

# WINDS FROM METEOSAT AND GMS WV-IMAGERY USING VARIATIONAL TECHNIQUES

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## ABSTRACT

A new method is described where motion analysis is represented by a variational problem. Based on this optical flow concept, a modification has been introduced which derives wind fields by a separate control of the vector flow gradient components, namely divergence, vorticity, and deformation. By the aid of Meteosat-WV data of a cutoff low the general performance of the variational approach is discussed. A second case study on Meteosat-WV data together with a quantitative comparison to ALPEX wind fields is used to reveal the quality of the derived information. This verification shows an underestimation of high wind speed. The vector differences are  $\text{rmse}_{\vec{u}} = 11.3$  m/s for high level winds ( $p \leq 400$  hPa) and  $\text{rmse}_{\vec{u}} = 9.6$  m/s for medium level winds ( $p > 400$  hPa). The mean absolute direction difference indicates a good reconstruction of the wind direction for both levels ( $\overline{\phi_{\vec{u}}} = 21.7^\circ$  for  $p \leq 400$  hPa and  $\overline{\phi_{\vec{u}}} = 16.6^\circ$  for  $p > 400$  hPa). The analysis of the components divergence, deformation, and vorticity of the vector gradient are in good agreement to the quasi-geostrophic scale analysis. Currently, an Internet service has been installed which presents daily GMS-5 WV vector fields over Australia, the Tasman Sea, and New Zealand. This shows the feasibility of an operational use of FAM for the motion analysis of WV imagery.

## 1. INTRODUCTION

In the past, a different variational approach for the derivation of winds from satellite imagery has been used by Eriksson (1988). The method was based on the so called Oriented Smoothness by Nagel (1987). The results showed a good potential for the derivation of winds from WV-images. However, high clouds often produced complete unrealistic vectors within the resulting wind fields. Furthermore, the numerical solution by a multi-grid algorithm needed an immense computation. Based on the fundamental work by Horn and Schunck (1981) the variational approach has been extended in various ways (Nagel, 1987; Wahl, D.D. and J.J. Simpson, 1991). A mathematical sound generalization of the variational concept has been given by Schnörr (1991). Furthermore, Schnörr (1991) implemented a Finite Element algorithm which drastically reduces the computation.

In the course of this contribution a modification is introduced which suits to the quasi-geostrophic concept. The kinematic of synoptic-scale flow in the upper troposphere is characterized by a quasi-nondivergent wind field (Holton, 1992). Hence, a selective smoothing of the components divergence, deformation, and vorticity of the vector gradient is desirable.

## 2. METHOD

Horn and Schunck (1981) first suggested the solution of a variational problem for the derivation of vector fields from subsequent digital images. If it is supposed that the grey value of a certain scene element remains constant, then the two-dimensional motion field can be reconstructed.

$$J(\mathbf{v}) = \int_{\Omega} \{(g_t + \mathbf{v} \cdot \nabla g)^2 + \lambda^2 (|\nabla u|^2 + |\nabla v|^2)\} d\mathbf{x} \quad (1)$$

The functional in (1) is given by an integration over the entire image plane  $\Omega$ . The functional contains two constraints which are defined as data term

$$\frac{dg}{dt} = g_t + \mathbf{v} \cdot \nabla g = 0 \quad (2)$$

and smoothness term

$$\int_{\Omega} (|\nabla u|^2 + |\nabla v|^2) d\mathbf{x} \rightarrow \text{Min.} \quad (3)$$

The first expression describes an advection equation of the physical quantity imaged by the greyvalue function  $g(x,y,t)$ . Since it gives only the vector component parallel to the grey-value gradient, a second constraint is needed. Horn and Schunck (1981) proposed the general smoothness constraint in (3). As the vector field has to satisfy both constraints (2), (3) the solution is found by the minimization of the deviations from (2) and (3). Then one obtains the quadratic functional (1) where the smoothness term is weighted by the parameter  $\lambda$ . Hence, a solution  $\mathbf{u} \in \mathcal{H}$  is sought for the variational problem:

$$J(\mathbf{u}) = \inf_{\mathbf{v} \in \mathcal{H}} J(\mathbf{v}) \quad (4)$$

The ideal solution of the smoothness constraint given in (3) is pure translational motion. Therefore, the approach in (1) prefers rigid body motion. Since atmospheric motion is dominated by divergent, rotational, and deformational flow pattern a main drawback of the original approach by Horn and Schunck (1981) for the derivation of meteorological vector fields becomes obvious. Therefore, the following modification of the smoothness constraint in (1) is proposed. The constraint (3) can be separated into the kinematic components divergence, deformation, and vorticity of the vector field gradient:

$$|\nabla u|^2 + |\nabla v|^2 = \frac{1}{2} (\text{div}^2(\mathbf{v}) + \text{rot}^2(\mathbf{v}) + \text{def}^2(\mathbf{v})) \quad (5)$$

with

$$\text{divergence : } \text{div}(\mathbf{v}) = \partial u / \partial x + \partial v / \partial y \quad (6)$$

$$\text{deformation : } \text{def}(\mathbf{v}) = \sqrt{(\partial v / \partial y - \partial u / \partial x)^2 + (\partial u / \partial y + \partial v / \partial x)^2} \quad (7)$$

$$\text{vorticity : } \text{rot}(\mathbf{v}) = \partial v / \partial x - \partial u / \partial y \quad (8)$$

This allows to choose different weights for each of the kinematic quantities and leads to the modified variational approach for a selective control of the flow gradient:

$$J(\mathbf{v}) = \int_{\Omega} \left\{ (\nabla g \cdot \mathbf{v} + g_t)^2 + \frac{1}{2} \left( \lambda_{\text{div}}^2 \text{div}^2(\mathbf{v}) + \lambda_{\text{rot}}^2 \text{rot}^2(\mathbf{v}) + \lambda_{\text{def}}^2 \text{def}^2(\mathbf{v}) \right) \right\} dx \quad (9)$$

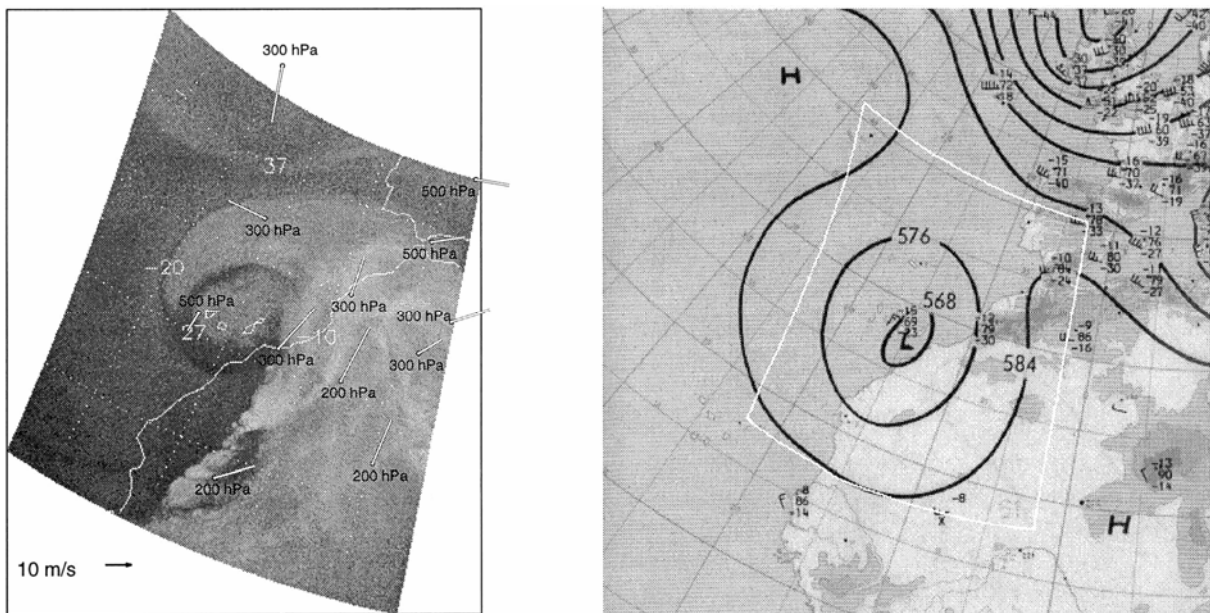
The input data of the variational technique consists of the gradient and the time derivative of the image function  $g(x,y,t)$ . The first-order derivatives have been estimated using a Derivative-of-Gaussian filter (Hashimoto and Sklansky, 1987). In the spatial domain a filter size of 41 pixel has been used while the time derivative is represented by a central difference. Simultaneously, the results have been convolved in the remaining coordinates by a Gaussian of corresponding size in order to diminish the influence of noise.

The minimization of both functionals (1) and (9) is performed using a Finite Element algorithm. A mesh-length unit of 16 pixel has been used for the discretisation of the image data.

### 3. CASE STUDIES

#### 3.1 CUTOFF LOW OVER CANARY ISLANDS

The first case study illustrates the general performance of the modified variational approach. A Meteosat-2 WV-image sequence of a cutoff low situation over the Canary Islands is studied (Fig. 1). Two vector fields have been computed using the approach by Horn and Schunck (1981)



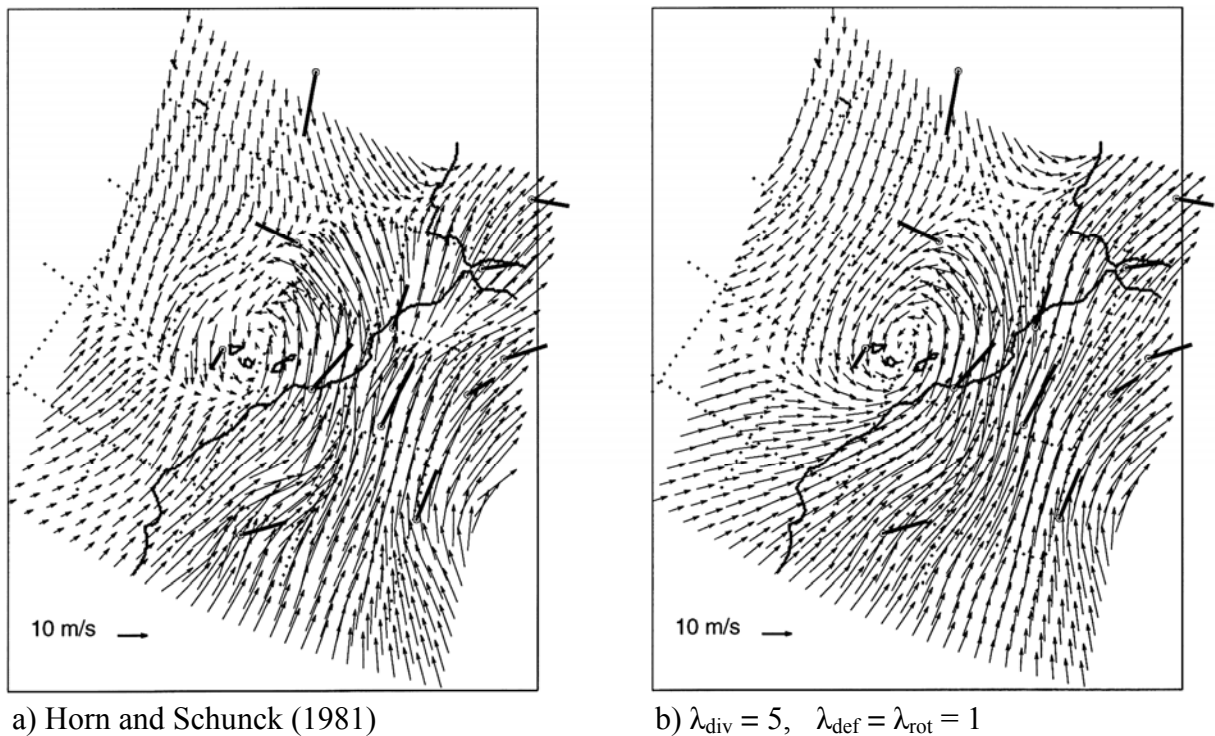
a) Meteosat-2 WV-data in polar stereographic projection

b) 500 hPa chart.

**Fig. 1:** Cutoff low situation over the Canary Islands (September 20, 1984, 22:30, 23:00, 23:30 GMT). Heavy white flags in a) indicate synchronous radiosonde winds at different levels. The studied area is marked by a thin white frame in b).

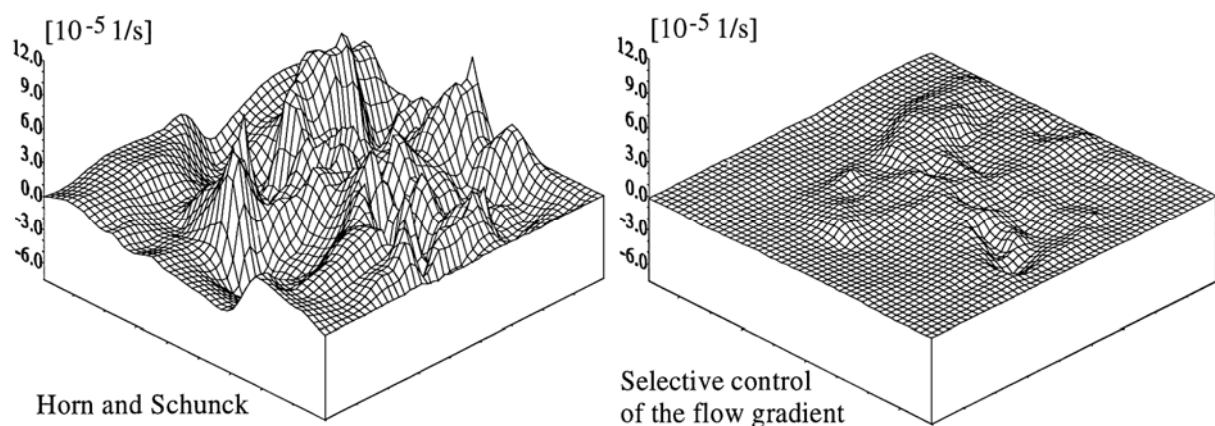
with a weight parameter  $\lambda = 1$  as well as the modified constraint using a higher weight  $\lambda_{\text{div}} = 5$  for the divergence compared to  $\lambda_{\text{rot}} = \lambda_{\text{def}} = 1$ . The motivation of this empirical parameter choice is the quasi-geostrophic concept which leads to a divergence of smaller magnitude than

vorticity and deformation (Holton, 1992). The results are shown in Fig. 2. At first sight both vector fields look similar. The anticyclonic motion is well reflected.

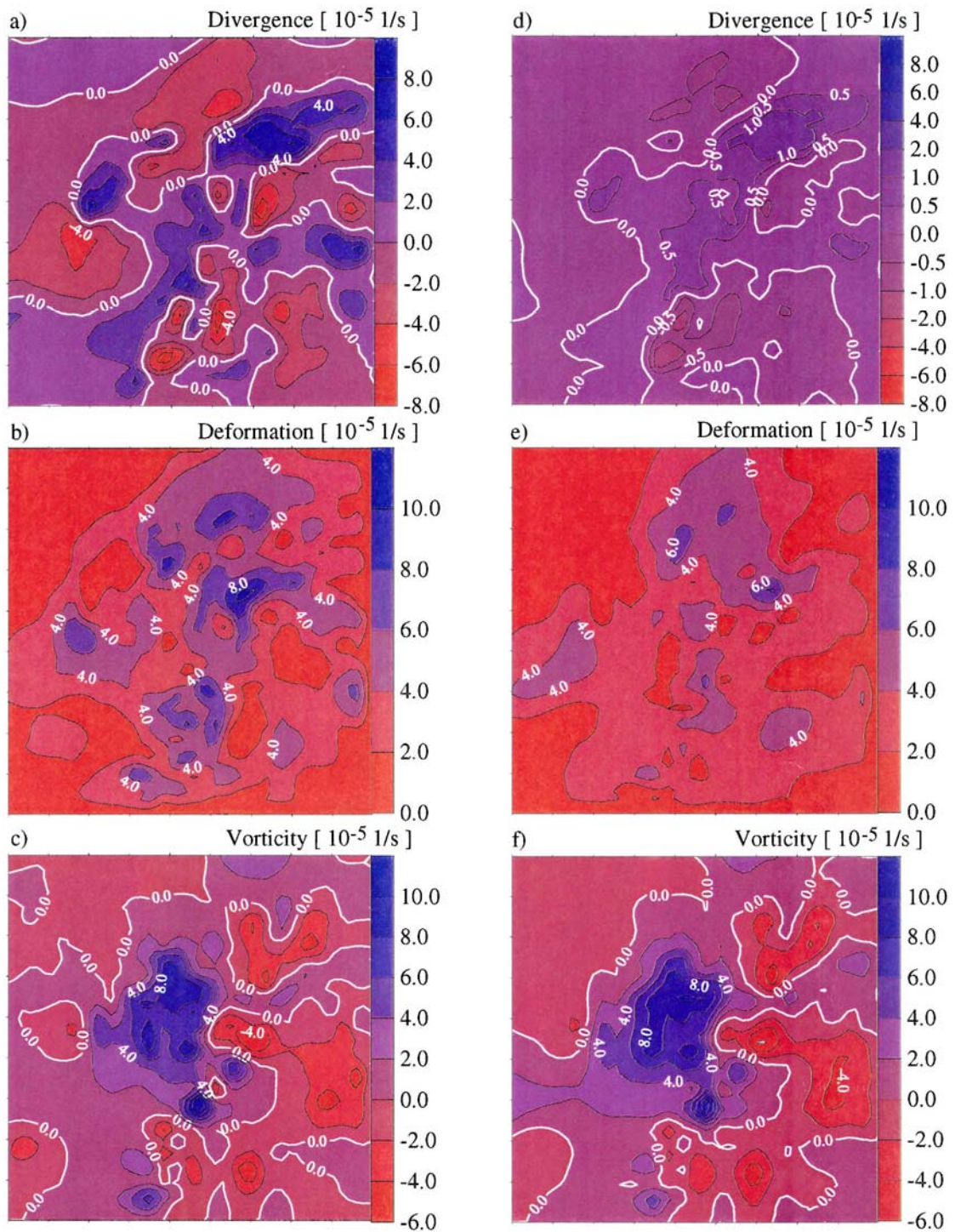


**Fig. 2:** Vector fields derived from Meteosat-2 WV-data (September 20, 1984, 22:30, 23:00, 23:30 GMT).

Furthermore, a clear deformation pattern is visible in the north of the studied area in both cases. The differences between both results become obvious by analysing the divergence in Fig. 3. The divergence has been reduced by almost one order of magnitude to maximum values of about  $1.4 \cdot 10^{-5}$  1/s compared to  $1.2 \cdot 10^{-4}$  1/s for the approach by Horn and Schunck (1981). The comparison of all kinematic quantities in Fig. 4 reveals further details.



**Fig. 3:** Surface plots of the divergence fields resultant from the approach by Horn and Schunck (1981) and the selective control of the flow gradient.

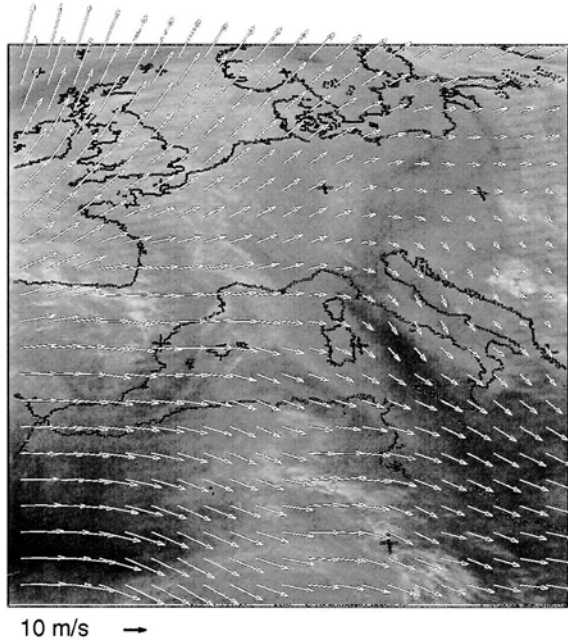


**Fig. 4:** Kinematic fields derived from Meteosat-WV data (September 20, 1984, 22:30, 23:00, 23:30 GMT), left: Horn and Schunck  $\lambda = 1$ , right: Separate smoothing of gradient components ( $\lambda_{\text{div}} = 5$ ,  $\lambda_{\text{def}} = \lambda_{\text{rot}} = 1$ ).

While the order of magnitude of divergence is diminished the main pattern are preserved. Both deformation fields show maximum contributions in the vicinity of the deformational flow in the north of the studied area. The vorticity fields indicate an improved reconstruction of the cyclonic motion around the center of depression by a broader pattern of maximum vorticity. The order of magnitude of all components corresponds to the scale analysis of the upper tropospheric flow.

### 3.2 METEOSAT-4 WV-DATA, MAY 16, 1993

A second case study is presented together with a quantitative verification. The image sequence consists of three Meteosat-4 WV-images from May 16, 1993 (22:00, 22:30, and 23:00 GMT). The middle image of this sequence is shown in Fig. 4 together with the vector field resulting from a separate smoothing of the kinematic quantities ( $\lambda_{\text{div}} = 5$ ,  $\lambda_{\text{def}} = \lambda_{\text{rot}} = 1$ ). The verification data is based on an analysis scheme which has been developed in the course of the Special



**Fig. 4:** Meteosat-4 WV-data (16 May 1993, 22:30 GMT) together with the resulting vector field. The parameter choice is identical to the case study in 2.1 besides a different mesh-length of 24 pixel.

**Tab. 1:** WV-winds minus ALPEX winds (17 May 1993, 00:00 GMT).

Level	$\text{rmse}_{\vec{u}}$ [m/s]	$\overline{\phi_{\vec{u}}}$ [ $^{\circ}$ ]	speed bias [m/s]	$\overline{ \vec{u} }_{\text{ALPEX}}$ [m/s]
$p \leq 400\text{hPa}$ N = 818	11.3	21.7	-6.3	19.8
$p > 400\text{hPa}$ N = 206	9.6	16.6	-2.5	18.4

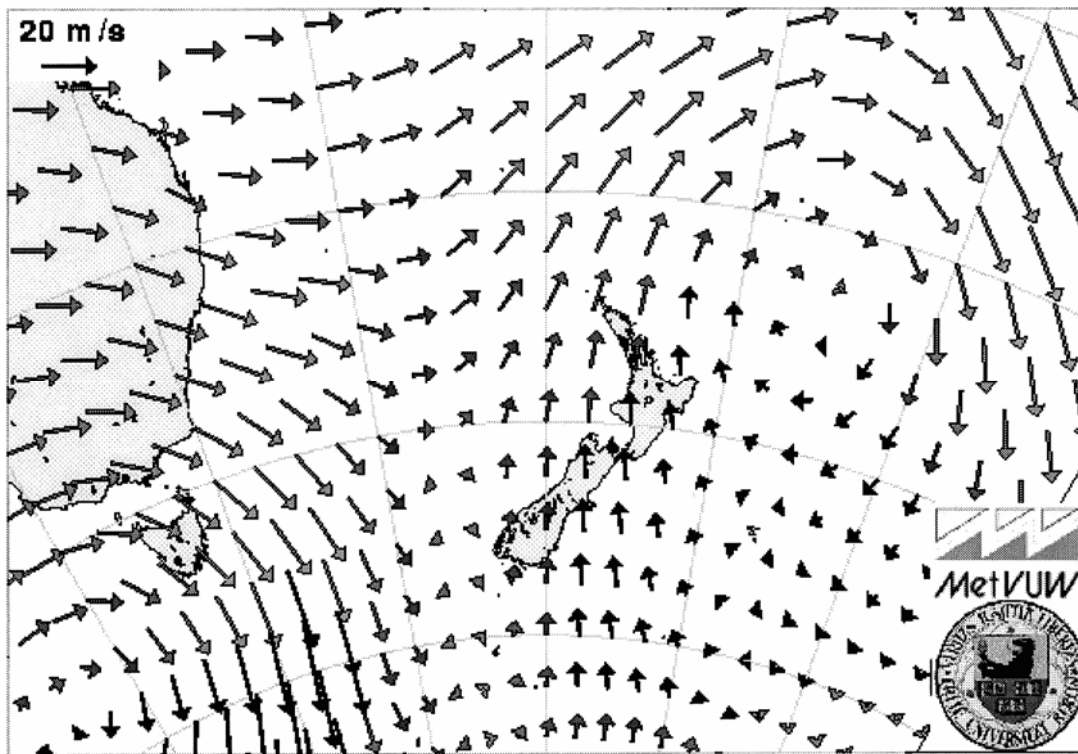
- rmse vector difference:  
$$\text{rmse}_{\vec{u}} = \sqrt{\Sigma(\Delta u^2 + \Delta v^2)/N}$$
- mean absolute direction difference:  
$$\Delta \overline{\phi_{\vec{u}}} = \Sigma \Delta \phi_{\vec{u}}/N$$
- speed bias:  $\overline{|\vec{u}|}_{\text{WV}} - \overline{|\vec{u}|}_{\text{ALPEX}}$
- mean observational wind speed:  
$$\overline{|\vec{u}|} = \Sigma |\vec{u}|/N$$

Observing Period (SOP) of ALPEX (Reimer, 1985). Using the WV-brightness temperature two layers below and above 400 hPa have been roughly discriminated. Following a former quality study by Thoss (1991) WV-winds are compared to the ALPEX-winds separately for the medium and high level. The statistical measures of this comparison are given together with Tab. 1. It has to be noted that this comparison is based on a single image sequence which restricts the scope of this verification. Furthermore, the presented statistical results likely reflect the particular meteorological situation.

## 4. DAILY GMS-5 WV MOTION FIELDS ON INTERNET

The applicability of the variational technique to GMS-5 WV-data has been evaluated (Rohn, 1996). Since December 1995 GMS-5 WV-motion fields have been daily derived at the Victoria University of Wellington, New Zealand. The presentation of the results via Internet ([http://www.rses.vuw.ac.nz/meteorology/satwind/gms\\_wv.html](http://www.rses.vuw.ac.nz/meteorology/satwind/gms_wv.html)) includes a brief description of the variational technique and provides additional access to concurrent weather charts. As an

example Fig. 5 shows the vector field on January 25, 1996 when an extratropical cyclone north-east of the North Island of New Zealand caused heavy rainfall along the East Coast.



**Fig. 5:** GMS-5 WV-winds (25 January 1996, 11:00 GMT).

## 5. CONCLUSIONS

The variational approach for a selective smoothing of divergence, deformation, and vorticity results in a scaling of the kinematic fields which corresponds to the quasi-geostrophic concept. A drawback is the underestimation of high wind speed which is indicated by a strong speed bias for high level winds. However, the speed bias cannot be fully related to existing quality studies of WV-winds since it is based on a single image sequence. The vector differences are  $rmse_{\vec{u}} = 11.3$  m/s for high level winds and  $rmse_{\vec{u}} = 9.6$  m/s for medium level. The reconstruction of the wind direction is characterised by mean absolute direction differences of  $\overline{\phi_{\vec{u}}} = 21.7^\circ$  ( $p > 400$  hPa) and  $\overline{\phi_{\vec{u}}} = 16.6^\circ$  ( $p \leq 400$  hPa).

At this stage, the vector field is derived purely from the image data. One reason for the underestimation of high wind speed might be the isotropic character of the smoothing constraint which therefore needs to be modified.

A verification over at least one month time is necessary in order to relate the results to the operational derivation of WV-winds. Following former suggestions (Kelly, 1993) further activity should aim on understanding how the motion information from WV-imagery is related to the flow within the broad layer mainly contributing to the WV-signal. The presented variational approach possibly hints at a direct use of WV-radiances within the variational data assimilation scheme in order to provide motion information from WV-data.

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