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Surface Wind Fields (on Earth)

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1 Introduction

This document sets out to clarify the role of fronts and other atmospheric features on the form of surface wind fields. This is intended as a basic meteorological review of the typical features we will encounter in wind fields. Thus there is a strong emphasis on description at a fairly rudimentary level. The document should prove useful as we think about different models we could adopt for wind fields. Footnotes are used (extensively) to explain non-vital meteorological *jargon*.

2 The Global Circulation

The wind we observe at the surface is driven (indirectly) by one energy source; the sun. The fact that we have winds (even '*weather*') can be attributed to the differential solar heating due to the shape, orientation and orbit of the earth. In this section I will briefly review the global circulation - since this has some relevance to our work.

Simply, the equator receives more energy than the poles. Thus there has to be some energy flux from the equator to the poles if an equilibrium is to be maintained. This flux is our '*weather*' and the ocean currents. If the earth were not rotating this flux would take the form of a direct cell circulation with warm air rising in equatorial regions, cooling as it travelled north and descending in polar latitudes. Thus at the surface we might experience dominant cool, northerly winds. Of course this does not occur - our circulation is far more complex.

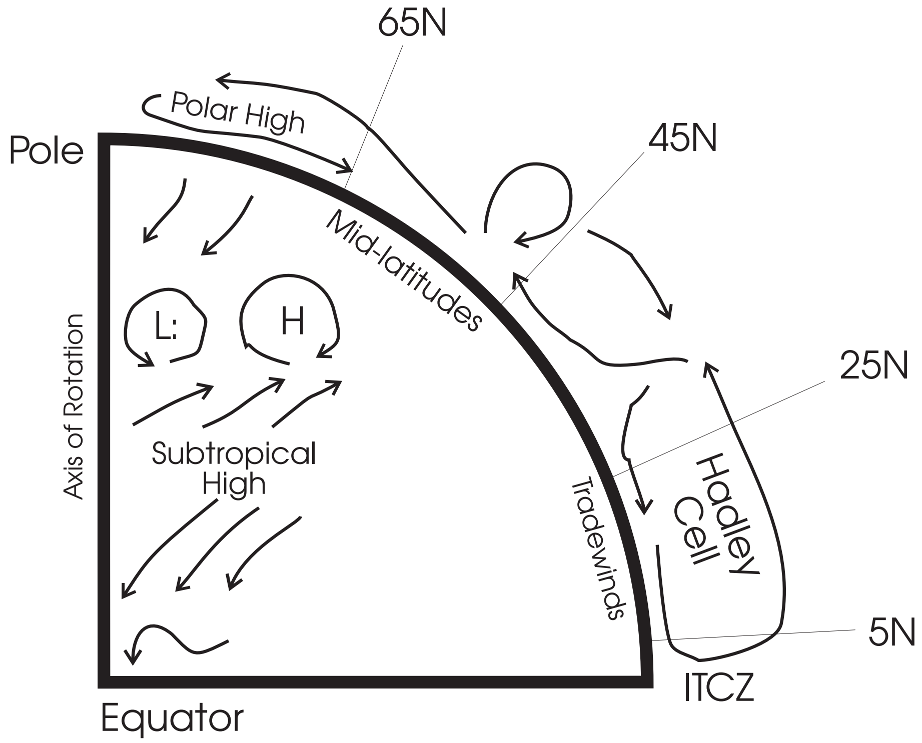

Figure 1: A simplified view of the global circulation (Northern Hemisphere only) showing a cross-section through the atmosphere (on the right) and the expected surface flows (on the left). Features are labelled (L = low, H = high).

2.1 Tropics and sub-tropics

In our real atmosphere, the rising air in equatorial latitudes is an observed feature. Not only is this air warm it is also generally moist and thus produces cloud and rain[1]. Since mass in the atmosphere must be conserved, all this rising air must go somewhere. The air cannot rise indefinitely - eventually in meets the *tropopause*[2]

The *tropopause* acts as a lid to vertical motion in the troposphere. Thus the rising air has nowhere to go except sideways - and in the Northern Hemisphere (NH) - on which I shall concentrate - this means generally northwards motion (Figure 1). As the air travels northwards it cools (by radiation to space) but since we are on a rotating planet it is also subjected to another force. This is the *Coriolis* force which is attributable to the conservation of angular momentum. As the air travels northwards it gets gradually closer to the axis of rotation of the earth (looking from the north pole the earth spins in a clockwise (westerly[3]) sense). Thus in order to conserve angular momentum the air must increase its westerly velocity[4]. Thus, aloft, the southerly winds turn towards the east (that is become more westerly) as they travel northwards.

[1]the region of maximum cloudiness and raininess is known as the Inter-Tropical Convergence Zone (ITCZ) and wanders north of the equator in the Northern Hemisphere summer, south in our winter

[2]the tropopause marks the sharp division between the troposphere (wherein our '*weather*' occurs) and the stratosphere (a very stably stratified layer above the troposphere). The division is marked by a rapid increase in temperature and is maintained through radiative effects. The tropopause occurs at a height of about $\sim 20km$ in the tropics and $\sim 12km$ at the poles.

[3]meteorologists refer to a westerly wind as a wind which blows from the west to the east

[4]this is analogous to the ice skater, who draws in their outstretched arms - which were at the equator - the maximum distance from the axis of rotation, to their sides (i.e. their 'mid-latitudes ') closer to their axis of rotation and thus spin faster (i.e. gain velocity to conserve angular momentum)

At around $30^o N$ the winds have attained an essentially westerly trajectory, and further cooling causes the now dense[5] cooler air descends. As the air descends it is compressed and warmed and it becomes relatively dry[6]. This causes the persistent, sunny, dry anticyclone known as the Sub-tropical High.

As this air nears the surface it can go one of two ways. If it returns south (and much of it must - since there is a requirement for mass balance) then the impact of the rotation of the earth turns in to the west, to produce the persistent northeasterly winds known as the Tradewinds. Of course these winds are not totally homogeneous in practice since the effect of land/sea contrasts[7] and topography[8] causes alteration of the flow. Generally the Tradewinds are the most stable and persistent on the planet - although they do occasionally experience synoptic scale[9] disturbances, known as easterly waves (since they travel towards the west) which are troughs[10] that may develop into hurricanes during the autumn (NH).

Hurricanes are extremely energetic cyclones whose circulation is sustained by the local conservation of angular momentum due to rapid convergence at the surface (Wallace and Hobbs, 1977, p. 421), driven by large vertical velocities near the centre, which are sustained by energy from the warm sea surface. Hurricanes can generate sustained wind speeds of $60ms^{-1}$ and have a typical diameter of $500km$, with the strong winds concentrated in a quite narrow zone. At the centre there is usually a feature known as the *eye* which has lights winds and often clear skies. This is generally of small size ($\sim 10km$). They are restricted in their possible locations by their requirement for warm ocean surface temperatures and are generally confined to $5 - 30^o N$ in the NH.

The air that does not return southwards, tends to get mixed in with the general flow. From the sub-tropical high the surface wind flows northwards, and as before is deflected to the east. This gives us largely southwesterly winds in the zone $30 - 40^o N$. North of this the motion becomes much less homogeneous. This is for rather complex reasons, but is related to the conservation of angular momentum and the dissipation of the kinetic energy. Essentially by $45^o N$ the westerly wind would be blowing very fast indeed if there were not some dissipative mechanism. This is friction. In a *very* simplified sense the mid-latitude circulation is 'designed' to loose kinetic energy through friction while maintaining the northward heat flux.

2.2 Mid-latitudes

The flow in mid-latitudes is more complex (and hence interesting) than anywhere else on the globe. The mid-latitudes are the buffer between the warm moist (due to the long journey over relatively warm oceans) sub-tropical air, and cold (but also relatively[11] moist) air from polar regions. The

[5] recall cold air is denser than warm air - warm air rises - cool air descends

[6] the temperature of air affects its ability to hold water (vapour) - warm air can hold much more water

[7] Water has the highest specific heat capacity of all materials and can store heat in a deeper layer by (turbulent) mixing and thus is relatively insensitive to changes in heating on short time scales (less than a week) while land surfaces typically have lower specific heat capacities and are heated in a much shallower layer thus responding to changes in heating on short (even hourly) time scales.

[8] that is the effect of mountains etc.

[9] There are several characteristic scales in the atmosphere. Planetary scale features (e.g. the long waves that steer the large scale flow in the mid-latitudes) have characteristic length scales of $\sim 7000km$ and time scales of weeks. Synoptic scale features (e.g. highs and lows, hurricanes) have characteristic length scales of $\sim 1000km$ and time scales of many days. Meso-scale features (e.g. fronts and troughs) have characteristic length scales of ~ 100's of km and time scales of days. Finally, micro-scale features (e.g. thunderstorms, cumulus clouds) have characteristic length scales of $\sim 10km$ and time scales of hours.

[10] a trough is an area of wind with cyclonic vorticity - see later section

[11] The absolute humidity is the actual amount of water (vapour) in the air, while the relative humidity is the amount it does hold over the amount it could theoretically hold at its temperature. Typically relative humidities are between $40 - 95\%$.

region where these two largely anticyclonic airmasses[12] meet is termed the mid-latitudes. The region is characterised by wave-like motion (as can be much of the atmosphere).

A typical mid-latitude flow pattern can be seen in Figure 4. This shows the the height of the $500mb$[13] level in the NH. This picture is typical, showing the large planetary waves that dominate the upper level[14] flow. There are 4 quasi-stationary waves[15] around the pole as well as some more transient features such as the low off the west of Britain, in the Atlantic. These large scale upper waves dominate the development and movement of the smaller scale synoptic features (the highs and lows). The main zone of activity is concentrated along the *jetstream*[16] which can be seen on the chart as the region of strongest winds - which can be assessed from the spacing of the contours of height (tight spacing $\Longrightarrow$ strong winds). There are cutoff features and the *jetstream* occasionally splits (for example to the west of Britain) - but this chart shows a real situation rather than an idealised one and is thus more complex.

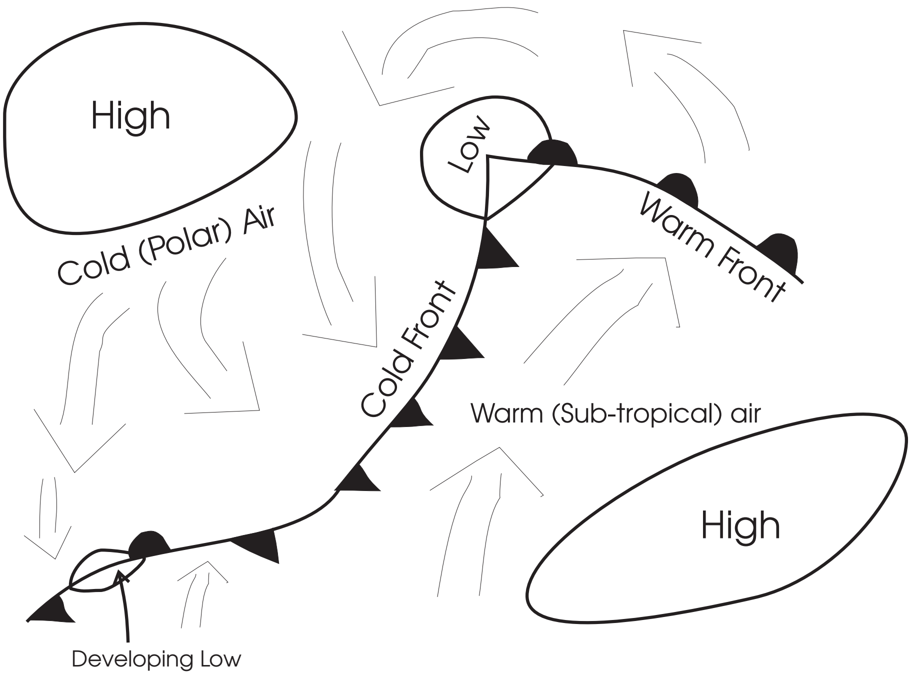

Figure 2: A typical surface surface chart for the mid-latitudes. The developed depression has a typical cyclonic circulation with a defined warm sector (the bit behind the warm front and in front of the cold front). The direction of movement of the front (which tends to 'go with the flow') can be judged from the in which direction the symbols on the front 'point'. High pressure is to the southeast (possibly an extension of the sub-tropical high) and building behind the cold front to the northwest. A small 'wriggle' is developing on the trailing cold front. This will probably develop into the next big depression.

At the surface the picture is even more confused. A series of depressions are generally interspersed with anticyclones, and these mobile features are steered along and develop or decay as determined

[12]an airmass is a large ($\sim$ hundreds to thousands of km across) body of air that can be considered homogeneous

[13]$500mb$ is roughly half way up the atmosphere (in pressure terms). Surface pressure is roughly $1000mb$ and the $500mb$ level lies between $5 - 6km$ depending on the surface pressure and the temperature of the air between the surface and $500mb$. The units on the chart are decameters (10's of m) and lower heights are observed over the poles. The wind flows parallel to the lines of geopotential (i.e. height) to a good approximation.

[14]that is the atmosphere well above the surface, typically $300mb$

[15]typically there are between 2 to 8 large scale waves

[16]the *jetstream* is the zone of very strong winds ($\sim 80ms^{-1}$) which lies at a height of about $10km$ above the zone where the sub-tropical and polar air meet. As a rule wind speed increases with height in the *troposphere*

by the upper level flow and the thermal pattern of the atmosphere. Lows typically form at the boundary between colder air and warmer air (since this contrast is one of their energy sources) - and quite often along a trailing cold front (which produces *families of depressions*). The formation of lows, highs and fronts is very complex - and this is not the place to explain it. However some of the consequences will be described when these are relevant to surface wind fields.

3 Highs and Lows

Rather that being a description of the typical research project, this section discusses the large scale circulations observed at the surface (with particular emphasis on winds above the oceans). Highs and lows are relatively transient features (time scales of days) and are characteristic of mid-latitudes. In general they are steered by the upper atmosphere flow, although occasionally this flow pattern becomes 'locked' into a *blocked* pattern.

3.1 Highs

Highs, also called anticyclones are less regular in shape than lows. When in the zone of active westerlies (that is the active mid-latitudes) they are generally rather small and transient features (like lows) having diameters of $\sim 1000km - 3000km$ and being roughly circular. However where they are distant from the *jetstream* (particularly in the ridges of the planetary waves) they can be much more persistent and large, lasting for weeks and being anything up to $\sim 7000km$ in diameter. In this condition the high is also less likely to be circular, often having an elliptical shape with the major axis aligned east-west, or slightly tilted from that. The flow in a anticyclone is almost always divergent hence:

$$\nabla \cdot \boldsymbol{u} = \frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} > 0 \tag{1}$$

Furthermore due to the impact of the *Coriolis force* the vorticity in a high is always anticyclonic:

$$\nabla \times \boldsymbol{u} = \frac{\partial v}{\partial x} - \frac{\partial u}{\partial y} < 0 \tag{2}$$

Areas with positive vorticity organised into a linear feature, but without a circulation are called ridges. These are common features in the flow, with almost every warm front preceded by a ridge and every cold front having a ridge or high building behind it. Wind speeds can be surprisingly large around the edges of highs because the wind speed (which is generally controlled by the pressure gradient) can be larger than that around a low[17] due to the centrifugal force acting in the same direction as the pressure gradient - which is balanced by the *Coriolis force*. The central parts of highs are characterised by light winds (often with variable direction, particularly when near land where thermal driven circulations can occur - the land / sea breeze) which can extend over a large area (e.g. a full scatterometer swathe).

3.2 Lows

Lows, also called cyclones or depressions are generally quasi-circular features of $\sim 800 - 3000km$ diameter although there are some monster depressions that form in favourable regions (over the

[17] despite the fact that the pressure gradient is generally larger in lows

mid-Atlantic and mid-Pacific at about 55^oN) that have diameters of $\sim 5000km$[18]. They form at the interface between moist warm (sub-tropical) air and cold (polar) air, often along a trailing cold front - although by no means exclusively. Unlike hurricanes which form in a generally homogeneous airmass, lows are generally constituted of the two airmasses mentioned above. The divisions between these two airmasses are known as **fronts** and are very important features for us and thus have a section to themselves. Lows have several characteristic wind features which we may find useful when modelling. Because the air is generally rising within a low there is surface convergence, that is:

$$\nabla \cdot \boldsymbol{u} < 0 \tag{3}$$

Furthermore due to the impact of the *Coriolis force* the vorticity in a low is always cyclonic:

$$\nabla \times \boldsymbol{u} > 0 \tag{4}$$

This may be useful, particularly if we want to use feature based priors. Of course this does rather suggest that vorticity and divergence are not uncorrelated in the real atmosphere (which is a pretty common assumption in most previous work which deals with analysis increments, the difference between the model forecast and observations).

Lows produce most of the high wind speed cases, but not all. The wind speed in a low is controlled by the surface pressure gradient, through the *geostrophic*[19] approximation. This ignores friction (which acts to cause the winds to blow toward the centre of the low) and the centrifugal force (which acts to slow the flow, since it acts in the same sense as the *Coriolis force* which over the long time scales we are considering acts to balance the other forces). This is unlike the anticyclonic case. In general, the area of strong winds extends from the 'edge' of the low to very near the centre, with the actual centre having lighter winds. The size of the centre typically depends on the amount of development the low has undergone - 'old' lows can have large centres of $\sim 200km$ diameter. Sustained wind speeds as high as $50ms^{-1}$have been observed in mid-latitude lows.

4 Fronts over the Ocean - Surface Features

Fronts are characteristic features of mid-latitude weather (Wallace and Hobbs, 1977). In simple terms fronts mark the zone of transition between air-masses from two different source regions, which have different characteristics (especially in terms of temperature and humidity). Fronts are almost always associated with an area of low pressure, which tend to correspond to their starting points. They are not linear features, but some may have a very narrow zone near the surface - rendering them essentially linear at the 50 km resolution we are working at.

There are three types of front in the atmosphere;

- cold fronts
- warm fronts
- occluded fronts

Cold fronts have colder air behind them and are usually the most active of fronts. They generally have a much more defined frontal zone, which can be rather narrow. Warm fronts (the warmer

[18] These are usually formed by the merging of several smaller lows

[19] This simply says that the wind blows parallel to the isobars (lines of equal pressure), with the force exerted by the pressure gradient being balanced by the *Coriolis force* - which is due to the rotation of the Earth

air is behind) tend to be more diffuse at the surface although some are quite active. Occluded fronts occur when a cold front (which tends to travel rather faster than a warm front - especially at the surface) catches up the warm front associated with the 'parent' cyclone. Thus the warm air is lifted off the surface. Occluded fronts have characteristics similar to cold fronts but tend to be less intense.

4.1 Cold Fronts over the Ocean

Cold fronts are generally the narrowest features at the surface, and thus will be the most difficult to represent in any model of the *global* wind field. We will therefore focus on cold fronts - since any technique which can model the changes in wind field across cold fronts will also be able to represent warm and occluded fronts.

Cold fronts typically extend from the surface of the Earth to the *tropopause* in a continuous zone (Bond and Shapiro, 1991). In the upper troposphere differential vertical motion (often referred to as *tilting*) is thought responsible for frontogenesis (the initialisation and maintenance of a defined frontal zone), while at the surface convergence is thought more influential (Bond and Shapiro, 1991). For our purposes it is only necessary to examine the practical implications of the theory of frontogenesis in the boundary layer. Frontal dynamics are consistent with a frontal zone near the surface (typically at a height of $500m$) of $1km$ width. Unfortunately little is know about the region below this (where our interest lies), especially with reference to the spatial distribution of wind vectors. One reason for this is the logistical difficulty of measuring the wind field over a large extent of ocean at high spatial resolution. Ironically this is exactly what scatterometers can provide.

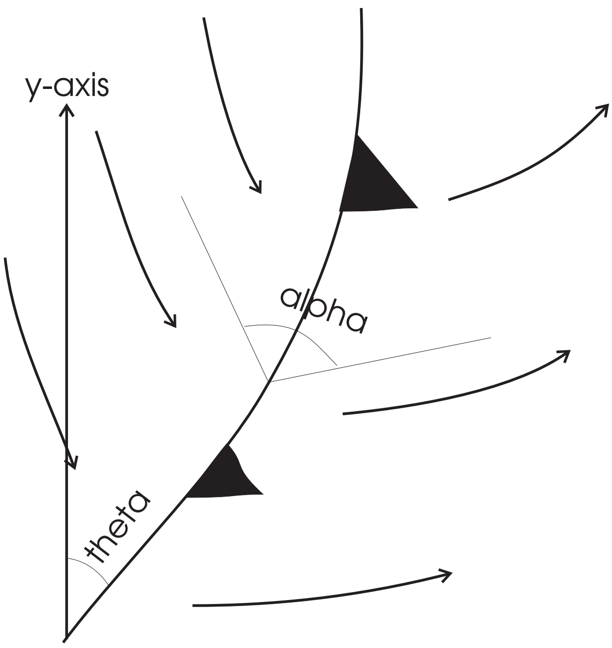

Figure 3: A figure showing a typical surface cold front. The angle between the two air flows either side of the front is realistic.

Observational (Bond and Fleagle, 1985; Bond and Shapiro, 1991) and numerical model (Dudhia, 1993) based studies both confirm the existence of sharp frontal zones at the surface. Bond and Shapiro (1991) suggest a surface frontal zone of approximately $1km$, with wind shear across the front (measured by aircraft cross sections) of $6ms^{-1}$ in just $500m$. A buoy over which the front crossed measured changes of $9ms^{-1}$ in cross-frontal wind speed in one hour, most of which is thought to have occurred across the narrow frontal zone. The vertical wind speed of $\sim 3ms^{-1}$ in the frontal zone was shown to imply a change of $5ms^{-1}$ in the cross-frontal wind speed in the layer from the surface to 600 m. Thus at fronts we almost always have convergence:

$$\nabla \cdot \boldsymbol{u} < 0 \tag{5}$$

From Figure 3 we can see a typical section through a front. The angle α of the winds across the front is crucial. The more active the front, the smaller α will be and it is always less than π. This means that at fronts we have that:

$$\nabla \times \boldsymbol{u} > 0 \tag{6}$$

indeed we can give the vorticity we would expect in terms of alpha (under the assumption of no divergence[20]) as:

$$\nabla \times \boldsymbol{u} \propto \cos\left(\frac{\alpha}{2}\right) \tag{7}$$

This means that for α less than π we will always have positive (cyclonic) vorticity at fronts. The alpha parameter may be useful since it will be easier to put a prior on - as the angle between the winds is something I can relate to more easily than vorticity - which is very difficult to quantify subjectively from wind fields, although easy to compute approximately.

5 Implications for Wind Field Modelling

For our purposes we need to assess whether a given numerical technique for fitting some form of model to the scatterometer retrieved wind vectors will accurately and realistically represent fronts.

The estimates above suggest that at the surface the main frontal shear is confined to a zone approximately $1km$ in width. Typical magnitudes of this shear will be $\sim 10^{-3}s^{-1}$ using the calculations from the vertical velocity. Very near the surface ($10m$) surface drag may have an impact, reducing the figure somewhat, however $\sim 10^{-3}s^{-1}$ is probably a realistic estimate. Since relative vorticity (due to shear and curvature) is typically $\sim 10^{-5}s^{-1}$ in the atmosphere, fronts will need some careful consideration.

The sampling method of the satellite borne scatterometers means that they have an effective scale of $50km$, so it is likely that the σ^o value measured by the satellite will sample from both sides of the front. Thus any technique used must account for this disparity in scales. At the process scale, fronts can have transition zones of roughly $1km$, while the sample scale is much larger at $50km$.

If we want our model scale to be consistent with the sample scale then we will probably have few problems. This is because if we believe the scatterometer observations then we can use div-curl splines with a small penalty on the data-fit term and accept some degradation in the immediate vicinity of the fronts, which at the scale of $50km$ will not be too significant - especial not for numerical weather prediction, which has model scales of $\sim 200km$.

If on the other hand we want to try to get wind vectors with properties that are consistent with the process scales in the boundary layer over the ocean we will have to be more intelligent.

[20]Not very realistic but vorticity dominates.

6 Helmholtz Theorem

The Helmholtz theorem allows us to separate a vector flow field into two scalar components - a non-divergent (rotational) component and an irrotational (divergent) component. Both derivations in Euclidean (x, y) space and on the sphere (λ, ϕ) are given[21].

$$\xi = \frac{1}{A\cos\phi}\left(-\frac{\partial(u\cos\phi)}{\partial\phi} + \frac{\partial v}{\partial\lambda}\right) = k\cdot\nabla\times\boldsymbol{u} = \text{vorticity}$$

$$D = \frac{1}{A\cos\phi}\left(\frac{\partial(v\cos\phi)}{\partial\phi} + \frac{\partial u}{\partial\lambda}\right) = \nabla\cdot\boldsymbol{u} = \text{divergence}$$

where A is the radius of the Earth ($= 6.37\times10^6 m$). Then if we define Ψ (stream function) and Φ (velocity potential) using:

$$u = \frac{1}{A}\left(-\frac{\partial\Psi}{\partial\phi} + \frac{1}{\cos\phi}\frac{\partial\Phi}{\partial\lambda}\right) = -\frac{\partial\Psi}{\partial y} + \frac{\partial\Phi}{\partial x}$$

$$v = \frac{1}{A}\left(\frac{1}{\cos\phi}\frac{\partial\Psi}{\partial\lambda} + \frac{\partial\Phi}{\partial\phi}\right) = \frac{\partial\Psi}{\partial x} + \frac{\partial\Phi}{\partial y}$$

Now we have:

$$\xi = \nabla^2\Psi, \qquad D = \nabla^2\Phi$$

where ∇^2 is the Laplacian operator (on the plane or sphere). Now Ψ and Φ are often observed to be uncorrelated in practice and can be analysed more easily. This decomposition will prove useful as it will allow us to specify the relative contributions of divergent and rotational flow in our model of wind fields. Thus by placing a prior on the stream function and velocity potential and their relative importance one can formulate realistic priors for wind fields.

7 Why is this Useful?

This section briefly reviews why the above discussions are relevant to the problem of wind retrieval from satellite scatterometer data.

7.1 Div-Curl Splines for Inverse Models

Div-curl splines (see report) are suitable models for almost all atmospheric features and are based on *Helmholtz theorem.* At fronts we are presented with a problem: div-curl splines are not flexible enough to cope with the rapid changes in direction (and speed) across a front. To apply div-curl splines successfully in all situations we will probably have to use some iterative procedure whereby frontal zones are determined from regions in which div-curl splines produce large vorticities (or in which there is a considerable region of miss-fit between the splines and the data). These regions could then be 'stretched' using the space transformations of Sampson and Guttorp (1992). The div-curl splines will then be fitted in the transformed coordinate system which attempts to 'squeeze' the vorticity into as narrow a zone as possible.

[21] my preference is to work in local Euclidean space but everything is *fairly* readily transformed to spherical coordinates

Alternatively we could have a spatially varying smoothness parameter, which would probably have to be set iteratively (Luo and Wahba, 1997). Yet another alternative is to get away from the spline problem and pose the div-curl basis in the context of radial basis function networks (Poggio and Girosi, 1990). By controlling regularisation through the number of basis functions rather than the smoothness parameter we may get more efficient algorithms, albeit with a lot of heuristics. With sensible heuristics it would seem possible to locate extra basis functions at or near fronts, so that they are well represented. For this work we must not forget that the problem is made more difficult by inherently ambiguous solutions.

This means (I believe) that we must choose a large scale (plausible) wind field before trying to identify frontal zones. We need to spend some more time with real wind fields derived from real scatterometer data. However we also helped by the fact that the vorticity at fronts is necessarily cyclonic, which may suggest other algorithms. There is considerable scope for improved models here.

7.2 Bayesian Methods for Forward Models

This is a dual approach to the wind retrieval problem which focuses on using Bayes theorem to obtain our wind vectors:

$$p(\boldsymbol{u}|\boldsymbol{\sigma^o}) = \frac{p(\boldsymbol{\sigma^o}|\boldsymbol{u})p(\boldsymbol{u})}{p(\boldsymbol{\sigma^o})} \tag{8}$$

and our problem involves obtaining sensible priors $p(\boldsymbol{u})$ on the wind fields. We could use the same prior we are (effectively) assuming in the div-curl spline case (Cornford, 1997). However we may be able to develop more appropriate priors, which can include fronts without any ad-hoc algorithms.

An interesting approach could be founded on feature based priors on vorticity and divergence, together with a covariance based prior on the stream function and velocity potential. By matching these two (using *Helmholtz theorem*) we may be able to produce a sensible prior. This is not a trivial task, and we must ensure that sampling from this prior is practical (with Monte-Carlo Markov Chain algorithms).

A more feasible method would be to use hierarchical models for fronts, which are the only feature we have real trouble with, so that we first simulate the presence or absence of a front, then its location, orientation and strength. Conditionally on the front, we then simulate the wind field either side.

If we produce a good prior model here then there is no reason why this cannot be used with inverse models instead of div-curl splines (although these may still have considerable computational advantages).

8 Acknowledgements

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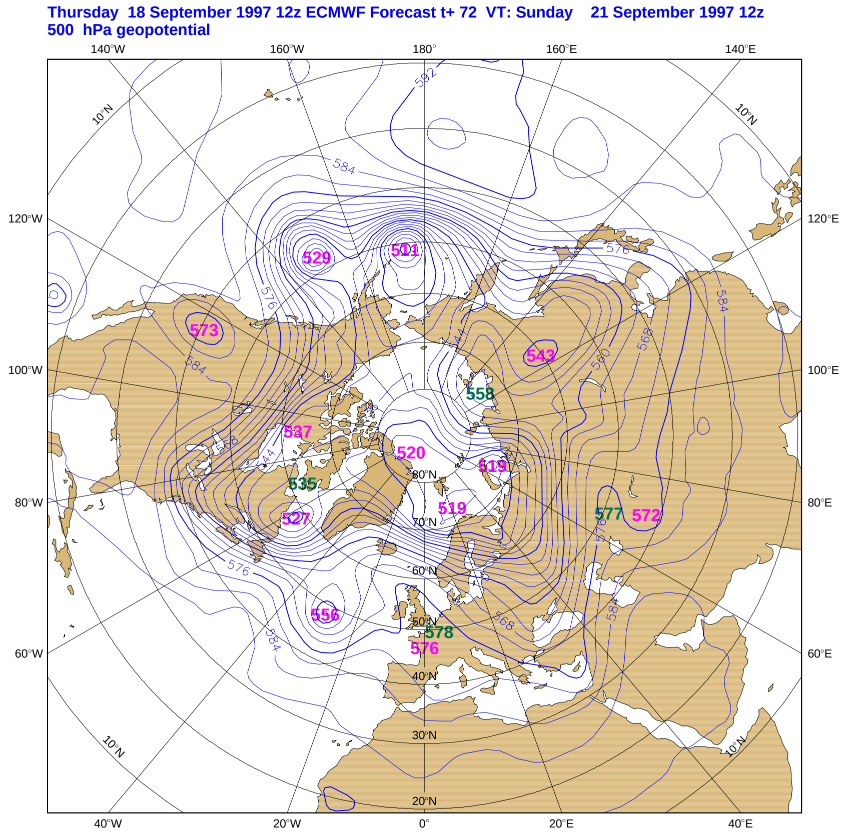

Figure 4: The height of the $500mb$ pressure surface for the Northern Hemisphere, based on the European Centre for Medium Range Weather Forecasting (ECMWF) model, for 21/9/97. See text for full explanation.