TEXT 100 CALL - 9361 UTAB 3: PRINT "HENU": FOR HT - 0 TO 391 PRINT "-"11 HENT 8 GET AS 9 NO = .25 HT 101 PRINT I PRINT "1 ... ZONAL HIND COMPONENTS" 10 REH FIELDS PRINT : PRINT "2... HERIDIONAL HIND COMPONENTS" 11 RAD = 630 / 11:6 = 9.81 102 PRINT : PRINT "J ... DISPLAY" 12 CALL - 936: FOR HT . 8 TO 39 103 PRINT : PRINT "4 ... RECALL DATA" 14 UTAB 10: PRINT "O" IS NEXT HT 184 PRINT & PRINT "5 ... SAVE DATA" 16 PRINT "PROGRAM TO PRODUCE FIELDS" 105 PRINT : PRINT "6 ... RATES OF CHANGE" PRINT : PRINT "7 ... UORTICITY ETC" 18 FOR HT . & TO 39: PRINT "#"# HEXT HT 106 19 FOR HT - @ TO 10001 NEXT HT 107 PRINT : PRINT "8 ... VELOCITY": PRINT : PRINT "9 ... QUIT" 20 DS + CHRS (13) + CHRS (4) 108 21 DIN 01(11.9): DIN 02(11.9): DIN 03(11.9): DIN 04(11.9) PRINT : PRINT : INPUT A: CALL - 936 109 22 DIM TX(11.9): DIM TX(11.9) 110 IF A = 6 THEN BOTO 790 23 DIH HX(11,9): DIN HX(11,9) IF A = 1 THEN GOTO 200 111 IF A . 3 THEN GOTO 380 24 DIM 0(11,9); DIM ADU(11,9); DIM SIP(11,9) 112 DIN VIVICIIN DIN VZVT(11) DIN T(11.9) 113 IF A . 4 THEN 29 . A 25 26 DIM ZO(13): DIM NO(13): DIM EO(13) 114 IF A = 4 THEN BOTO 35 116 1F A . 7 THEN GOTO 1200 27 DIM VIX(11.9): DIM U2W(11.9) 117 IF A = 8 THEN GOTO 382 28 DIN XBX(13) DIN YBY(13) DIH X00(13): DIH YW(13): DIH 2.6(2) 118 IF A = 5 THEN BOTO 488 29 DIN 2(11.9): DIN U(11.9): DIN U(11.9): DIN U(X(11.9): DIN U2W(11.9) 119 IF A = 9 THEN 90TO 999 70 120 CALL - 936 31 DIM HK 11.9) DIM DIS(11.9) 121 INPUT " HX .. THX OR THOUSK "INC 32 DIM HO(11.5): DIM UB(11.5): DIM UB(11.5) 123 INPUT "DATE "JD: 609UB 1215 DIM 0% 11,9>: DIM 08(11,9): DIM 07(11.9): DIM 08(11.9) 13 124 FOR J = JI TO J2 34 60TO 100: CALL - 936 125 FOR 1 = 11 TO 12 35 PRINT D&"CATALOS": GET AS 127 8010 145 CALL - 936: UTAB & PRINT "TYPES OF CHART": FOR HT - & TO 39: PRINT " 138 Y = SP + J + JVIX = 1X - SP + 1 -"JI NEXT HT 132 RAD = 630 / 11 PRINT : PRINT : PRINT "HEIGHTS, PRESSURE, THICKNESS, THOUS. , TENP. , " PRINT 135 X8X(1) = X: VBW(1) = 2(1,J) I PRINT "HIND. UORTICITY" 140 NEXT I PRINT : INPUT "CHORT NONE "INS 39 PRINT : INPUT " 141 X8X(11) = X8X(@) + SP1X8X(12) = X8X(10) - SP DATE "+01 60TO 42 142 YBY(11) = YBY(0): YBY(12) = YBY(10) 42 08 = STRS (0)+C8 = H8 + Q8+ CALL - 936 143 005UB 2100 44 PRINT DS; "OPEN" .CS 144 FOR CS = 11 TO 12:1 = CS 45 PRINT DE ."READ" .CE 145 RRD = 630 / 11:6 = 9.81 INPUT HS 46 146 Y = SP + J + JVIX = IX - SP + IIF + 4 + 22 + SIN (V / RAD) / (7 + 24 + INPUT JY: INPUT IX: INPUT SP 47 INPUT J1: INPUT I1: INPUT J2: INPUT 12 68 . 68) 48 FOR J = JI TO JZ 147 U([,J) = (6 / F) + HOK([,J) + 10 60 FOR I - 11 TO 12 148 H(L,J) = ((L,J) 75 INPUT HKI.J) 150 NEXT 1 605UB 162 152 NEXT J 76 NEXT I: NEXT J 160 60T0 100 162 IF NS = "THOUSK" THEN LET HX(I,J) = H(I,J) 83 PRINT OF "CLOSE".C# 163 IF HE . "THOUSY" THEN LET HW I, J) . HI I, J) 84 IF A = 4 THEN 80TO 91 164 IF HE . "THK" THEN LET HOK (1, J) . HK (, J) 91 6010 168 165 IF HE . "THY" THEN LET HW(1,J) . HE 1,J) 32 PRINT "LOCATION OF THE BOTTOM LEFT GRID POINT* 94 PRINT "LAT "I INPUT JY 166 IF HE . "H2. HOK" THEN LET TX(1.J) . H(1.J) 95 PRINT "LONG "I IMPUT IX 167 IF NS . "HS. HWY" THEN LET TWI.J) . HILJ) 168 IF NS . "THX" THEN LET TX(1.J) . W(1.J) 96 J = 0:1 = 0 169 IF NS . "THY" THEN LET TWI, J) = H(1, J) 97 Y = SP + J + JVIX = [X - SP + 1 170 IF HS = "HEIGHTS" THEN Z(1,J) = H(1,J) · ·) = #(1,J)

439 PRINT JL: PRINT IL: PRINT J2: PRINT 12 440 FOR J = JI TO J2 450 FOR I = I1 TO 12 460 PRINT H(I.J) 470 NEXT LI NEXT J 499 PRINT DE . "CLOSE" .C. 482 IF A . 6 THEN GOTO 828 484 IF A . 7 THEN BOTO 1485 489 IF A = 8 AND AR = 2 THEN BOTO 8885 498 IF HS - "GRAD VEL" THEN BOTO 1588 491 IF A = 8 AND AA = 1 THEN GOTO 1850 495 6010 168 500 CALL - 936 502 IMPUT "FACTOR "JP 503 PF = 1 / (10 ~ P) 305 PRINT PF 510 INPUT . HAXINUM VALUE "HU 512 00 - HU . PF 515 PRINT 520 INPUT "GRADUATION INTERVAL "+6 525 Q = 6 + PF 532 GR 534 FOR J = 36 TO 4 STEP - 4 536 FOR 1 = 0 TO 30 STEP 3 538 C = INT ((00 - HK(1 / 3),(J - 4) / 4)) / 0) 558 COLOR= C 552 PLOT 1.36 - J: PLOT 1 + 1.36 - J: PLOT 1 + 2.36 - J 554 PLOT 1.37 - JI PLOT I + 1.37 - JI PLOT I + 2.37 - J 556 PLOT 1.38 - JI PLOT 1 + 1.38 - JI PLOT 1 + 2.38 - J 558 PLOT 1.39 - J: PLOT 1 + 1.39 - J: PLOT 1 + 2.39 - J 568 NEXT II HEAT J 565 FOR N . 8 TO 38 STEP 2 567 SC = N / 2 578 COLOR= SC 575 PLOT N. 391 NEXT H 580 FOR H = 1 TO 15 STEP 2 584 NR = INT ((00 - (N + 0)) / PF) 565 IF HA > 99 THEN LET HA . INT (HA / 18) SHE PRINT NRA" "+ 390 NEXT N 593 PRINT : PRINT "X" PF 597 GET ANI CALL - 936: TEXT : 60TO 189 SOU CALL - SIGI PRINT "1 HEIGHTS AND HINDS": PRINT : PRINT "2 UDRTIC ITY": PRINT : PRINT "3 ... URRIOUS ": PRINT : INPUT ABC SOI IF HS - "VORTICITY2" THEN LET HO - 1ES 582 IF ABC = 3 THEN 90TO 728 GR3 PRINT 684 PRINT HSI" "ITOI" DATE "I INT (0 / 18): PRINT HO 685 IF ABC - 1 THEN 80TO 618 GAG IF HE . "VORTICITY" THEN LET HO . IES 510 FOR J = JI TO J21 FOR I = II TO 12 611 KK = 8.5 613 Ht = (H(1,J) + H0) + KK

614 DIS(1,J) = H2 616 NEXT II NEXT J 617 GOTO 628 618 FOR J . JI TO J2: FOR I . II TO 12 S19 IF HIL . "THOUS" THEN GOTO SOOD 629 IF NA - "PRESSURE" THEN GOTO 9828 621 DIS(1.J) = INT (W1.J)) 522 IF MS - "GRAD DIR" THEN DIS(1,J) = INT ((DIS(1,J) + 5) / 10) GOTO 1500 623 624 IF NS . "TEMP" THEN DIS(1.J) = INT (BIS(1.J) / 18) 525 IF NS = "HINDU" THEN DIS(1,J) = INT (DIS(1,J)) 526 IF NB . "WINDU" THEN DIS(1,J) . INT (DIS(1,J)) 627 HEXT II NEXT J 628 CALL - 936: FOR I = 11 TO 12 629 TP = 1X - SP + 1 639 IF TP) . 100 THEN TP . TP - 108 631 IF TP (@ THEN TP = - TP 632 IF TP (10 THEN 60TO 638 634 PRINT * "ITPI 633 6010 648 630 PRINT " TP: 640 NEXT I 650 FOR J = J2 TO J1 STEP - 1 PRINT I PRINT 670 FOR 1 - 11 TO 12 688 685 IF DIS(1.J) (@ THEN GOTO 695 686 IF DIS(I.J) (10 THEN GOTO 693 690 PRINT * "+019(1,J)+ 692 60T0 718 PRINT " "JOIS(I.J) 693 60TO 710 694 IF DIS(1.J) (- S THEN GOTO 788 695 696 PRINT * "+DIS(1+J)+1 00TO 710 700 PRINT DIS(1,J)) 710 NEXT LI NEXT J 714 IF HO - 8 THEN GOTO 716 715 PRINT 1 PRINT "X "11 / HD 716 PRINT | PRINT | 905UB 2000 718 IF X# - "V" THEN GOTO 1888 720 IF N = 2 THEN BOTO 8895 725 90T0 199 INPUT " HO SCALE ... Y/H "IBS 728 729 NO = 1E16, MO = 1E11 230 IF NS . "OI" THEN HO . HO 731 IF NS . "02" THEN HO . HO 732 IF MS = "0.7" THEN HO = HO 733 IF HE = "OA" THEN HO = HO 734 IF N# = "05" THEN NO = NO 735 IF NS = "OG" THEN HO = HO 736 IF NS = "07" THEN HO = NO 737 IF NS = "08" THEN HO = HO 738 IF NS = "Q-VECTOR" THEN HO = NO 740 IF 84 - "Y" THEN GOTO 745 742 6010 750

171 IF N# = "GRADIENT U" THEN U(1,J) = H(1,J) 172 IF NS = "PRESSURE" THEN HK [.J) = HK [.J) IF NS = "GAGOIENT U" THEN U(1.J) = H(1.J) 171 IF NO = "THICKNESS" THEN Z(1,J) = H(1,J) 175 IF HE . "THOUS" THEN Z(I.J) . H(I.J) 177 178 IF HE . "TEMP" THEN T(1,J) = H(1,J) IF HE = "HINDU" THEN UK (.J) = H(.J) 160 IF NS = "G. TX" THEN LET TX(1.J) = H(1.J) 181 IF NS . "WINDU" THEN W(I,J) . HKI,J) 182 IF NS = "B. TY" THEN LET TW(1.J) = HK1.J) 183 IF NS . "B.UK" THEN LET UIX(1.J) = H(1.J) 184 185 IF NS = "05" THEN LET 05(1.J) = H(1.J) IF NS = "G.UY" THEN LET U2W I.J) = HK I.J) 196 187 IF HS = "06" THEN LET 06(1.J) = H(1.J) IF HS . "G.UX" THEN LET VIX(1,J) . H(1,J) 168 189 IF NS . "07" THEN LET 07(1.J) . H(1.J) IF NS . "B.UY" THEN LET UZW(1.J) . HKI.J) 190 191 IF NS . "08" THEN LET 08(1,J) . H(1,J) 192 IF N# = "G. UORTX" THEN LET TX(1,J) = H(1,J) 193 IF HE . "HY" THEN LET HY(I,J) = H(I,J) 194 IF HS = "G. UORTY" THEN LET TY(I,J) = H(I,J) 195 IF HE = "HK" THEN LET HOK [. J) = HK [. J) 196 IF HS = "UORTAD" THEN LET ADUX (,)) = HK (, J) 198 60908 285 199 OK I.J) = HK I.J) AETURN 200 CALL - 936 INPUT " HY .. THY OR THOUS " HE 202 INPUT "DATE "JO: BOSUB 1215 283 207 FOR 1 = 11 TO 12 FOR J = JI TO J2 200 60T0 247 299 210 RAD - 630 / 11 220 V = SP + J + JV1X = 1X - SP + 1 230 XBX(J) = YIVBY(J) = 2(1,J) 232 NEXT J 235 XBX(9) = XBX(0) - SPIXBX(10) = XBX(0) + 236 YBY(9) = YBY(8): VBY(10) = YBY(8) 248 60508 2580 245 FOR CS = J1 TO J2: J = CS 247 V = SP + J + JVIX = IX - SP + 1 248 890 = 638 / 1116 = 9.81 268 F = 4 + 22 + SIN (Y / RAD) / (7 + 24 + 68 + 68)(8 = 9.81 261 6010 263 262 U(1,J) = (6 / F) + (- H9(CS) + 18) 263 U(1,J) = (6 / F) # (- HY(1,J) # 10) 264 H(1,J) = U(1,J) 267 0010 270 NEXT CS 268 278 NEXT JE NEXT I 60T0 188 298 IF HS = "T4. THICADOX" THEN LET TX(I.J) = H(I.J) 285 IF NS = "T7. THICROWY" THEN LET TW(I.J) = H(I.J) 266 IF HS = "HU" THEN LET UK [.J) = HK [.J) 287 IF NS = "HU" THEN LET WI,J) = H(I,J) 288

290 IF NS = "UORTAD" THEN LET TX(1.1) = H(1.1) 292 IF NS = "LAPTHICAD" THEN LET TW(1, 1) = H(1,1) 299 RETURN 300 CALL - 936: UTAB 6 302 PRINT "TYPE OF DISPLAY" 304 FOR HT - 8 TO 39: PRINT "-" ... NEXT HT 305 PRINT : PRINT "1., TABLE": PRINT "2., CHART": PRINT "3., COLOR CHART" 306 INPUT B 307 00 = 0 = 10:01 = INT (0):02 = 01 + 10:T = INT (00 - 02): PRINT T IF T = @ THEN LET TS = "500" 308 309 IF T = 1 THEN LET TS = "1000" 310 IF T . 2 THEN LET TE . "THICK" 311 CALL - 936: IF 8 - 1 THEN GOTO 315 312 IF 8 = 2 THEN GOTO 600 313 IF 8 . 3 THEN GOTO 588 315 PRINT 316 PRINT : PRINT : PRINT "DISPL AV SPEED": PRINT : PRINT : PRINT 1 INPUT HAT I CALL - 936 317 60SU8 2088 PRINT HE," ",TE," ", INT (0 / 18) 310 319 PRINT JI.J2 320 FOR J = J1 TO J2 325 PRINT : FOR HT . & TO HHT: NEXT HT 330 FOR 1 = 11 TO 12 340 PRINT SP + J + JV.IX - SP + L.H(L.J) 345 FOR HT . . TO HHT: NEXT HT NEXT II NEXT J 350 355 BET RE 360 60SUB 2858 300 6010 168 382 CALL - 936: 00TO 1000 384 FOR J = J1 TO J21 FOR 1 = 11 TO 12 386 HIN = U(1,J) - 2 + U(1,J) - 2 388 H(I.J) = SOR (HIN) 390 NEXT II HEAT J IF BS . "BA" THEN LET HE . "GRAD HEL" 391 60T0 416 392 FOR J = 1 TO 7: FOR I = 1 TO 9 393 IF A = 1 THEN LET H(I.J) = U(I.J) 394 395 00T0 100 396 IF A = 2 THEN LET HKI.J) = IKI.J) 397 IF A . 6 THEN LET HKI,J) . SPI(1,J) 398 NEXT II NEXT JI RETURN 400 CALL - 936: VTAB 6: PRINT * SAVE DATA* 485 INPUT "CHORT NOME "INS 418 PRINT I INPUT "DATE " AD 412 PRINT : INPUT "HONTH AND VERR "INS 416 PRINT 417 Q5 = STR\$ (0):C8 = N\$ + Q8 418 PRINT "SAULNG "JNS PRINT D\$,"OPEN",C\$ 420 430 PRINT DS;"HRITE",CS 435 PRINT NS 437 PRINT JY: PRINT IX: PRINT SP

745 THPUT "HO SCOLE " HO 758 8010 683 752 CALL - 936: PRINT : PRINT : PRINT "1 ... ZONAL HINDS": PRINT : PRINT " 2... HERIDIONAL HIND S": PRINT : PRINT "6 ... VORTICITY" 753 INPUT AL CALL - 9361 PRINT | PRINT 754 PRINT "NOME OF CHART": PRINT : INPUT NE: CALL - 936 755 PRINT | PRINT "CHART DATE"; INPUT T 757 OF . STRS (T):CS . HE + OS 759 PRINT DE, "OPEN".CS 760 PRINT DS, "READ", CS 762 FOR J = 1 TO 7 764 FOR 1 = 1 TO 9 765 INPUT H(L.J) IF A = 1 THEN U(1.J) = H(1.J) 766 757 IF A = 2 THEN U(1.J) = H(1.J) IF A = 6 THEN SIP(1,J) = H(1,J) 768 769 HEXT IN HEXT J PRINT DE . "CLOSE" ,NE 780 792 GOTO 100 790 CALL - 936 792 INPUT "NAME OF CHART "INS 794 PRINT : INPUT "CHART DATE "JD G09UB 1215 796 CALL - 935: HAN - B: HANS - HS 798 799 IF NO . "HEIGHTS" THEN LET NO . "HOL" 988 IF HS . "THICKNESS" THEN LET HS . "THK" ART IF NO - "WINDL" THEN LET HO - "G.UX" AND IF HS - "WINDU" THEN LET HS - "G. UK" ROT IF HE - "TEMP" THEN LET HE - "O. TX" ARA IF HE - "UORTICITY" THEN LET HE - "R. UORTX" 985 IF HE - "THOUS" THEN LET HE - "THOUSK" 986 80518 851 888 805U8 888 889 FOR J = J1 TO J2: FOR 1 = 11 TO 12 910 V = SP + J + NIX = IX - SP + 1 812 X8X(1) = X: Y8V(1) = 0(1,.) R14 NEXT I 815 X8X(11) = X8X(0) + SP:X8X(12) = X8X(10) - SP 816 VBW(11) = YBV(0)(VBW(12) = VBV(10) 818 BOSUB 2160 828 FOR CS = 11 TO 1211 = CS 822 H(1,J) = E0(CS) 825 NEXT CS 826 NEXT J 927 GOTO 416 828 IF HAN = 2 THEN BOTO 958 **R29 GOSUB 968** 838 GOSUB 898 831 FOR I = I1 TO 12 832 FOR J = J1 TO J2 RT3 Y = SP + J + JY1X = IX - SP + I 934 XBX(J) = Y: VBV(J) = 0(1.J) 935 NEXT J S35 XEN(S) = XEN(O) - SPIXEN(IO) = XEN(O) + SP 10.14

837 YEW 9) = YEW (8); VEW 18) = YEW 8) 940 GOSUB 2500 842 FOR CS = JI TO J21 J = CS 943 H(1,J) = HG(CS) 846 NEXT CS 847 HEXT I 848 NM = 2 849 GOTO 416 858 8010 168 IF NS = "THICAD" THEN LET NS = "T2. THICADX" 851 IF HS = "Q1" THEN LET HS = "05" 852 IF NS - "02" THEN LET NS - "06" 853 854 IF HS = "03" THEN LET HS = "07" IF HE = "04" THEN LET HE = "08" 855 IF HANS . "HOX" THEN LET NO . "H2. HOOK" 856 IF HHS = "HY" THEN LET HS = "H3. HYX" 857 IF HHE . "T2. THICROX" THEN LET ME . "T4. THICROOK" 858 859 6010 1159 IF HE . "G.UK" THEN LET HE . "G.UV" 868 BEL IF HS = "HK" THEN LET NS = "HY" 862 IF NS . "6.UX" THEN LET NS . "6.UY" 963 IF HS - "THX" THEN LET HS - "THY" 864 IF HS . "6. TX" THEN LET HS . "6. TY" BGG IF HE = "G. UORTX" THEN LET HE = "G. UORTY" 867 IF NS . "THOUSK" THEN LET NS . "THOUSY" 868 IF HE = "H2, HOK" THEN LET NS = "H4, HKY" 969 IF NS = "H3. HVX" THEN LET NS = "H5. HVY" R70 IF NS = "T2. THICROX" THEN LET NS = "T3. THICROY" 871 IF HE = "T4. THICADXX" THEN LET NO . "T5. THICADXY" 872 IF HS = "TE. THICADYX" THEN LET HS = "T7. THICADYY" 879 RETURN IF NS = "95" THEN GOTO 889 888 IF NS = "06" THEN GOTO 089 891 IF NS - "07" THEN BOTO 838 892 883 IF NS = "08" THEN BOTO 830 668 RETURN 830 IF NS = "Q5" THEN 60T0 858 IF NS . "06" THEN GOTO 850 891 IF NS - "07" THEN GOTO 831 892 IF NS - "96" THEN 60TO 831 893 899 RETURN CALL - 936 988 UTAB & INPUT "SCALE LON" FF 982 PRINT : IMPUT "SCALE HIGHR ",FH 985 932 934 FOR J = 36 TO 12 STEP - 4 936 FOR I = 0 TO 24 STEP 3 937 IF HK(1 + 3) / 3.() - 8) / 4) (FF THEN BOTO 942 938 IF HK(1 + 3) / 3.(J - 8) / 4) > FH THEN 60TO 945 940 C = 71 80TO 958 942 C = 1: 60T0 958 945 C = 15: 80T0 958 958 COLOR= C 952 PLOT 1.38 - Jr PLOT I + 1.36 - Jr PLOT I + 2.36 - J 954 PLOT 1.37 - J: PLOT I + 1.37 - J: PLOT I + 2.37 - J

956 PLOT 1.38 - J: PLOT 1 + 1.38 - J: PLOT 1 + 2.38 - J 950 PLOT 1.39 - JI PLOT 1 + 1.39 - JI PLOT 1 + 2.39 - J 960 NEXT II NEXT J 965 FOR SC = 0 TO 15: COLOR= SC 975 PLOT SC + 4,391 NEXT SC 398 GET A#: CALL - 336: TEXT : 60TO 108 999 END 1000 PRINT 1000 INPUT "CHART DATE" ID 1009 6010 1050 1812 INPUT "U TERM" ING: 80518 1215 1013 INPUT "U TERM" INFI GOSUB 1215 1818 IF AR - 1 THEN BOTO 1894 1019 IF AA . 3 THEN GOTO 1094 1024 M# = "6.UK"; 005UB 1215 1826 NE = "6.UV": BOSLE 1215 1827 N# = "6.UX": 605UB 1215 1828 H# = "8, UV": 805U8 1215 1838 IMPUT "HE THE OR THOUSE "INS 1031 00SUB 1215 1832 INPUT "HY THY OR THOUSY " AND 1033 60SUB 1215 1848 6010 1894 1050 PRINT *1.... UELOCITY* 1951 PRINT *2.... 6840 COMP* 1852 PRINT "3....DIRECTION" 1053 PRINT "4 HENU" PRINT "5 GRAD VEL DIR" 1954 1868 INPUT AR 1961 IF AA = 3 THEN GOTO 1094 1062 IF AA = 4 THEN BOTO 108 1863 IF AA = 5 THEN GOTO 7018 1865 6070 1812 1894 IF AR . I THEN HE . "VELOCITY" 1895 IF AA = 2 THEN NO = "GRADIENT" 1096 IF AA = 3 THEN NO = "DIRECTION" 1100 PRINT " CRECILIATING "INC 1184 IF RR = 1 THEN GOTO 384 1185 IF AA = 2 THEN BOTO GOND 1184 IF AR - 3 THEN 80TO 1588 1118 IF AR = 4 THEN GOTO 108 1128 IF AA = 5 THEN GOTO 7818 1158 IF NO . "T3. THICROY" THEN LET NO . THICROWY 1168 RETURN 1200 REH UORTICITY ETC 1201 CALL - 936 1202 PRINT "1... UORTICITY": PRINT 1203 PRINT "2... VORTRO": PRINT 1284 PRINT "3 ... O-VECTOR": PRINT "4 ... THICAD" 1205 PRINT "5 ... VORTICITY2" 1206 PRINT "6.. LAPTHICAD": PRINT : PRINT "7.. PHSL": INPUT AI 1207 INPUT "CHART DATE "+0 1208 60SUB 1428

1209 N# = "6.UX": 605UB 1215:N# = "6.UV": 605UB 1215:N# = "6.UX": 605UB 12 151N# = "6.UV": 805UB 1215: 60TO 1285 1218 HE - "HINDU": PRINT HE: INPUT "DATE "ID: GOSUE 1215:HE - "HINDU": PRINT NS.D: GOSUB 12151NS . "G. UORTX": PRINT HS: INPUT "DATE ".D: GOSUB 121 5:NI = "6. UORTY": PRINT NS.0: 605UB 1215: 60T0 1285 1211 INPUT "COMP REQUIRED. . YAN" : ASS: IF ASS . "N" THEN GOTO 1285 1212 INPUT "HIND DATE "10:NS = "6.UX": 605U8 1215:NS = "6.UV": 608U8 121 5:NS = "6.UX": 60SUB 1215:NS = "6.UV": 60SUB 1215 1213 INPUT "TEMP TEAM DATE "JOI INPUT "TEMP TEAM NAME "JNNI GOOLD 1215: INPUT "2 TENT TERM NAME "INSI GOSUB 1215 1214 6010 1285 1215 PRINT TRAK 5>"LORDING "INS 1218 OF . STR# (0):C# . N# + OF 1220 PRINT DS. "OPEN" .CS 1225 PRINT DES"READ" .CS 1237 IMPUT HS 1238 IMPUT JY: IMPUT IX: IMPUT SP 1239 INPUT JI: INPUT II: INPUT J2: INPUT 12 1240 FOR J = .11 TO .12 1241 FOR 1 = 11 TO 12 1242 INPUT H(L.J) 1245 GOSUB 162 1255 NEXT Is NEXT J 1258 PRINT D&, "CLOSE",CS 1260 RETURN 1267 6010 1282 1268 FOR J = JI TO J21 FOR 1 = 11 TO 12 1270 SIP(1,J) = (UQ(1,J) + LO(1,J)) / 2 1272 HK [.J) . SIP([.J) 1273 NEXT II NEXT J 1274 6010 188 1275 PRINT "HINUS TERM Y/N "I INPUT F# 1276 RETURN 1299 GOTO 109 1282 PRINT "PROCESS HOMES" 1284 PRINT "PHSL" 1205 PRINT "LAPTHICAD"; PRINT "DIVERGENCE"; PRINT "THICAD"; PRINT "UDITIC ITV2" 1296 PRINT : PRINT "UORTICITY"; PRINT "UORTRO"; PRINT "01"; PRINT "02"; PRINT "03": PRINT "04" 1287 PRINT "Q-UECTOR": PRINT "HEAU" 1288 INPUT " PROCEE HOME "ANS IF HE = "HENU" THEN GOTO 100 1289 1298 IF NS = "0-UECTOR" THEN BOTO 1458 1291 IF NS (> "VORTICITY" THEN BOTO 1293 1292 INPUT "RES VORTICITY YAN ":08 1293 GOSUB 1275: PRINT "EXECUTING ":HS 1294 FOR J = J1 TO J21 FOR 1 = 11 TO 12 1295 Y . SP . J + JVIF . 4 . 22 . 51N (Y / RAD) / (7 . 24 . 68 . 1297 IF HE = "PHSL" THEN GOTO 1370 1298 IF N# = "LAPTHICAD" THEN 80TO 1352 1299 IF HS = "WORTICITY2" THEN BOTO 1395 1388 IF HS - "THICAD" THEN GOTO 1385 1301 IF HE . "DIVERGENCE" THEN GOTO 1390

1302 IF N# = "Q-UECTOR" THEN GOTO 1350 1303 IF NO . "VORTICITY" THEN GOTO 1309 1304 IF NS = "VORTRO" THEN GOTO 1315 1385 IF HE . "01" THEN GOTO 1320 1386 IF NS . "02" THEN GOTO 1325 1307 IF NO - "03" THEN GOTO 1330 1308 IF HS - "04" THEN GOTO 1348 1309 SIP(1.J) = UIX(1.J) - U2W(1.J) 1310 IF OF . "N" THEN LET F . 0 1311 H(1,J) = SIP(1,J) + F 1313 GOTO 1400 1315 ADU(1,J) = ((U(1,J) = TX(1,J)) + (U(1,J) + TX(1,J))) 1317 H(1,J) = ADU(1,J) 1318 IF FS . "Y" THEN LET HKI.J) . - ADIKI.J) 1319 6010 1400 1320 01(1,J) = - U1X(1,J) = TX(1,J) 1321 H(1,J) = 01(1,J) 1323 6010 1468 1325 02(1.J) = - VIX(1.J) + TW(1.J) 1326 HK 1.J) = 02(1,J) 1328 GOTD 1488 1330 03(1.J) = - U2W(1.J) + TX(1.J) 1332 HK1.J) = 03(1.J) 1335 6010 1460 1340 04(1,J) = - U2W (,J) + TW (,J) 1342 H(1,J) = 04(1,J) 1345 6010 1408 1350 H(I,J) = 05(I,J) + 06(I,J) + 07(I,J) + 08(I,J) 1360 8010 1488 1362 M(1.J) = (287 / F) + (TK(1.J) + TW(1.J)) 1364 IF FS = "Y" THEN LET H(1,J) = - H(1,J) 1365 00TO 1400 1370 REN PHSL 1371 H(I,J) = TH(I,J) + TH(I,J)1375 0010 1480 1390 W(I,J) = U1W(I,J) + U2W(I,J) 1382 GOTO 1400 1384 REN THICKNESS IN ON 1 +10 FOR HETRES 1385 0 = INT (D) 1396 H(1,J) = - ((U(1,J) + HW(1,J)) + (U(1,J) + HW(1,J))) 1390 H(1.J) = 98.1 + H(1.J) / 287 1392 GOTO 1400 1395 M(1,J) = (90.1 / F) = (TX(1,J) + TV(1,J)) 1400 NEXT II NEXT J 1401 IF OS . "Y" THEN LET D . D + 8.81 1402 PRINT "SAVING "INS 1403 INPUT "DATE "101 60TO 416 1405 0010 1205 1428 IF AI - 1 THEN GOTO 1289 1422 IF RI = 2 THEN BOTO 1218 1424 IF AI = 3 THEN GOTO 1211 1426 IF AI = 4 THEN GOTO 1480 1428 IF A1 = 5 THEN GOTO 1448 1429 IF AI = 6 THEN BOTO 1498

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1430 IF AL . 7 THEN GOTO 1496
1438 RETURN
1448 N# = "H2. HXX"1 GOSUB 1215
1442 N# . "H5. HVV": GOSUB 1215: GOTO 1285
1458 IF HS - "Q-LECTOR" THEN OR - 1
1452 FOR H = 1 TO 4
1453 IF N = 1 THEN HS = "05"
1454 IF N # 2 THEN HE # "96"
1455 IF H = 3 THEN HS = "07"
1456 IF N . 4 THEN NS . "08"
1460 60500 1215
1465 NEXT N
1478 NS - "D-UECTOR"
1475 GOTO 1293
1480 REH THICK ADJECTION
1482 MS = "HINOU": INPUT "DATE" JD: GOSUB 1215
1483 NF = "WINDU": INPUT "DATE":D: 605U8 1215
1494 HE - "THX": INPUT "DATE ":D: 60508 1215
1485 Hs = "THY": INPUT "DATE" +D: 605UB 1215
1497 6010 1282
1498 H# = "T4. THICADXX": 605U8 1215
1492 NS = "17. THICADYY": 60508 1215
1495 GOTO 1282
1496 HS - "UORTAD" PRINT NO: INPUT "DATE "JO: 605UB 1215
1497 HS - "LAPTHICAD": PRINT HS: INPUT "DATE ":D: 60508 1215: 80TO 1282
1500 IF NS - "HEIGHTS" THEN DIS(1,J) - INT (DIS(1,J) / 10)
1585 IF NS = "THICKNESS" THEN DIS(I,J) = INT (DIS(I,J) / 10)
1510 IF NS = "DIRECTION" THEN DIS(1,J) = INT (DIS(1,J) / 10)
1550 6010 624
1580 IF 68 = "0+" THEN LET NS = "ORAD DIR"
1582 FOR J = J1 TO J2: FOR I = 11 TO 12
1680 IF UK 1.J) = 0 AND (K 1.J) > 0 THEN OV = 360
1681 IF U(1.J) = 8 AND U(1.J) ( 8 THEN OV = 188
1682 IF UKI, J) ( = 0 AND UKI, J) = 0 THEN OV = 270
1603 IF U(1.J) > = 0 AND ((1.J) = 0 THEN OV = 90
1684 IF UKT.J) . 0 THEN GOTO 1650
1686 IF U(1,J) = 0 THEN GOTO 1650
1610 OV = ATH (UK [. J) / UK [. J)):OV = OV + 57.3
1640 IF U(I.J) > = 8 AND U(I.J) > = 8 THEN OV = OV
1644 IF UK1.J) > = 0 AND (K1.J) ( = 9 THEN OV = 0V + 180
1646 IF U(I,J) ( . . . AND U(I,J) ( . . THEN OV . OV + 188
1650 HK [.J) = 0Y + 190
1655 IF H(1,J) > 360 THEN H(1,J) = H(1,J) - 360
1788 HK [...] . INT (HK [...]))
1730 NEXT II NEXT J
1740 GOTO 416
1998 PRINT HE," ",TS," DATE ", INT (D / 18)
1982 PRINT HS
1818 FOR I = 11 TO 12
1812 TP = IX - SP + 1
1815 (F TP ) = 100 THEN TP = TP - 100
1817 IF TP ( @ THEN TP = - TP
1818 IF TP ( 10 THEN GOTO 1825
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1828 PRINT " "ITPI" 60T0 1830 1822 ",TP." 1823 PRINT * 1839 NEXT 1 1832 FOR 1 = 11 TO 12 1833 PRINT " 1.74 1834 NEXT I 1035 FOR J = J2 TO J1 STEP - 1 1838 PRINT | PRINT | PRINT 1940 FOR 1 = 11 TO 12 1941 IF ABC = 3 THEN GOTO 1000 1942 IF H(1.J) > = 1000 THEH BOTO 1984 1944 IF HK (,J) > = 100 AND HK (,J) < 1000 THEN 00TO 1910 1848 IF HKI, J) > = 18 AND HKI, J) (100 THEN 80TO 1920 1848 IF H(I,J) > . . . AND H(I,J) (18 THEN 80TO 1938 1850 IF H(I,J) > - 10 AND H(I,J) (0 THEN GOTO 1940 1852 IF H(I,J) > - 100 AND H(I,J) (= - 10 THEN GOTO 1950 1854 IF H(L,J) (= - 100 THEN GOTO 1975 1868 H([, J) = H([, J) + H0 1862 6010 1842 PRINT " "; INT (H(1.J));" "; 1960 1985 00T0 1960 PRINT " "> INT (H(1,J));" ") 1910 1915 00TO 1960 1920 PRINT " "> INT (H(I,J)))" 1925 00T0 1984 PRINT " ", INT (H(I.J))," 1938 1935 80TO 1968 1940 PRINT " ": INT (H(I.J))" 90TO 1999 1943 PRINT " ", INT (H(L,J))" 1930 1952 00TO 1980 1955 PRINT " "+ INT (H(L,J))+" "+ +" IL NEXT I 1968 NEXT I: HTRB 1: FOR 1 = 11 TO 12: PRINT " 1961 NEXT J 1962 PRINT : PRINT 1963 IF HO = 0 THEN 00TO 1965 1964 PRINT "X ">1 / HO 1965 60SUB 2656: 60TO 99 INPUT "PRINT Y/H "1X8 2000 2010 IF X\$. "Y" THEN GOTO 2020 2015 RETURN 2020 PRINT DSI"PROI" 2038 RETURN 2059 IF XS = "V" THEN 80TO 2008 2055 RETURN 2068 PRINT DS, "PROS" 2070 RETURN 2130 PRINT 2101 PRINT "EXECUTING INTERPOLATION" 2102 REN HORIZONTAL 2103 REH YYIT EAST UALUE 2194 REN **WY2T HEST UALUE** 2105 HEH CUB SPLINE

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2106 N = 4 2107 CSI = 11:CS2 = 12 2108 FOR CS = 11 TO 12 - 1 2109 X = IX - SP + CS 2110 PRINT 2112 IF CS . 8 THEN 80TO 2198 2114 IF CS = 9 THEN 80TO 2168 $2159 \ 100((1) = 100((CS - 1))(00(2) = 100((CS))(00(3) = 100((CS + 1))(00(4) = 1))$ BX(CS + 2) 2152 YAK1) = YEW(CS - 1): YAK2) = YEW(CS): YAK3) = YEW(CS + 1): YAK4) = Y BYKCS + 21 2154 6010 2288 2166 X0X(1) = X8X(11); X0X(2) = X8X(CS); XXX(3) = X8X(CS + 1); XXX(4) = X8X(C 5 + 2) 2162 YW(1) = V9(11); YW(2) = V9(C5); WW(3) = Y9(C5 + 1); YW(4) = Y9(C 5 + 2) 2163 Y2YT(8) = YYW(2) 2164 8010 2288 2168 PRINT $2179 \times 00((1) = \times 80(CS - 1)) \times 000(2) = \times 80((CS)) \times 000(3) = \times 80((CS + 1)) \times 000(4) = X$ BX(12) 2172 VW(1) = VBW(CS - 1) VW(2) = VBW(CS) VW(3) = VBW(CS + 1) VW(4) = VW(CS + 1) = VW(CS + 1) VW(CS + 1) = VW(CS + 1) VW(CS + 1) = VW(BY(12) 2175 VIVI(10) = WW(3) 2198 6010 2288 2199 CO = 21 GOTO 2285 2200 PRINT 2292 CO = 1 2285 IF CO = 1 THEN LET YONT = X - HO 2287 IF CO = 2 THEN LET XONT = X - SP + HO 2218 NUM = N - 1 2228 FOR K = 1 TO NUM 2230 YWNT = 0 2235 KP = K + 1 2248 FOR IL6 = 1 TO KP 2243 PROCT = *** ILG> 2250 FOR JLG = 1 TO KP 2253 IF ILG - JLG THEN BOTO 2278 2268 FU = (XOMT - XOOK JLB)) / (XOOK ILB) - XOOK JLB)) 2263 PROCT . PROCT . FU 2278 NEXT JLG 2273 WHIT = WHIT + PROCT 2289 NEXT ILS 2298 NEXT K 2292 IF CO = I THEN LET VIVT(CS) = WANT 2294 IF CO = 2 THEN LET Y2YT(CS + 1) = YWWT 2298 IF CO = 1 THEN 80TO 2199 2299 NEXT CS 2300 FOR CS = 11 TO 12 2385 ZD(CS) = Y1VT(CS) - Y2VT(CS) 2320 E6(CS) = Z0(CS) / (2 + HQ + 60 + 18% + COS (Y / RAD)) 2330 IF CS = II THEN EB(CS) = 2 + EB(CS) 2332 IF CS = 12 THEN EB(CS) = 2 + EB(CS) 2342 PRINT V2VT(CS); PRINT H(CS,J); PRINT VIVT(CS)

2343 PRINT J.II PRINT * *JEG(CS) 2345 MEXT CS 2330 RETURN 2598 PRINT 2501 PRINT "EXECUTING INTERPOLATION" 2502 REH VERTICAL 2983 REN VIVT-HORTH AND Y2VT-SOUTH 2505 REN CUB SPLINE 2386 N = 4 2568 FOR CS = J1 TO J2 - 1 2589 Y = SP + CS + JV 2518 PRINT 2312 IF CS = @ THEN BOTO 2368 2514 IF CS = 7 THEN 6010 2569 2530 100((1) = XBX(CS - 1))(00X(2) = XBX(CS))(00X(3) = XBX(CS + 1))(00X(4) = XBX(CS))(00X(4) (00X(4) = XBX(CS))(00X(4))(BX(CS + 2) 2552 WW(1) = VEW(CS - 1): WW(2) = VEW(CS): WW(3) = VEW(CS + 1): WW(4) = V BW(CS + 2) 2354 8010 2888 2590 X00(1) = X8X(9):X00(2) = X8X(CS):X00(3) = X8X(CS + 1):X00(4) = X8X(CS + 2) 2562 YW(1) = Y8K(9): YW(2) = Y8K(C5): YW(3) = Y8K(C5 + 1): YW(4) = Y8K(C5 + 2) 2563 Y2VT(8) = WW(2) 2564 8010 2688 2568 PRINT $2378 \ 1000(1) = 1000(CS - 1)(1000(2) = 1000(CS)(1000(3) = 1000(CS + 1)(1000(4) = 1)$ SD((10) 2572 WW(1) = VeW(CS - 1) VWW(2) = VeW(CS) VWW(3) = VeW(CS + 1) VWW(4) = VeW(CS)BW(18) 2575 VIVT(8) = VVV(3) 2598 8010 2688 2599 CO = 2: 00TO 2585 2688 PRINT 2662 CO = 1 2665 IF CO = 1 THEN LET XXMT = Y + HO 2807 IF CO = 2 THEN LET XONT = V + 9P - HD 2618 NUH = N - 1 2620 FOR K = 1 TO HUH 2638 YWWY = 0 2635 KP = K + 1 2640 FOR ILS = 1 TO KP 2645 PROCT = YVW ILG) 2638 FOR JL8 = 1 TO KP 2835 IF ILS - JLS THEN BOTO 2678 2000 FU = (XONT - XOOK JE)) / (XOOK IL6) - XOOK JE6)) 2665 PROCT = PROCT + FU 2670 HEXT JLS 2675 WWNT = WWNT + PROCT HENT ILS 2606 2685 PRINT 2850 NEXT K 2652 IF CO = 1 THEN LET VIVT(CS) = WHIT 2694 IF CO = 2 THEN LET V2VT(CS + 1) = VWNT

2698 IF CO = 1 THEN GOTO 2599 2699 NEXT CS 2700 FOR CS # J1 TO J2 2785 ZD(CS) = YIYT(CS) - YZYT(CS) 2728 N9(CS) = 20(CS) / (2 + N0 + 68 + 1858) 2730 IF CS = JI THEN HO(CS) = 2 + HO(CS) 2732 IF CS = J2 THEN HO(CS) = 2 + HO(CS) 2742 PRINT VIVT(CS): PRINT Q(1.CS): PRINT V2VT(CS) 2743 PRINT J.II PRINT . " HHK (CS) 2745 NEXT CS 2758 RETURN 6000 CALL - 936 6000 FOR J = J1 TO J2: FOR I = 11 TO 12 5010 Y . SP . J + JV1X . IX - SP . I 5013 F = 4 = 22 = SIN (V / ROD) / (7 = 24 = 68 = 68) 6 = 9.81 6830 61 - - 6 . HW(1,J) . 18 6035 62 = - WI.J) + V2W [.J) 6849 63 = VIX(I.J) 6842 6010 6835 6045 UB([.J) = (81 + 82) / (83 + F) 5850 6010 6888 6053 UG(1,J) = (01 + 62 - (U(1,J) + 63)) / F 6859 64 . - 6 . HX(1.J) . 18 5865 65 = - U(I.J) + U1X(I.J) 6979 96 = U2W L.J) 5072 00T0 6865 6075 UG(1,J) = (84 + 85) / (86 - F) 6090 GOTO 7888 6985 UB(1,J) = - (04 + 85 - (86 + U(1,J))) / F 7000 NEXT II NEXT J 7085 GOTO 8888 7010 NS = "GRADIENT U" 7013 00508 1215 7828 HE - "GRODIENT U" 7925 605UB 1215 7838 64 - "84" 7840 6010 384 86/80 N = 1 8985 FOR J = J1 TO J2: FOR 1 = 11 TO 12 8007 IF N = 3 THEN GOTO 1050 8668 IF N = 2 60TO 8628 BOOS NO . "BRODIENT U 0010 H(I.J) = U0(1.J) 9815 GOTO 8825 9920 H(I.J) = U9(I.J) B822 NS = "BRADIENT U" 9925 NEXT II NEXT J 8926 N = N + 1 8828 80TO 418 9839 80TO 1858 9000 DIS(I.J) = INT (H(I.J) / 10): 00TO 627 9828 IF H(I.J) > = 1888 THEN DIS(I.J) = H(I.J) - 1888 9825 IF H(1,J) (1088 THEN DIB(1,J) = H(1,J) - 988 9838 8010 627

Appendix F

Data used for analyse storm movement, showing location, tendency, actual movement, Ten indicator, warm sector wind field and the 500 mb wind indicators DATA for Direction Analysis

Month	1at1	ong	dp/dt	Move	ment	TEN		FIVE		WARM	
		100		Dirs	peed	Dirs	peed	Dirs	Speed	Dirs	Speed
May	44	38	-6.3	115	8		11.4	135	14.9		11.2
may	42	34	.4	120	15.4	105	13.6	105	10.7	95	8
May	53	50	-1.0	380	10	360	24.4	360	28.9	380	25.8
Jan	49	57	-12.0	55	8.5	35	17	40	35	30	22.5
Feb	54	39	-13.0	22	8.2	10	24	0	40	43	24
Mar	55	53	-10.0	25	10	10	21.5	50	24.7	70	26.9
Sep	57	40	-4.6	68	17.4	74	15.9	74	23.2	68	19.2
Sep	50	49	-2.8	48	10.3	60	6.3	60	15.9	52	18.4
Sep	52	37	2.0	90	13.9	90	9.3	90	12.3	110	15.4
Sep	54	54	-1.7	68	10.3	45	19.5	45	17.2	45	16.2
Aug	49	47	.0	55	17.5	57	22.5	57	16.9	57	23.8
Aug	52	44	-5.5	315	0	320	13.9	320	22.8	405	17.5
Aug	58	22	-1.9	415	7.7	340	14.3	340	19.1	395	14.7
Rug	54	41	-2.3	58	11	52	13.5	52	12.5		18
Jun	55	50	-1.0	365	5.1	320	9.6	320	13.2	360	19
Jun	58	43	.4	428	9.3	325	10	325	11.5	440	14
Jun	47	42	-5.1	68	14.4	65	17.2	65	16.3	50	23.4
Jun	47	48	.0	320	7.7	320	10.8	320	20.4	360	17.5
Dec	51	30	5.1	373	2.6	360	3.1	360	13.9	395	23.4
Dec	47	59	-28.4	57	12.8	48	38.3	48	30.2	70	21.4
Dec	55	40	-15.6	425	11.6	315	13.3		14.8	430	19.5
Dec	51	41	-4.3	90	14.1	38	12.5	37	16.5	58	17.5
Nov	40	32	2.0	55	6.4	30	23.6	30	25.2	48	16.8
Nov	56	36	-8.7	110	11.8	55	21.2	55	15.7	50	20.2
Nov	53	38	-10.1	50	18	55	33.5		26.5		18.5
Nov	47	49	-21.3	65	21	35	39		36.9		25.9

Nov	50	54	2.3	450	7.2	328	2.4	328	12.1	375	31.8	
Nov	47	24	-1.9	300	3.1	314	3.3	314	14.8	315	23.4	
Feb	62	18	-25.0	65	20	65	37.7	61	50	66	35	
Apr	48	58	-2.5	25	12	24	15	22	29	36	15	
Mar	64	10	1.0	28	3.8	23	4	27	25	45	14	
Mar	54	35	-11.0	38	19.2	50	33.8	50	42.3	45	35.9	
Mar	53	12	7.0	130	4.8	135	15.2	130	30.2	105	18.5	
Mar	52	37	4	130	7.2	25	22.2	25	23.4	30	18.4	
Feb	43	30	-9.5	22	11.6	20	15.1	20	25.4	10	30.3	
Feb	65	35	-5.7	50	9.8	50	18.4	50	27.8	65	13.7	
Feb	52	28	5.8	50	9.5	42	35.4	42	45.3	42	27.8	
Feb	45	50	-18.8	76	25.7	68	36	68	39.6	95	24.1	
Jan	43	45	-6.0	90	10.8	75	24.9	70	23	80	30	
May	53	50	-1.0	20	10	0	24.4	0	28.9	20	25.8	
Jan	49	57	-12.0	55	8.5	35	17	40	35	30	22.5	
Feb	54	39	-13.0	22	8.2	10	24	0	40	43	24	
Mar	55	33	-10.0	25	10	10	21.5	50	24.7	70	26.9	
Jan	59	50	-2.3	350	7.7	315	26.2	315	30.8	385	16.2	
Jan	46	60	-9.7	360	7.7	355	21.1	360	28.6	400	16.1	
Jan	50	23	-10.4	78	17.5		20.6	72	22.7	55	15.8	
Jan	45	22	-15.6	50	15.9	42	34.4	45	34.4	50	25.7	
Apr	50	34	-1.8	385	5.1		15.1	328		380		
Apr	56	32	-7.9	40	17.5	18	17.2	18	34.1	70	21.6	
Apr	55	42	-10.0	390	7.2	300	11.7	300	16.9	428	18.8	
Apr	47	54	-2.6	335	5.1	380	3.4	380	34.4	380		
May	52	50	.0	48	14.1	22	23.1		23.1	50	10.9	
May	48	34	-1.8	56	11.6	85	29.4	85	34.4	68	15.2	
May	48	43	-6.3	20	11.6	18	25.3	18	34.4	53	23.1	
Sep	53	20	-2.5	90	12.8	0	12.9	0	15.2	60	16.7	
Sep	45	50	2.2	70	15.4	62	13.7	62		50	24.2	
Sep	53	38	-4.7	360	10.3	350	12.9	350	15.2	385	18	
Sep	49	55	-7.5	35	14.1	35	21.7	35	42.9	90	12.5	

Sep	62	20	.0	68	11	0	4.1	0	24.0	75	21.6
Sep	45	31	-9.4	60	9	38	22.3	38	22.9	35	21.9
Sep	53	38	1.4	110	8	10	28.1	10	30.4	20	10.8
Sep	53	54	-2.5	75	9	53	17.5	53	17.4	75	7.8
Oct	52	28	-10.7	80	7.7	48	27	48	29.4	55	15.4
Oct	53	41	1.0	18	25.7	0	21.6	0	24.3	0	23.1
Oct	65	34	-7.8	18	15.4	12	24.8	12	22	12	23.4
Oct	51	56	-1.9	42	7.7	5	23.4	5	27.2	55	17.5

Appendix G

Data output from the Oceanroutes Operational Routeing Model. Two runs were accomplished using analysis and forecast data. Each run provides an optimum route and the time taken if the least time track was followed.

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ROUTEING MODEL OUTPUT FORECAST DATA AT 1st May 1991

(+) EAS GREAT 59.0 59.0 57.1 55.0 52.8 50.4 48.0		238.19 231.84			11765.07	
GREAT 59.0 59.0 57.1 55.0 52.8 50.4 48.0	CIRCLE PO 0 -15.00 0 -15.00 3 -20.22 07 -24.92 14 -29.14	238.19 231.84	-1.000	000		
59.0 59.0 57.1 55.0 52.8 50.4 48.0	$\begin{array}{r} 0 & -15.00 \\ 0 & -15.00 \\ 3 & -20.22 \\ 07 & -24.92 \\ 4 & -29.14 \end{array}$	238.19 231.84				
59.0 59.0 57.1 55.0 52.8 50.4 48.0	$\begin{array}{rrrr} 0 & -15.00 \\ 0 & -15.00 \\ .3 & -20.22 \\ 07 & -24.92 \\ .4 & -29.14 \end{array}$	238.19 231.84				
59.0 57.1 55.0 52.8 50.4 48.0	$\begin{array}{rrrr} 00 & -15.00 \\ 3 & -20.22 \\ 07 & -24.92 \\ 4 & -29.14 \end{array}$	231.84				
57.1 55.0 52.8 50.4 48.0	3 -20.22 7 -24.92 4 -29.14	231.84				
55.0 52.8 50.4 48.0	7 -24.92					
52.8 50.4 48.0	4 -29.14	220 10				
50.4	0 -22 04	226.19	•			
48.0		222.00				
	1 -36.37					
42.4	5 -39.47					
	1 -42.31					
	0 -44.91					
	0 -45.00					
		TANCE =	1607.4:	35		
		RCLE COURS			126024	
	OF STAGES		10			
				**** LEA	ST DISTA	NCE ROUTE
		TO THE PO				1000000000
CRDIS	T ON GREAT	CIRCLE =				
LAT	LON	TOT TIME	HEADNG	TIME	SPEED	DISTNC
Deg	Deg	Hours	Degs	Hr	Kts	Nms
10 00	- 45 00	04 EC03			10 50	
40.00	-45.00	94.5691 94.1909	214.98	10.27	19.50	7.4
						200.2
42.81		83.9258		10.27		200.3
45.45		73.6556	219.80			200 4
	26.27	CO 1000	200 00	13.53		200.4
	-36.37	60.1228	222.22	13.84	14.48	200.5
	-36.37	60.1228	222.22	13.84	14.48	200.5
	-36.37	60.1228	222.22	13.84	14.48	200.5 200.5 200.6
50.48 52.84 55.07	-36.37 -32.94 -29.14 -24.92	60.1228 46.2813 33.9624 20.5893	222.22 225.00 228.19 231.84	13.84 12.32 13.37 10.29	14.48 16.28 15.00 19.50	200.5 200.5 200.6 200.7
50.48 52.84 55.07 57.13	-36.37 -32.94 -29.14 -24.92 -20.22	60.1228 46.2813 33.9624 20.5893 10.2966	222.22 225.00 228.19 231.84 235.99	13.84 12.32 13.37 10.29 10.30	14.48 16.28 15.00 19.50 19.50	200.5 200.5 200.6 200.7 200.8
50.48 52.84 55.07 57.13	-36.37 -32.94 -29.14 -24.92 -20.22	60.1228 46.2813 33.9624 20.5893	222.22 225.00 228.19 231.84 235.99	13.84 12.32 13.37 10.29 10.30	14.48 16.28 15.00 19.50 19.50	200.5 200.5 200.6 200.7 200.8 0.0
50.48 52.84 55.07 57.13	-36.37 -32.94 -29.14 -24.92 -20.22	60.1228 46.2813 33.9624 20.5893 10.2966	222.22 225.00 228.19 231.84 235.99	13.84 12.32 13.37 10.29 10.30	14.48 16.28 15.00 19.50 19.50	200.5 200.5 200.6 200.7 200.8
50.48 52.84 55.07 57.13	-36.37 -32.94 -29.14 -24.92 -20.22	60.1228 46.2813 33.9624 20.5893 10.2966	222.22 225.00 228.19 231.84 235.99 0.00	13.84 12.32 13.37 10.29 10.30 0.00	14.48 16.28 15.00 19.50 19.50 0.00	200.5 200.5 200.6 200.7 200.8 0.0
50.48 52.84 55.07 57.13	-36.37 -32.94 -29.14 -24.92 -20.22	60.1228 46.2813 33.9624 20.5893 10.2966	222.22 225.00 228.19 231.84 235.99 0.00 AV SP	13.84 12.32 13.37 10.29 10.30 0.00	14.48 16.28 15.00 19.50 19.50 0.00	200.5 200.5 200.6 200.7 200.8 0.0 1611.2
50.48 52.84 55.07 57.13 59.00	-36.37 -32.94 -29.14 -24.92 -20.22 -15.00	60.1228 46.2813 33.9624 20.5893 10.2966 0.0000	222.22 225.00 228.19 231.84 235.99 0.00 AV SP	13.84 12.32 13.37 10.29 10.30 0.00	14.48 16.28 15.00 19.50 19.50 0.00	200.5 200.5 200.6 200.7 200.8 0.0
50.48 52.84 55.07 57.13 59.00	-36.37 -32.94 -29.14 -24.92 -20.22 -15.00	60.1228 46.2813 33.9624 20.5893 10.2966 0.0000 TO THE POI	222.22 225.00 228.19 231.84 235.99 0.00 AV SP *****	13.84 12.32 13.37 10.29 10.30 0.00 EED - MINIMUM	14.48 16.28 15.00 19.50 19.50 0.00 17.04 TIME ROU	200.5 200.5 200.6 200.7 200.8 0.0 1611.2
50.48 52.84 55.07 57.13 59.00 ALUES LAT	-36.37 -32.94 -29.14 -24.92 -20.22 -15.00 ARE THOSE LON	60.1228 46.2813 33.9624 20.5893 10.2966 0.0000 TO THE POI TOT TIME	222.22 225.00 228.19 231.84 235.99 0.00 AV SP ***** INT HEADNG	13.84 12.32 13.37 10.29 10.30 0.00 EED = MINIMUM TIME	14.48 16.28 15.00 19.50 19.50 0.00 17.04 TIME ROU SPEED	200.5 200.5 200.6 200.7 200.8 0.0 1611.2 DISTNCE
50.48 52.84 55.07 57.13 59.00	-36.37 -32.94 -29.14 -24.92 -20.22 -15.00	60.1228 46.2813 33.9624 20.5893 10.2966 0.0000 TO THE POI	222.22 225.00 228.19 231.84 235.99 0.00 AV SP *****	13.84 12.32 13.37 10.29 10.30 0.00 EED = MINIMUM TIME	14.48 16.28 15.00 19.50 19.50 0.00 17.04 TIME ROU	200.5 200.5 200.6 200.7 200.8 0.0 1611.2
50.48 52.84 55.07 57.13 59.00 ALUES LAT	-36.37 -32.94 -29.14 -24.92 -20.22 -15.00 ARE THOSE LON	60.1228 46.2813 33.9624 20.5893 10.2966 0.0000 TO THE POI TOT TIME	222.22 225.00 228.19 231.84 235.99 0.00 AV SP ***** INT HEADNG	13.84 12.32 13.37 10.29 10.30 0.00 EED = MINIMUM TIME	14.48 16.28 15.00 19.50 19.50 0.00 17.04 TIME ROU SPEED	200.5 200.5 200.6 200.7 200.8 0.0 1611.2 DISTNCE
57.13 59.00 ALUES LAT Deg 40.00	-36.37 -32.94 -29.14 -24.92 -20.22 -15.00 ARE THOSE LON Deg	60.1228 46.2813 33.9624 20.5893 10.2966 0.0000 TO THE POI TOT TIME Hours 91.5665	222.22 225.00 228.19 231.84 235.99 0.00 AV SP ***** INT HEADNG Degs 214.98	13.84 12.32 13.37 10.29 10.30 0.00 EED = MINIMUM TIME Hr	14.48 16.28 15.00 19.50 19.50 0.00 17.04 TIME ROU SPEED	200.5 200.5 200.6 200.7 200.8 0.0 1611.2 UTE ***** DISTNCE Nms 7.4
50.48 52.84 55.07 57.13 59.00 ALUES LAT Deg	-36.37 -32.94 -29.14 -24.92 -20.22 -15.00 ARE THOSE LON Deg	60.1228 46.2813 33.9624 20.5893 10.2966 0.0000 TO THE POI TOT TIME Hours	222.22 225.00 228.19 231.84 235.99 0.00 AV SP ***** INT HEADNG Degs 214.98	13.84 12.32 13.37 10.29 10.30 0.00 EED - MINIMUM TIME Hr	14.48 16.28 15.00 19.50 19.50 0.00 17.04 TIME ROU SPEED Kts	200.5 200.5 200.6 200.7 200.8 0.0 1611.2 UTE ***** DISTNCE Nms
50.48 52.84 55.07 57.13 59.00 ALUES LAT Deg 40.00 40.10	-36.37 -32.94 -29.14 -24.92 -20.22 -15.00 ARE THOSE LON Deg -45.00 -44.91 -41.34	60.1228 46.2813 33.9624 20.5893 10.2966 0.0000 TO THE POI TOT TIME Hours 91.5665 91.1883 80.5158	222.22 225.00 228.19 231.84 235.99 0.00 AV SP ***** INT HEADNG Degs 214.98 231.00 232.80	13.84 12.32 13.37 10.29 10.30 0.00 EED = MINIMUM TIME Hr 0.38 10.67	14.48 16.28 15.00 19.50 19.50 0.00 17.04 TIME ROU SPEED Kts	200.5 200.5 200.6 200.7 200.8 0.0 1611.2 UTE ***** DISTNCE Nms 7.4
50.48 52.84 55.07 57.13 59.00 ALUES LAT Deg 40.00 40.10 42.28	-36.37 -32.94 -29.14 -24.92 -20.22 -15.00 ARE THOSE LON Deg -45.00 -44.91 -41.34	60.1228 46.2813 33.9624 20.5893 10.2966 0.0000 TO THE POI TOT TIME Hours 91.5665 91.1883 80.5158	222.22 225.00 228.19 231.84 235.99 0.00 AV SP ***** INT HEADNG Degs 214.98 231.00 232.80	13.84 12.32 13.37 10.29 10.30 0.00 EED = MINIMUM TIME Hr 0.38 10.67 10.65	14.48 16.28 15.00 19.50 19.50 0.00 17.04 TIME ROU SPEED Kts 19.50 19.50	200.5 200.5 200.6 200.7 200.8 0.0 1611.2 DISTNCE Nms 7.4 208.1 207.7 208.0
50.48 52.84 55.07 57.13 59.00 ALUES LAT Deg 40.00 40.10 42.28 44.38 46.33	-36.37 -32.94 -29.14 -24.92 -20.22 -15.00 ARE THOSE LON Deg -45.00 -44.91 -41.34 -37.56 -33.50	60.1228 46.2813 33.9624 20.5893 10.2966 0.0000 TO THE POI TOT TIME Hours 91.5665 91.1883 80.5158 69.8635 57.1203	222.22 225.00 228.19 231.84 235.99 0.00 AV SP ***** INT HEADNG Degs 214.98 231.00 232.80 235.64 238.80	13.84 12.32 13.37 10.29 10.30 0.00 EED = MINIMUM TIME Hr 0.38 10.67 10.65 12.74 13.52	14.48 16.28 15.00 19.50 19.50 0.00 17.04 TIME ROU SPEED Kts 19.50 19.50 19.50	200.5 200.5 200.6 200.7 200.8 0.0 1611.2 DISTNCE Nms 7.4 208.1 207.7 208.0 208.2
50.48 52.84 55.07 57.13 59.00 ALUES LAT Deg 40.00 40.10 42.28 44.38 46.33 48.13	-36.37 -32.94 -29.14 -24.92 -20.22 -15.00 ARE THOSE LON Deg -45.00 -44.91 -41.34 -37.56 -33.50 -29.14	60.1228 46.2813 33.9624 20.5893 10.2966 0.0000 TO THE POI TOT TIME Hours 91.5665 91.1883 80.5158 69.8635 57.1203 43.5998	222.22 225.00 228.19 231.84 235.99 0.00 AV SP ***** INT HEADNG Degs 214.98 231.00 232.80 235.64 238.80 228.22	13.84 12.32 13.37 10.29 10.30 0.00 EED - MINIMUM TIME Hr 0.38 10.67 10.65 12.74 13.52 11.14	14.48 16.28 15.00 19.50 19.50 0.00 17.04 TIME ROU SPEED Kts 19.50 10.83 15.40 18.06	200.5 200.5 200.6 200.7 200.8 0.0 1611.2 DISTNCE Nms 7.4 208.1 207.7 208.0
50.48 52.84 55.07 57.13 59.00 ALUES LAT Deg 40.00 40.10 42.28 44.38 46.33 48.13 50.36	-36.37 -32.94 -29.14 -24.92 -20.22 -15.00 ARE THOSE LON Deg -45.00 -44.91 -41.34 -37.56 -33.50 -29.14 -25.33	60.1228 46.2813 33.9624 20.5893 10.2966 0.0000 TO THE POT TOT TIME HOURS 91.5665 91.1883 80.5158 69.8635 57.1203 43.5998 32.4601	222.22 225.00 228.19 231.84 235.99 0.00 AV SP ***** INT HEADNG Degs 214.98 231.00 232.80 235.64 238.80 228.22 217.01	13.84 12.32 13.37 10.29 10.30 0.00 EED = MINIMUM TIME Hr 0.38 10.67 10.65 12.74 13.52 11.14 10.53	14.48 16.28 15.00 19.50 19.50 0.00 17.04 TIME ROU SPEED Kts 19.50 19.50 19.50 19.50 19.50 19.50 19.50 19.50 19.50 19.50 19.50	200.5 200.5 200.6 200.7 200.8 0.0 1611.2 DISTNCE Nms 7.4 208.1 207.7 208.0 208.2
50.48 52.84 55.07 57.13 59.00 ALUES LAT Deg 40.00 40.10 42.28 44.38 46.33 48.13 50.36	-36.37 -32.94 -29.14 -24.92 -20.22 -15.00 ARE THOSE LON Deg -45.00 -44.91 -41.34 -37.56 -33.50 -29.14 -25.33	60.1228 46.2813 33.9624 20.5893 10.2966 0.0000 TO THE POI TOT TIME Hours 91.5665 91.1883 80.5158 69.8635 57.1203 43.5998	222.22 225.00 228.19 231.84 235.99 0.00 AV SP ***** INT HEADNG Degs 214.98 231.00 232.80 235.64 238.80 228.22 217.01	13.84 12.32 13.37 10.29 10.30 0.00 EED - MINIMUM TIME Hr 0.38 10.67 10.65 12.74 13.52 11.14	14.48 16.28 15.00 19.50 19.50 0.00 17.04 TIME ROU SPEED Kts 19.50 18.06	200.5 200.5 200.6 200.7 200.8 0.0 1611.2 DISTNCE Nms 7.4 208.1 207.7 208.0 208.2 201.1
50.48 52.84 55.07 57.13 59.00 ALUES LAT Deg 40.00 40.10 42.28 44.38 46.33 48.13 50.36 53.09	-36.37 -32.94 -29.14 -24.92 -20.22 -15.00 ARE THOSE LON Deg -45.00 -44.91 -41.34 -37.56 -33.50 -29.14 -25.33	60.1228 46.2813 33.9624 20.5893 10.2966 0.0000 TO THE PO TOT TIME HOURS 91.5665 91.1883 80.5158 69.8635 57.1203 43.5998 32.4601 21.9263	222.22 225.00 228.19 231.84 235.99 0.00 AV SP ***** INT HEADNG Degs 214.98 231.00 232.80 235.64 238.80 228.22 217.01 217.55	13.84 12.32 13.37 10.29 10.30 0.00 EED = MINIMUM TIME Hr 0.38 10.67 10.65 12.74 13.52 11.14 10.53	14.48 16.28 15.00 19.50 19.50 0.00 17.04 TIME ROU SPEED Kts 19.50	200.5 200.5 200.6 200.7 200.8 0.0 1611.2 UTE ***** DISTNCE Nms 7.4 208.1 207.7 208.0 208.2 201.1 205.4 203.3 224.2
50.48 52.84 55.07 57.13 59.00 ALUES LAT Deg 40.00 40.10 42.28 44.38 46.33 48.13 50.36 53.09 55.78	-36.37 -32.94 -29.14 -24.92 -20.22 -15.00 ARE THOSE LON Deg -45.00 -44.91 -41.34 -37.56 -33.50 -29.14 -25.33 -22.01	60.1228 46.2813 33.9624 20.5893 10.2966 0.0000 TO THE PO TOT TIME HOURS 91.5665 91.1883 80.5158 69.8635 57.1203 43.5998 32.4601 21.9263	222.22 225.00 228.19 231.84 235.99 0.00 AV SP ***** INT HEADNG Degs 214.98 231.00 232.80 235.64 238.80 228.22 217.01 217.55 210.16	13.84 12.32 13.37 10.29 10.30 0.00 EED = MINIMUM TIME Hr 0.38 10.67 10.65 12.74 13.52 11.14 10.53 10.43	14.48 16.28 15.00 19.50 19.50 0.00 17.04 TIME ROU SPEED Kts 19.50 19.50 19.50 19.50 19.50 19.50 19.50 19.50 19.50 19.50 19.50 19.50 19.50 19.50	200.5 200.5 200.6 200.7 200.8 0.0 1611.2 UTE ***** DISTNCE Nms 7.4 208.1 207.7 208.0 208.2 201.1 205.4 203.3

AV SPEED = 18.28

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ROUTEING MODEL OUTPUT ANALYSIS DATA FROM 1st May 1991

16.00 19.50 23.00 POWER 11765.07 SHIP SPEEDS (+) EAST (-) WEST MOVEMENT -1.000000 GREAT CIRCLE POINTS 59.00 -15.00 59.00 -15.00 238.19 57.13 -20.22 231.84 55.07 -24.92 228.19 52.84 -29.14 225.00 50.48 -32.94 222.22 -36.37 219.80 48.01 -39.47 217.69 45.45 42.81 -42.31 215.85 40.10 -44.91 214.98 -45.00 40.00 GREAT CIRCLE DISTANCE = 1607.435 INITIAL GREAT CIRCLE COURSE (RADS) = 2.126024 NUMBER OF STAGES = 10

CRDIST	10 10 St. 10 10 10 10 10 10 10 10 10 10 10 10 10	CIRCLE =	1607.	and the second second	Sec. 1	a santan
LAT Deg	LON Deg	TOT TIME Hours	HEADNG Degs	TIME Hr	SPEED Kts	DISTNCE Nms
40.00	-45.00	90.1308	214.98	0.38	19.50	7.4
40.10	-44.91	89.7527	215.85	10.27	19.50	200.2
42.81	-42.31	79.4875	217.69	10.27	19.50	200.3
45.45	-39.47	69.2174	219.80	11.40	17.58	200.4
48.01	-36.37	57.8199	222.22	13.06	15.34	200.5
50.48	-32.94	44.7556	225.00	12.97	15.46	200.5
52.84	-29.14	31.7830	228.19	11.19	17.92	200.6
55.07	-24.92	20.5893	231.84	10.29	19.50	200.7
57.13	-20.22	10.2966	235.99	10.30	19.50	200.8
59.00	-15.00	0.0000	0.00	0.00	0.00	0.0
						1611.29
			AV SPI	EED =	17.88	

H	LAT Deg	LON Deg	TOT TIME Hours	HEADNG Degs	TIME Hr	SPEED Kts	DISTNCE Nms
4	0.00	-45.00	89.9383	214.98	0.38	19.50	7.4
- 4	0.10	-44.91	89.5601	215.85	10.27	19.50	200.2
- 4	2.81	-42.31	79.2950	217.69	10.27	19.50	200.3
- 4	5.45	-39.47	69.0248	219.80	11.40	17.58	200.4
4	8.01	-36.37	57.6298	237.90	12.95	16.16	209.3
4	9.86	-31.88	44.6750	226.06	12.71	15.79	200.7
5	2.18	-28.07	31.9608	229.31	11.15	18.01	200.8
5	4.36	-23.84	20.8111	230.73	10.20	19.50	199.0
5	6.46	-19.33	10.6068	222.34	10.61	19.50	206.8
59	.00	-15.00	0.0000	0.00	0.00	0.00	0.0
							1624.90
				AV SPI	EED =	18.07	

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Diagnostic Indicators in Trough-Ridge Systems applied to Real Time Ship Routeing

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dulu Signed.

B.J.Manhire