SUB-GRID PHYSICAL OPTICAL FLOW FOR REMOTE SENSING OF SANDSTORM

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1. ABSTRACT

Satellite observations are currently of major importance in geosciences. Remote sensing is a strong tool to study atmospheric and earth phenomena. Dynamic natural phenomena in the atmosphere are generally turbulent due to a high Reynolds number. Geostationary satellites are now able to give a good compromise between spatial resolution and temporal rate acquisitions. However, with the high turbulence activity in the atmosphere, space and time resolution rates are still too low compare to turbulence characteristic dimensions of the fluid motion. We focus our work on Dust Storm events. These phenomena often appear over four of the five continents. Dust particles can be transported through the atmosphere over thousands of kilometers. Dust Storms have strong impact on health and economy of the touched regions. The computation of the particle concentration displacement from images is important for a better understanding and modeling of this phenomenon. However, recent motion estimation algorithms become weak when applied to scalar transported by turbulent fluid. Using Large Eddy Simulation (LES) theory, we propose, in this paper, a new physical formulation of the optical flow based on a filtered scalar transport equation where a sub-grid model defines small scale effects (missing information in images). Moreover for satellite sequences, brightness conservation over a day is not satisfied. This is a main problem for optical flow approaches that consider constant brightness assumption over a small time interval. Here, we make a simple assumption of global lighting variation over image domain in our flow equation. Promising results are obtained on synthetic Direct Numerical Simulation (DNS) of scalar propagation. We test our approach on real MTSAT-1R visible images of 09/22/2009 Australian dust storm event. Brightness variation and turbulence consideration, visually, improve satellite estimation of atmospheric motion.

2. STATE OF ART

Atmospheric motion from Geostationary remote sensing image was well studied in Meteorological community since 1968 [1]. Common methods used to estimate the flow field are based on cross-correlation techniques. These methods were easy to implement and robust to noise, but they need large interrogated windows size to be able to correctly detect the good correlation peak. Moreover they are not suitable for scalar motion estimation where the correlated peak is hardly detectable. From the late 90s, Optical Flow approaches were proposed to estimate cloud motion ([2],[3], [4]). Because classical optical flow theory was not adapted to atmospheric motion, authors proposed to use the continuity equation to define the flow equation. However, considering incompressibility property of the fluid and that dust storm displacement can be simplified has 2D propagation, the continuity equation is then similar to classical optical flow [5]. Recently, [6] proposed to use assimilation and regularization based on Navier-Stokes equations. Fluid mechanic and turbulence effects are dealing through the regularization functions. But flow equation formulation does still not incorporate turbulence notion. Moreover all these optical flow approaches consider that brightness is constant over small time interval. Preprocessing is used to remove day light variations.

3. CONTRIBUTION

In this work, we focus on scalar atmospheric transport from remote sensing images. We consider that satellite image intensity (I) represents the concentration ($C \approx \alpha.I$). This assumption only has meaning over cloud areas (water vapor, aerosols, ...). Scalar velocity field ($\vec{v}$) can be exactly computed from scalar transport equation with diffusion ([7]). Using an MRF framework to solve the optical flow, we have our classical physical optical flow approach (OF) based on the transport equation. To solve the ill-posed problem of OF equation, we use global constraint as [5] to spatially limit possible solutions. An hybrid unwarping multi-resolution and multi-grid approach allows to efficiently estimate large and small displacements.

Satellite sequences give discretized information about observed real quantities due to space resolution. Pixel concentration (C^+) can be interpreted as a filtered information of the real concentration (C) over the pixel surface. Because of high Reynolds number in the atmosphere, turbulence characteristic dimensions are smaller than space and time resolution of Geostationary satellites. Non observable small scales of turbulence ($C^- = C - C^+$), in our images, influence the flow field. Making a link with Large Eddy Simulation (LES) theory [8], we filter the OF transport equation using filter of pixel size, we get a new equation where appear a term depending to small scales. A turbulent viscosity (D_t) is used to model the effects of this new term. We call it a sub-grid model (SGS). We have, now, a sub-grid optical flow equation ($OF-SGS$) that physically interprets what we can observe in satellite images considering effects of smaller scales turbulence on the filtered observed flow field ($\vec{v}^+$).

Exterior parameters as day light variations are an important problem for optical flow approaches. OF and $OF - SGS$ estimate the velocity field from local variations of observed scalar concentration (C^+). However, day light variation changes value of observed intensity (I^+) without dependency with C^+. I^+ cannot be directly link to C^+. If considering a small enough image covering of the earth, we can define the assumption that depending to the time rate, $C^+ \approx \alpha.I^+ + \beta(t)$ where $\beta(t)$ is spatially invariant. Adding brightness variation ($Bvar$) assumption to the optical flow equation, we get a new constant term representing the day light variation effect.

4. RESULT ILLUSTRATION

We validate the efficiency of the sub-grid physical optical flow definition on synthetic DNS scalar sequence and we illustrate quality of flow estimation on real MTSAT-1R visible images.

Recall of different methods shown in results:

- $CORPETTI$ [4]: Optical Flow algorithm adapted to fluid motion.
- $LaVision$ [9]: Efficient cross-correlation algorithm (sofware).
- OF: Optical Flow based on transport equation.
- $OF - SGS$: Optical Flow based on transport equation with sub-grid model.
- $OF + Bvar$: Optical Flow based on transport equation with brightness variation assumption.
- $OF - SGS + Bvar$: Optical Flow based on transport equation with sub-grid model and brightness variation assumption.

On synthetic DNS, Fig.1, we voluntary degraded the sequence simulating day light variation effect. We trace RMS amplitude error between estimated and exact velocities for original and degraded images for different methods. $OF - SGS$ outperforms all other methods and $Bvar$ clearly reduces day light variation effect on the estimation.

Fig.2 illustrates 2 consecutive satellite images (a) and in (b,c,d) the corresponding estimated velocity field (right) and streamlines (left) for different approaches. We see the advantage of optical flow approach compare to cross-correlation (irregular estimation, need vary large interrogated window size, correct correlation peak difficult to localize due to smooth concentration). $OF - SGS + Bvar$ gives a better coherent estimated flow field than $OF - SGS$ that is more influenced by day light variation. Streamlines $OF - SGS + Bvar$ presents same behavior as $LaVision$. Dust cloud motion is more identifiable on $OF - SGS + Bvar$ results and seems closer to the reality than other methods.

5. CONCLUSION

This work proposed a sub-grid physical optical definition to study atmospheric motion from remote sensing images. It considers properties of observed information that we have in the sequence and models small scale effect of the turbulence through a turbulent diffusivity term. Brightness assumption is made to suppress day light variation problem. Results shown promising improvement of motion estimation for synthetic and real sequences. We currently work on sub-grid model definition for atmospheric condition, insertion of sub-grid model in the regularization function and better definition of brightness assumption (spherical light reflection, scattering models).

6. REFERENCES

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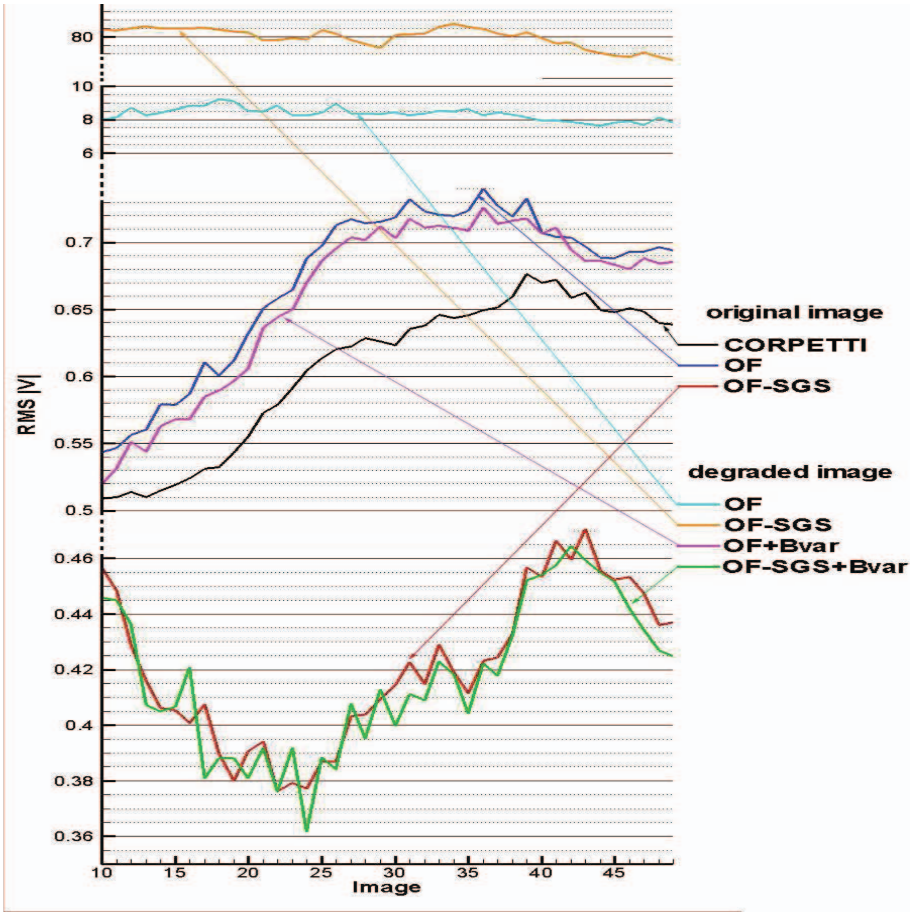
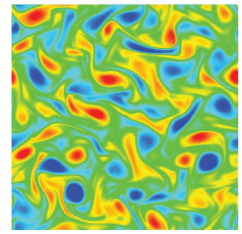
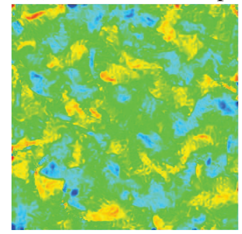


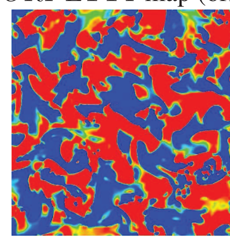
(a) RMS Amplitude error for 40 successive DNS images for different methods



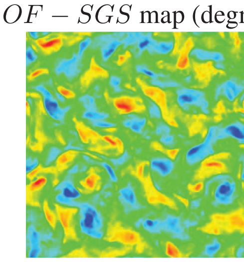
(b) Exact DNS map



(c) $CORPETTI$ map (original)



(e) $OF - SGS$ map (degraded)



(f) $OF - SGS + Bvar$ map (degraded)

Fig. 1. Synthetic DNS results on original images for $Corpetti$, OF and $OF - SGS$ and on degraded images (as satellite kind) for OF and $OF - SGS$ and for brightness variation approachs $OF + Bvar$ and $OF - SGS + Bvar$. On the left, RMS amplitude error between estimated and exact flow field, and on the right, estimated vorticity map at time $t = 30$.

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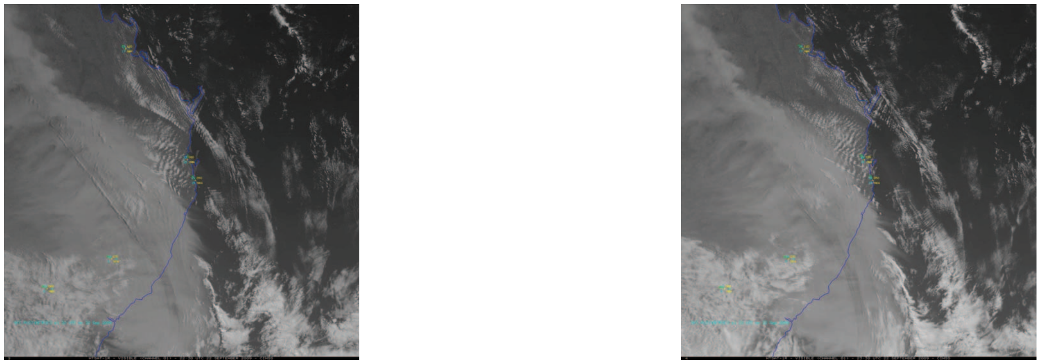
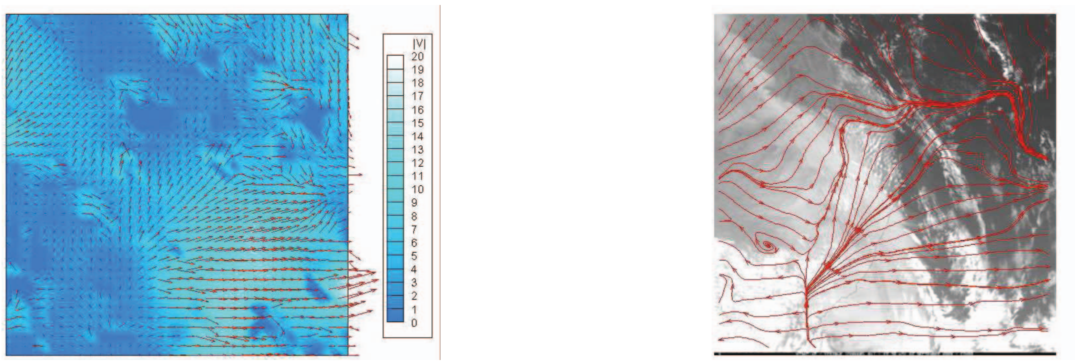
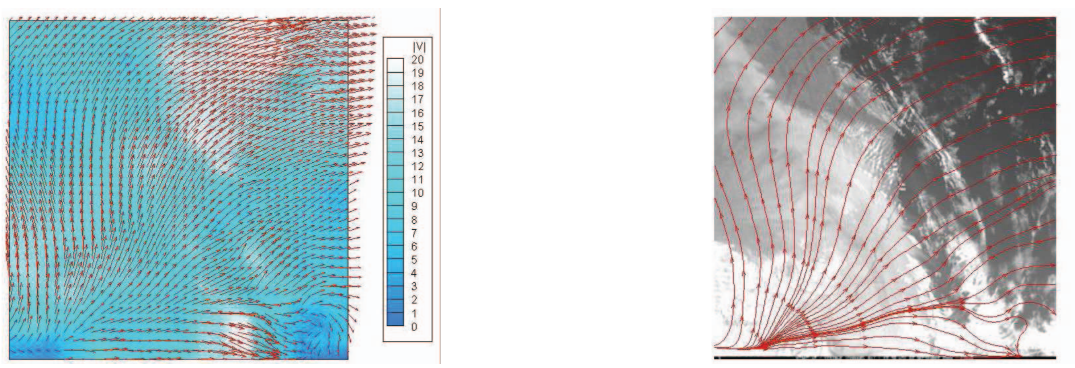


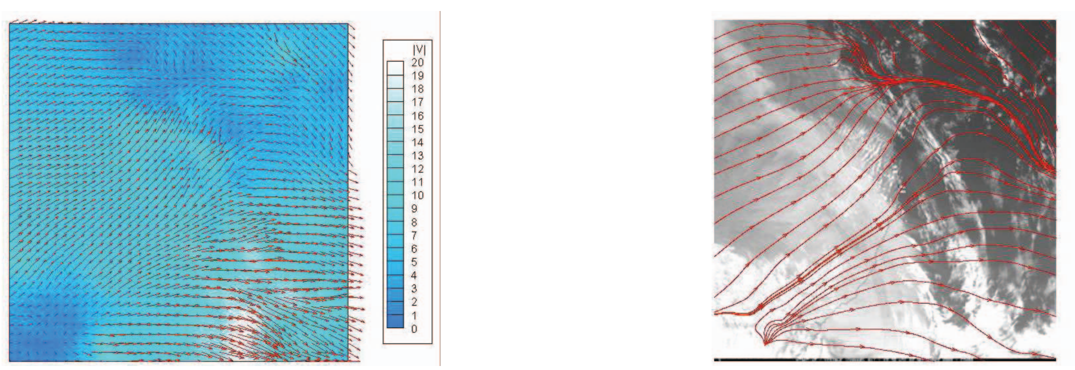
(a) 2 successive MTSAT-1R input satellite images the 09/22/2009 at 22:30 and 23:30.



(b) Corresponding estimated motion field and streamlines from $LaVision$ cross-correlation algorithm.



(c) Corresponding estimated motion field and streamlines from $OF - SGS$ algorithm.



(d) Corresponding estimated motion field and streamlines from $OF - SGS + Bvar$ algorithm.

Fig. 2. Real Australian dust storm event in 2009. Comparison of cross-correlation technique $Lavision$ with proposed $OF - SGS$ and $OF - SGS + Bvar$.