Dynamical Climatology

A study of a strong stratospheric warming during January 1982.

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DYNAMICAL CLIMATOLOGY TECHNICAL NOTE NO. 9

A STUDY OF A STRONG STRATOSPHERIC WARMING DURING JANUARY 1982

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1. Introduction

In January 1982 a strong warming took place in the stratosphere of the Northern Hemisphere. In this note, we present a descriptive account of the evolution of the warming, basing our discussion on maps of Ertel's Potential Vorticity, Q, evaluated on an isentropic surface. The maps clearly show planetary wave breaking in the stratosphere.

The advection of Q over long distances on isentropic surfaces was a striking feature of the flow during January. This could be identified because of our ability to follow the movement of material lines due to the approximate conservation of Q over several days.

In the course of the warming the polar vortex split into two distinct cyclonic vortices. Soon after, values of Q in the centre of one of these vortices were sharply reduced. We discuss how this locally poor conservation of Q may have occurred and consider the dynamical implications for the subsequent evolution of the circulation.

2. Data

The stratospheric data used in this study are taken from the daily analysis of data from a Stratospheric Sounding Unit (S.S.U.) on board the satellite NOAA-6. Thicknesses are computed by regression from radiance measurements and geopotential heights are obtained at standard pressure levels up to 1mb by adding these thicknesses to the 100mb height field, supplied by the National Meteorological Center (Washington). Temperature fields are obtained from the heights by a finite difference approximation to the hydrostatic equation. The method used to calculate maps of Q on isentropic surfaces is described in Clough et al. (1984) who give further details of the analysis of S.S.U. data.

Following Clough et al., we have assessed the reliability of the maps used in this study by comparing them with maps based on data from another S.S.U. on board the satellite NOAA-7 in independent orbit. The features to which we draw attention are closely reproduced in both sets of data.

3. Isentropic maps of Ertel's Potential Vorticity

Ertel's Potential Vorticity is defined by

$$Q = \rho^{-1} (\underline{\nabla} \times \underline{u} + 2\ \underline{\Omega}).\underline{\nabla}\ \theta$$

using conventional notation as detailed in the Appendix. Under adiabatic and inviscid conditions Q is conserved following the motion of the fluid, as is θ, so that contours of Q on isentropic surfaces mark material lines of the fluid to the extent that these conditions hold. To calculate Q on isentropic surfaces we use the approximation

$$Q \approx -g\ (\zeta_g + f)\ \frac{\delta\theta}{\delta p}$$

which assumes the flow to be hydrostatic and uses geostrophic winds (see Appendix). Full details of the calculation are given in Clough et al. who remark that the hydrostatic approximation is valid for large-scale atmospheric motions and that the use of geostrophic winds to calculate ζ does not lead to substantial error in Q at stratospheric levels.

The maps which we present here show Q on the 850K surface of potential temperature which lies near 10 mb in the middle stratosphere. Fels (1982) calculated a radiative damping time of about 20 days for deep disturbances in the lower and middle stratosphere. Our own calculations show that the area enclosed by particular contours of Q was generally well conserved in our maps over periods of a week or so. We therefore have some confidence in being able to follow the movement of material during events which develop over several days.

In the course of our discussion we remark on the extensive advection of Q over long distances on isentropic surfaces. This is a non-linear process because the changing distribution of Q influences the advecting wind field. By studying maps of Q, therefore, we not only follow the movement of material insofar as Q is conserved, but also the evolution of a quantity which is fundamental to the dynamics.

Fig. 1 shows a map of Q near the beginning of January. Arrows indicate the direction and relative strength of the geostrophic wind. Fields of geopotential height and temperature at 10 mb on the same day are shown in Fig. 2. The polar vortex is distinguished by an extensive area of high Q in Fig. 1. Q attains its highest values in the centre of the vortex and decreases rapidly towards the outer edge. Extending eastwards and northwards over Eastern Asia and the Northern Pacific is a tongue of low Q, almost coinciding with a ridge axis in the temperature field in Fig. 2. Minimum values of Q in the vicinity of the Aleutian high at 10 mb are characteristic of air much further south and suggest that the air comprising the anti-cyclone originated in low latitudes. To the south of the Aleutians is a tongue of relatively high Q with discrete maxima along its length. The tongue almost coincides with a trough axis in the temperature field in Fig. 2. Maximum values of Q within the tongue continue to be resolved on subsequent days, as are discrete minimum values in low latitudes over the Atlantic, Africa and Asia which mark the positions of weak, eastward-moving anti-cyclones (see Fig. 2).

The advection of Q over long distances on isentropic surfaces was a striking feature of the dynamics in early January. Successive maps of Q show that air from low latitudes was advected around the westerly vortex into the region of the Aleutian high. Meanwhile, air was drawn from the vortex into a tongue of high Q, with separate maxima along its length, which extended westwards around the southern side of the Aleutian high. These developments involve the time-irreversible deformation of material lines which is characteristic of planetary wave breaking in the stratosphere (see McIntyre 1982, and McIntyre & Palmer 1983, 1984).

Fig. 3 shows Q on 8 January shortly after one of the maxima within the tongue of high Q had recombined with the vortex over Eastern Asia. The area of low Q over the Aleutians had increased after advection of air from low latitudes, and at 10mb the Aleutian high was more intense than before.

Fig. 4 shows Q on 13 January. By this time the Aleutian high was weaker and disturbances to the flow over the Northern Pacific were less intense. A long tongue of low Q stretching over the Northern Pacific was still a notable feature, however, and a detached mass of high Q over Eastern Asia continued to be advected slowly westwards. A new quasi-stationary anti-cyclone was beginning to develop over the North Atlantic, marked by an intrusion of low Q. This occurred shortly after a ridge over Alaska became a marked feature of the tropospheric flow.

As the new Atlantic anti-cyclone grew and the Aleutian high weakened, between 13 and 19 January, disturbances to the flow over the North Atlantic became more intense. Air from low latitudes was advected around the westerly vortex into the region of the Atlantic high, and a tongue of high Q was drawn south over Europe, extending around the eastern side of the anti-cyclone. The polar vortex was elongated and two distinct centres of high Q were formed. These developments are shown in Fig. 5 for 18 January.

From 19 January, the Aleutian high began to intensify after a blocking system over Europe became a marked feature of the tropospheric flow. The stratospheric flow over the Northern Pacific became highly disturbed and, as the vortex was increasingly elongated, air of low Q was advected directly into polar latitudes. Fig. 6 shows the effect of these developments on the height and temperature fields at 10mb. By 24 January there was a strong warming of polar latitudes. The polar vortex was split into two distinct circulations, a strong vortex over Siberia and a weaker vortex over North America. These are distinguished by separate maxima of Q in Fig. 7.

After 24 January, values of Q in the centre of the North American vortex were sharply reduced. Fig. 8 shows that by 27 January only a long thin tongue of high Q remained. Meanwhile, the vortex rapidly weakened in the 10mb height field so that by 27 January, it was no longer a distinct feature. By 31 January, the distribution of Q was as shown in Fig. 9. This distribution remained relatively unchanged for the first week of February.

The locally poor conservation of Q associated with the weakening of the North American vortex was at least partly due to the limited resolution of the satellite data, particularly in the vertical. In an independent 10mb analysis of 27 January based on radiosonde and rocket data by Naujokat et al., the vortex was retained.

Extreme values of Q may be lost in the analysis of S.S.U data when vertical or horizontal structure is generated on scales below those which can adequately be resolved by the radiometer. Sufficiently strong vertical shears could be produced by the advection of Q at different rates on different isentropic surfaces (differential advection). Small-scale horizontal structure could be generated by the mixing of Q on isentropic surfaces (McIntyre, 1982). Radiosonde data clearly shows the presence of strong temperature stratification near 10mb in the vicinity of the North American vortex. This may be associated with differential advection of Q.

The introduction of strong vertical shears to the stratosphere by differential advection has important dynamical implications for the subsequent evolution of the circulation. Firstly, the vertical propagation of planetary waves depends on the coarse-grain field of Q because horizontal and vertical wavelengths are relatively large. When Q is taken up in comparatively small vertical scales, the distribution of Q which the waves 'feel' is altered and their propagation is affected. Secondly, non-conservative changes in Q due to radiation occur on shorter time-scales in regions where strong temperature gradients exist (Fels, 1982).

4. Summary

Our report on the stratospheric warming of January 1982 has concentrated on the behaviour of Ertel's Potential Vorticity, Q, during the event.

Non-linear advection of Q over long distances on isentropic surfaces was an important element of the dynamics. The westerly vortex became highly distorted by disturbances strong enough to break off air of high Q, and capable of bringing air from low latitudes directly over the polar cap. These developments could be identified because of the approximate conservation of Q over several days.

Values of Q in the centre of major stratospheric features were generally well conserved in our sequence of maps. We identify an occasion in late January, however, when conservation of Q was locally poor. This occurred when vertical structure was generated on scales below those which could adequately be resolved. In such circumstances the movement of material can no longer be followed, but the development of strong vertical shears has important dynamical consequences for the evolving circulation.

In a forthcoming paper, the warming of January 1982 will be discussed within the context of stratospheric sudden warmings in general. Several events will be compared and contrasted including the celebrated warming of February 1979 which also involved the splitting of the polar vortex.

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Appendix

Symbols used in the text

f	Coriolis parameter
g	Acceleration due to gravity
P	Pressure
Q	Ertel's Potential Vorticity
$\underline{u}$	Velocity relative to the rotating Earth
ζ	Vertical component of the relative vorticity
ζ_g	ζ calculated from geostrophic winds
θ	Potential temperature
ρ	Density
$\underline{\Omega}$	Angular velocity of the rotating Earth.

REFERENCES

Clough, S.A., Grahame, N.S. and O'Neill, A., 1984.
'Potential vorticity for the stratosphere derived from satellite data.'
(To be submitted to Q.J.R.M.S.)

Fels, S.B., 1982

'A parametrization of scale dependent radiative damping rates in the middle atmosphere'.

(J. Atmos. Sci., 39, 1141-1152).

McIntyre, M.E., 1982

'How well do we understand the dynamics of stratospheric warmings?'

(J. Met. Soc., Japan, 60, 37-65).

McIntyre, M.E. and Palmer, T.N. 1983

'Breaking planetary waves in the stratosphere'.

(Nature, 305, 593-600).

McIntyre, M.E. and Palmer, T.N. 1984

'The 'surf zone' in the stratosphere' (J. Atmos. Terr. Phys., in press).

Naujokat, B., Petzoldt, K. Labitzke, K. and Lenschow, R., 1982

'The fourth winter of PMP-1, 1981/82: A winter with several interesting features'.

(Beilage zur Berliner Wetterkarte, Free University, Berlin).

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Fig. 1 Q on the 850K surface of potential temperature for 3 January 1982. (Units: $K.m^2kg^{-1}s^{-1} \times 10^{-4}$).

Fig. 2. Geopotential heights ((DAM), full lines) and temperatures ((K), pecked lines) at 10 mb for 3 January 1982.

Fig. 3 As for Fig. 1 but for 8 January 1982.

Fig. 4 As for Fig. 1 but for 13 January 1982.

Fig. 5 As for Fig. 1 but for 18 January 1982.

Fig. 6 As for Fig. 2 but for 24 January 1982.

Fig. 7 As for Fig. 1 but for 24 January 1982.

Fig. 8 As for Fig. 1 but for 27 January 1982.

Fig. 9 As for Fig. 1 but for 31 January 1982.

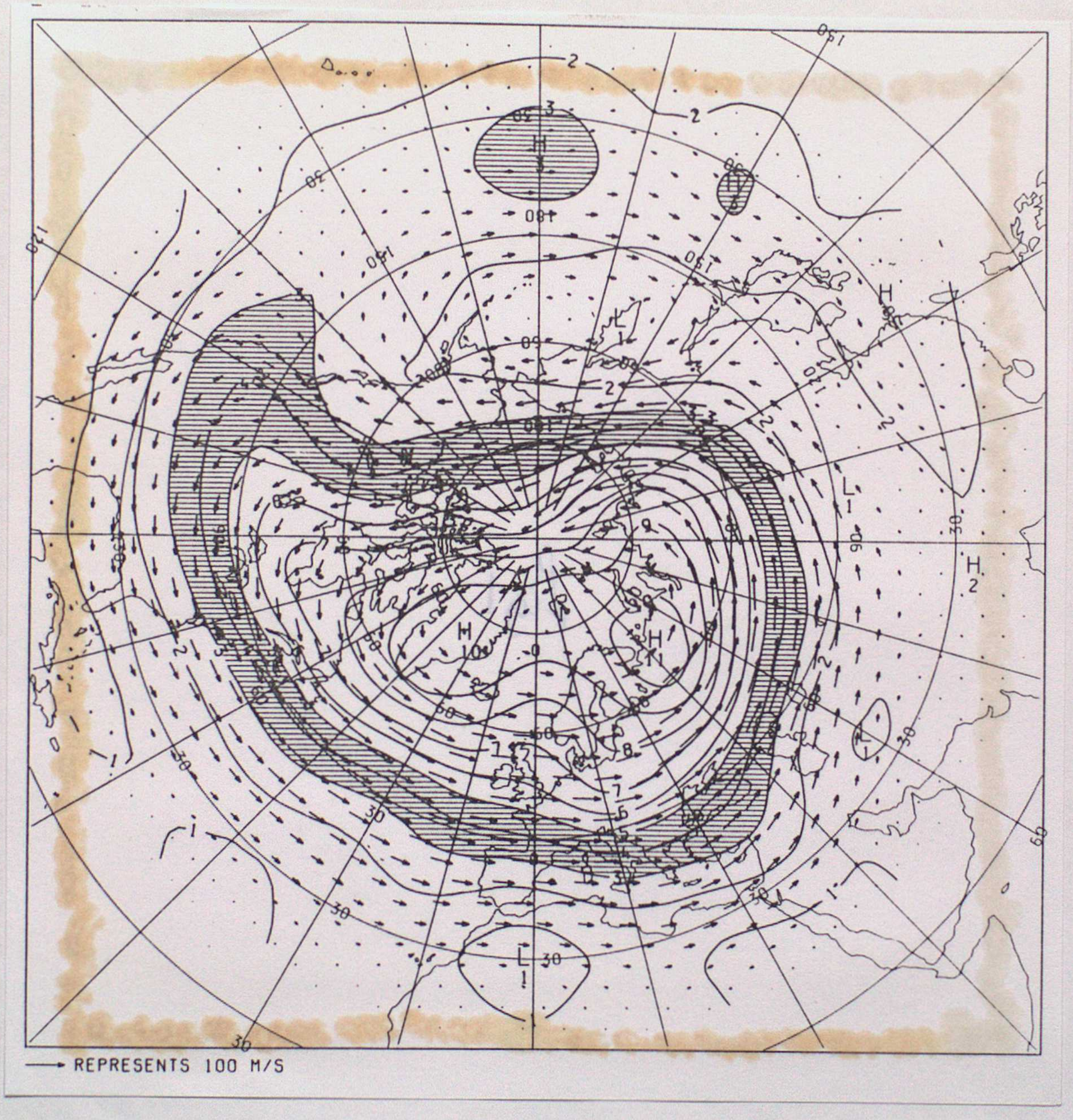

Fig 1

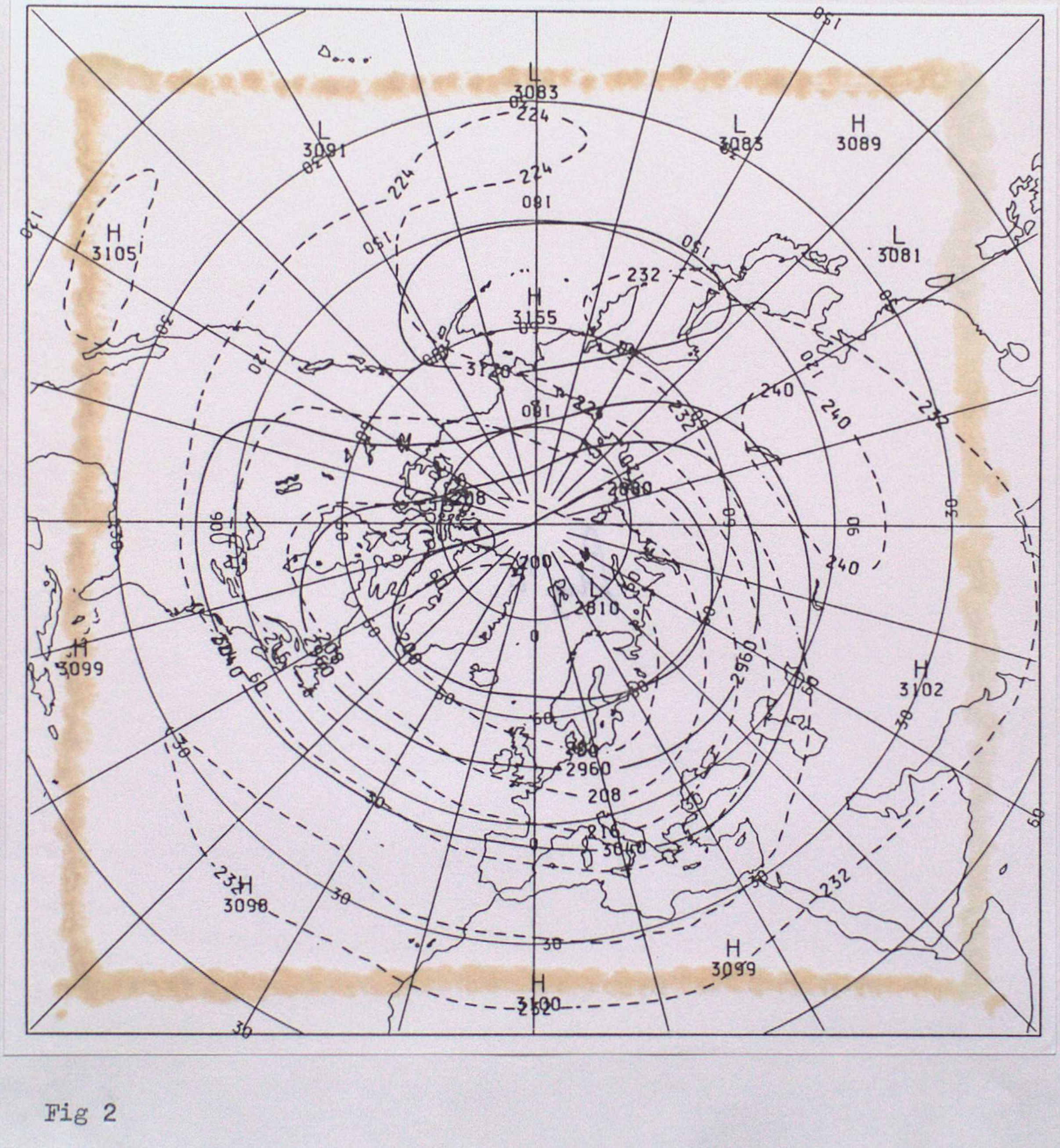

Fig 2

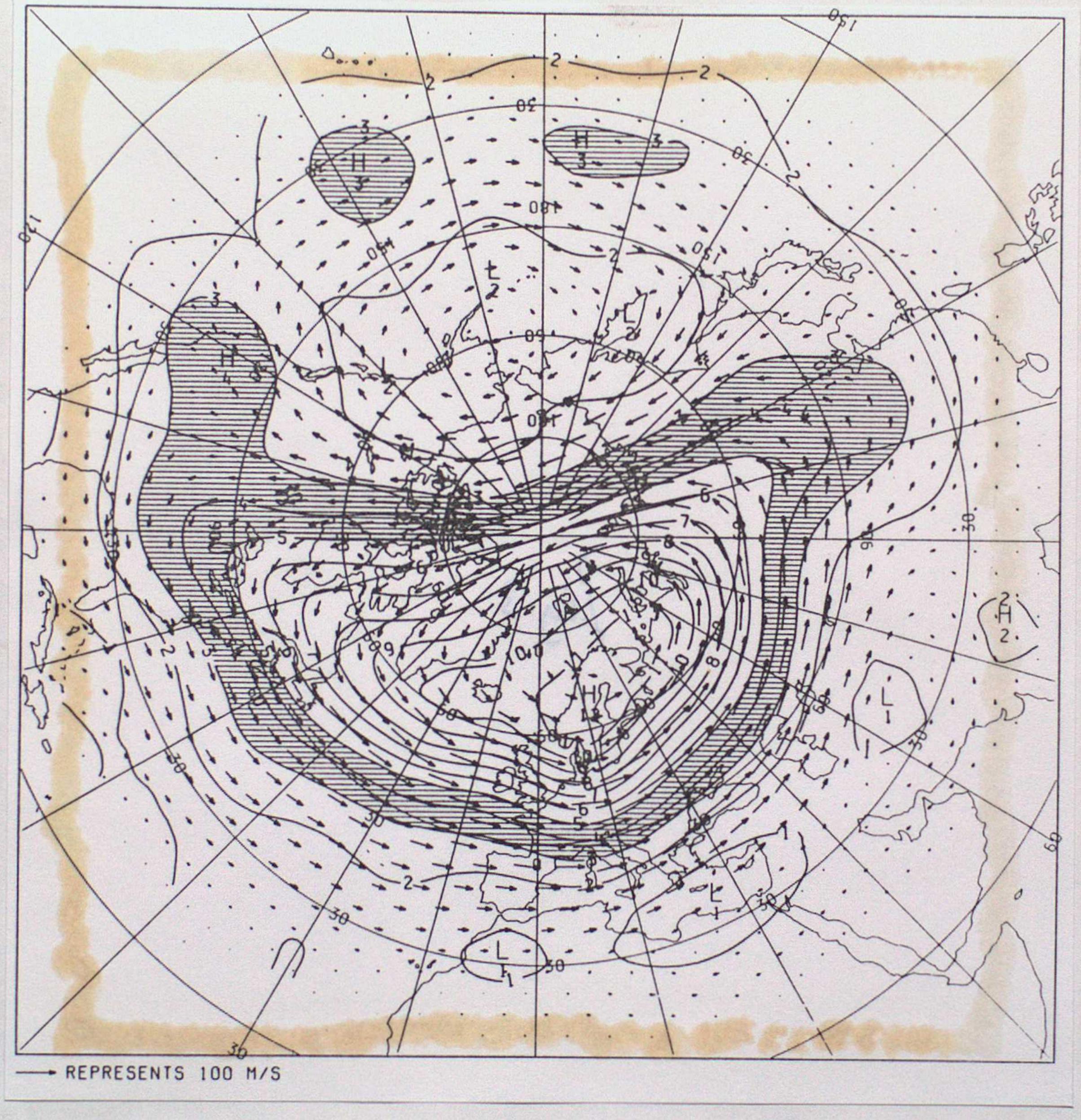

Fig 3

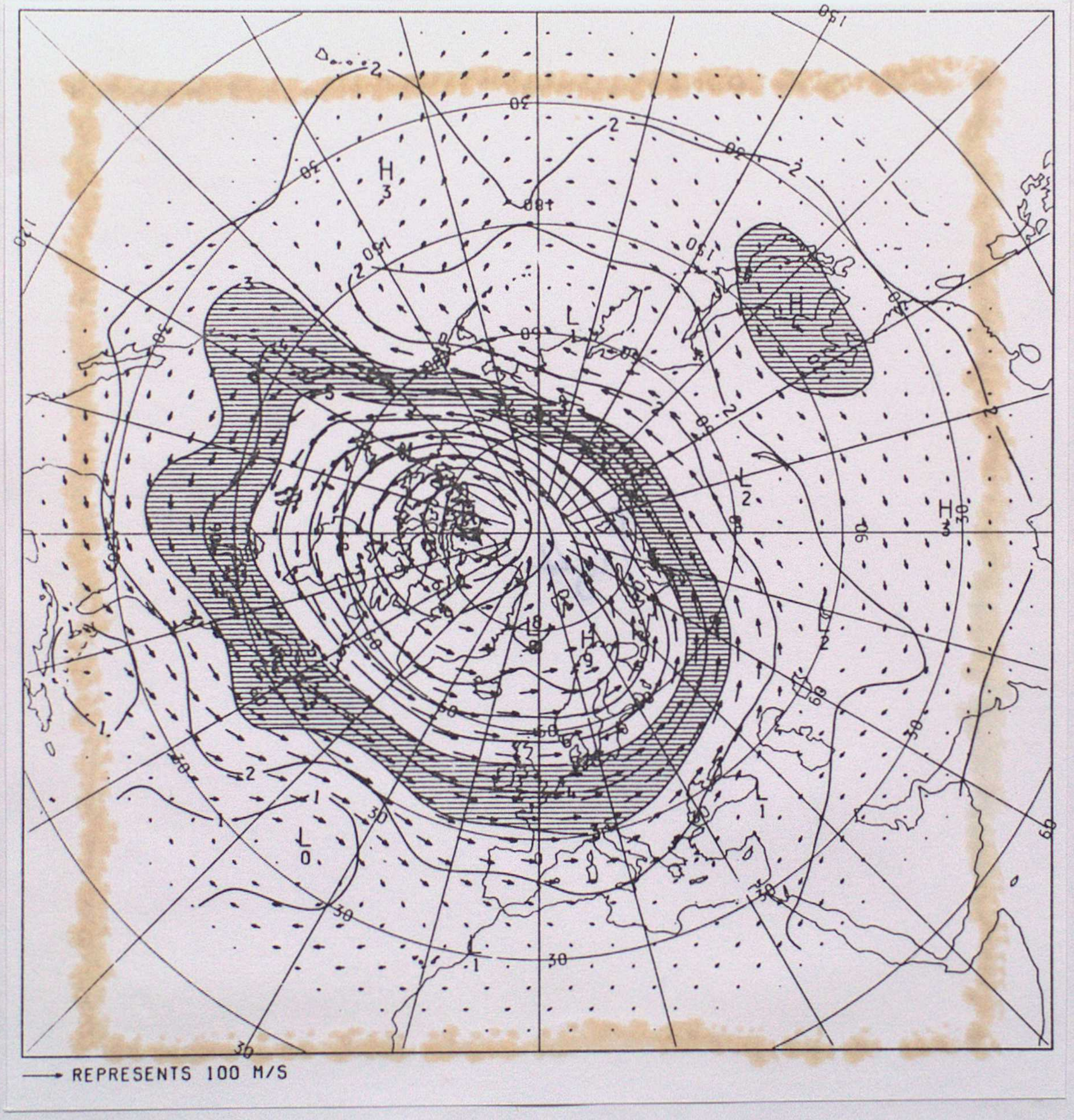

Fig 4

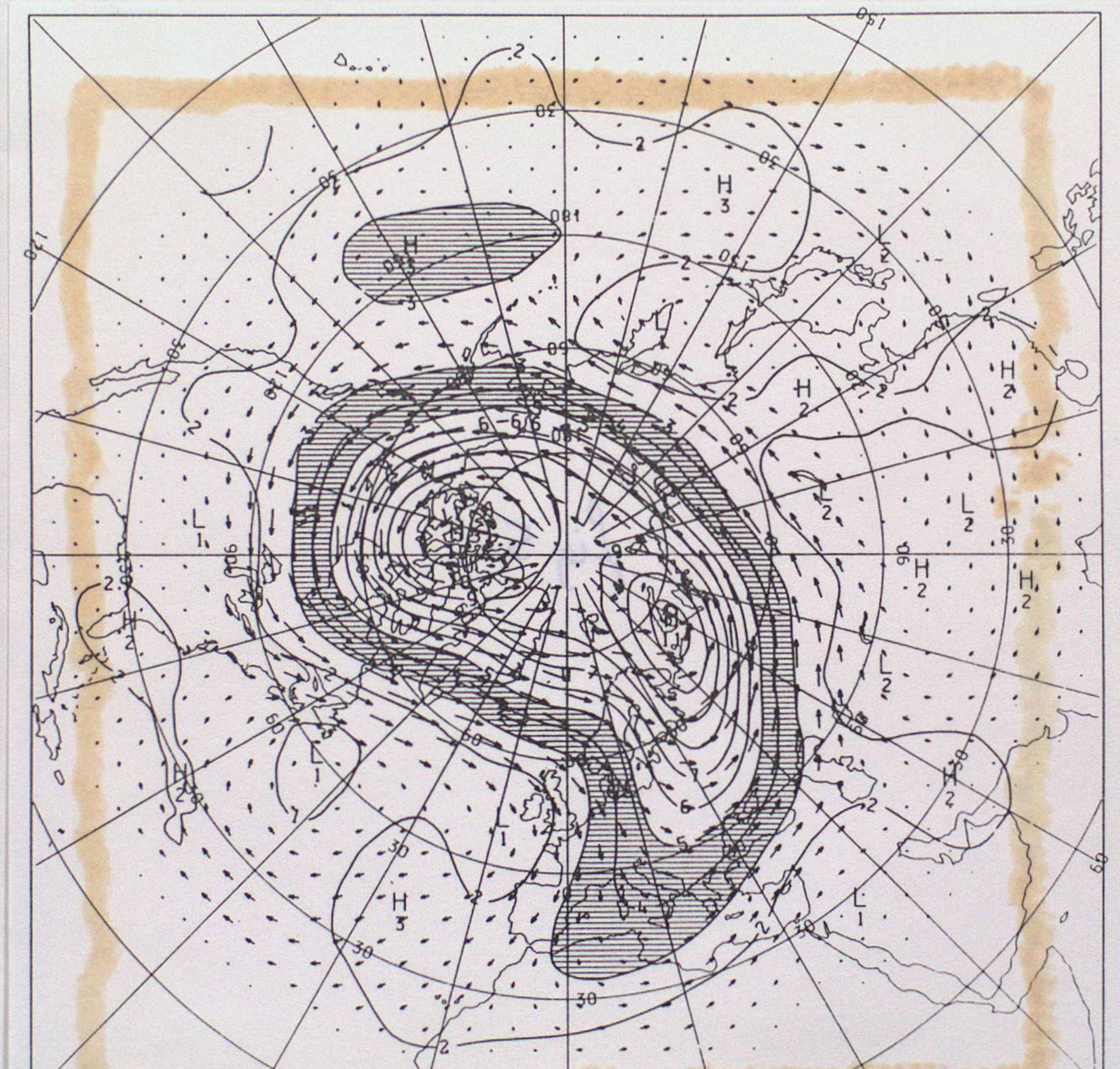

Fig 5

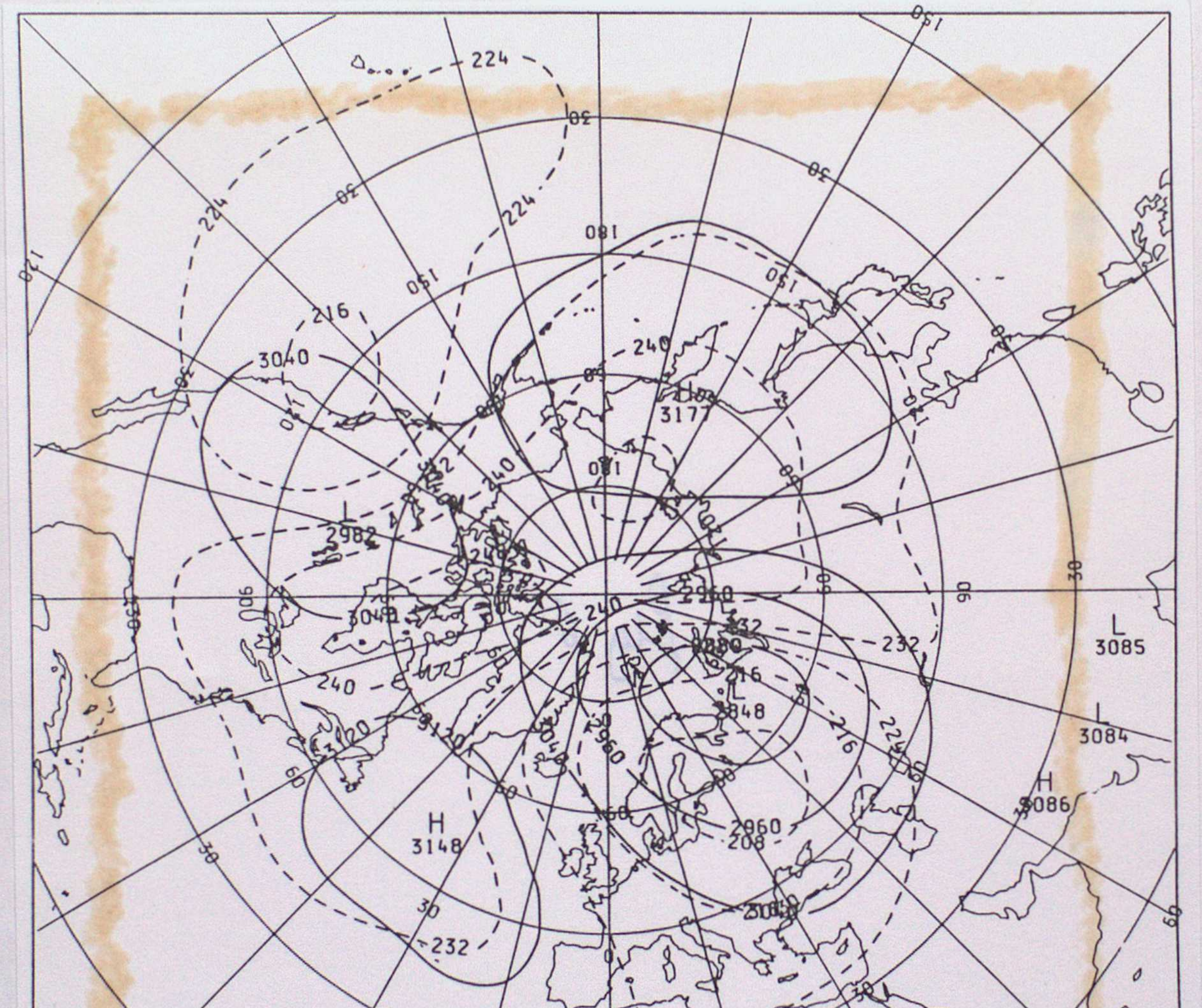

Fig 6

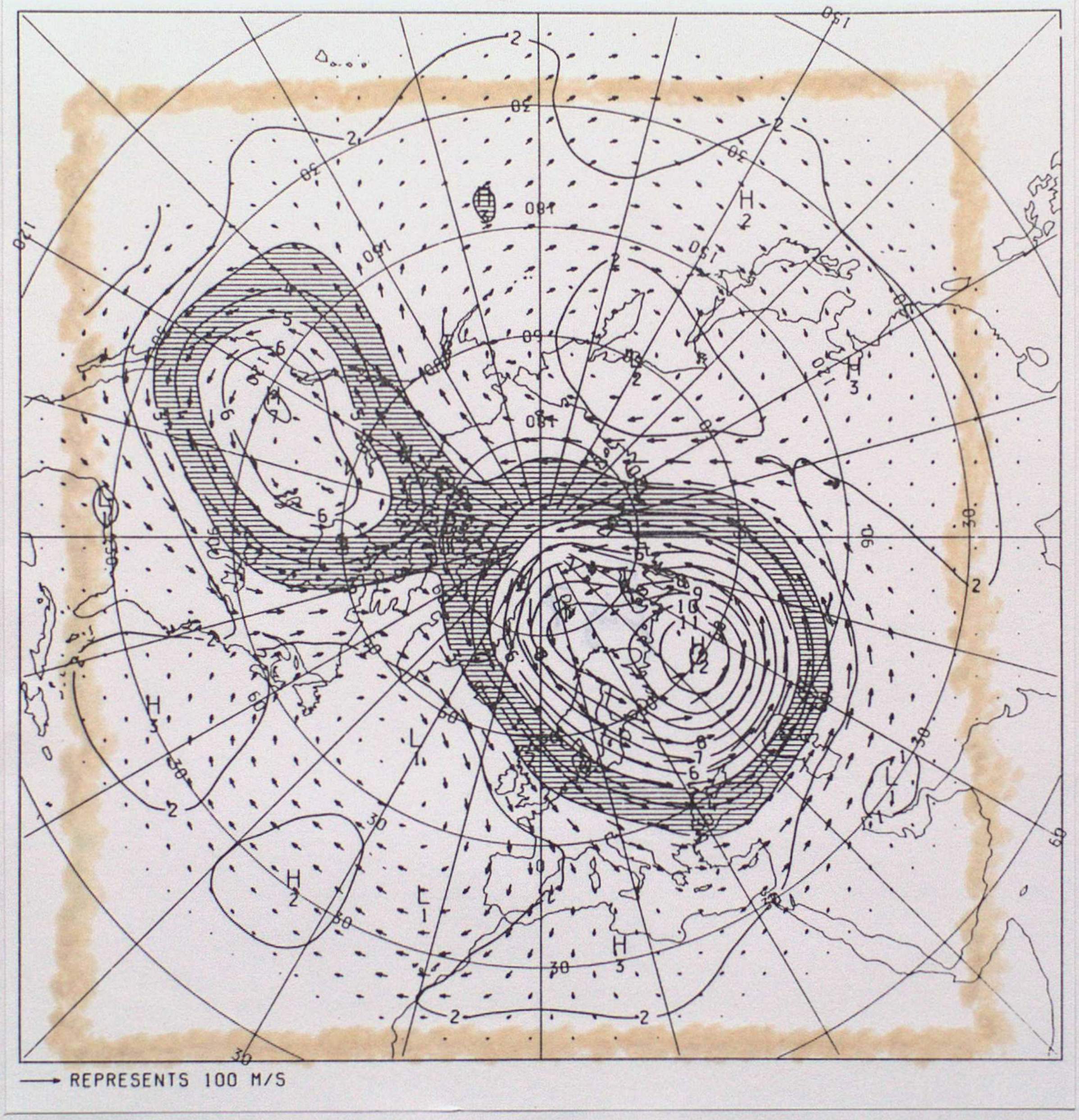

Fig 7

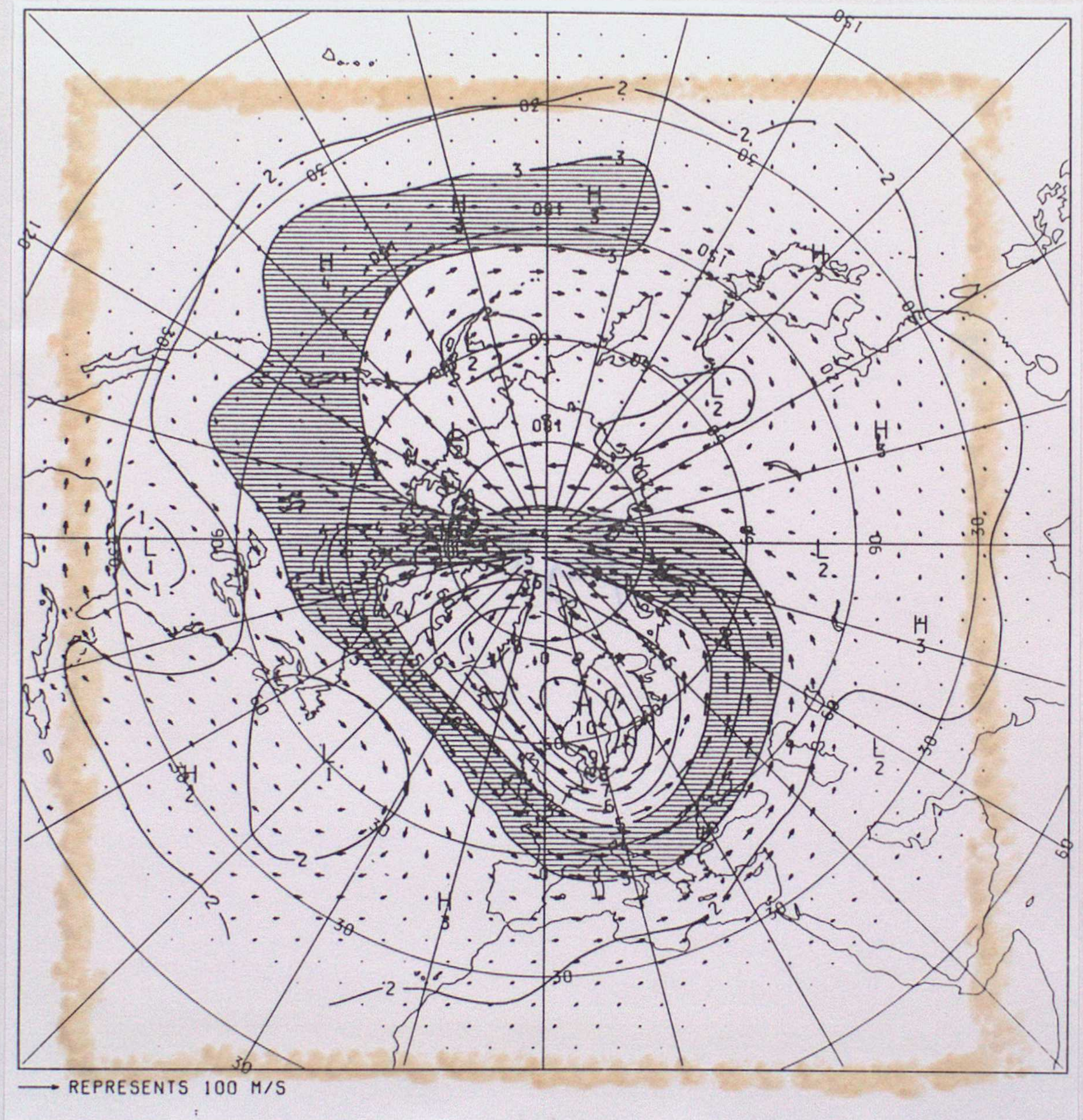

Fig 8

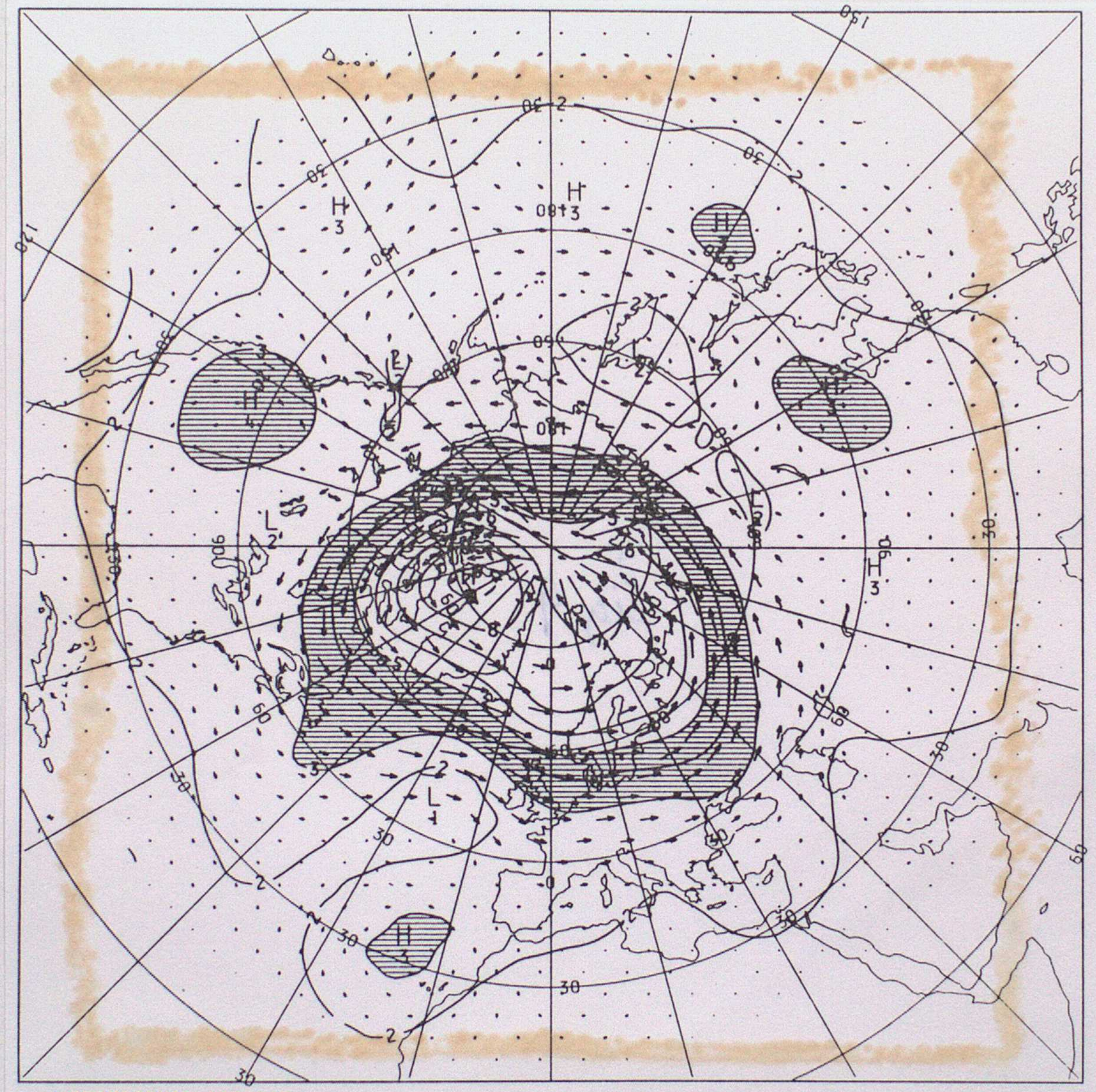

Fig 9