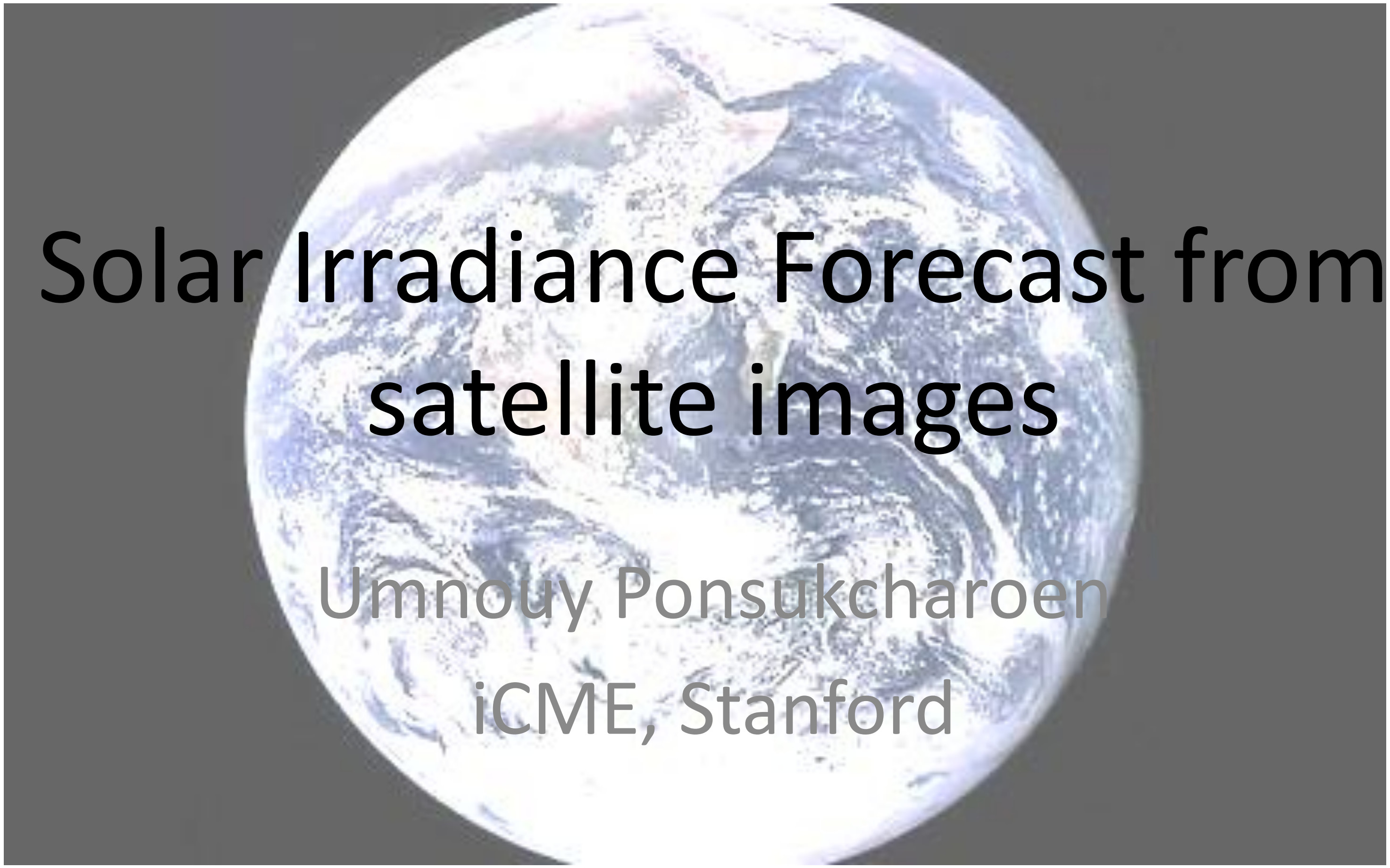

Solar Irradiance Forecast from satellite images

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iCME, Stanford

Why solar irradiance forecast?

PV Power Forecast

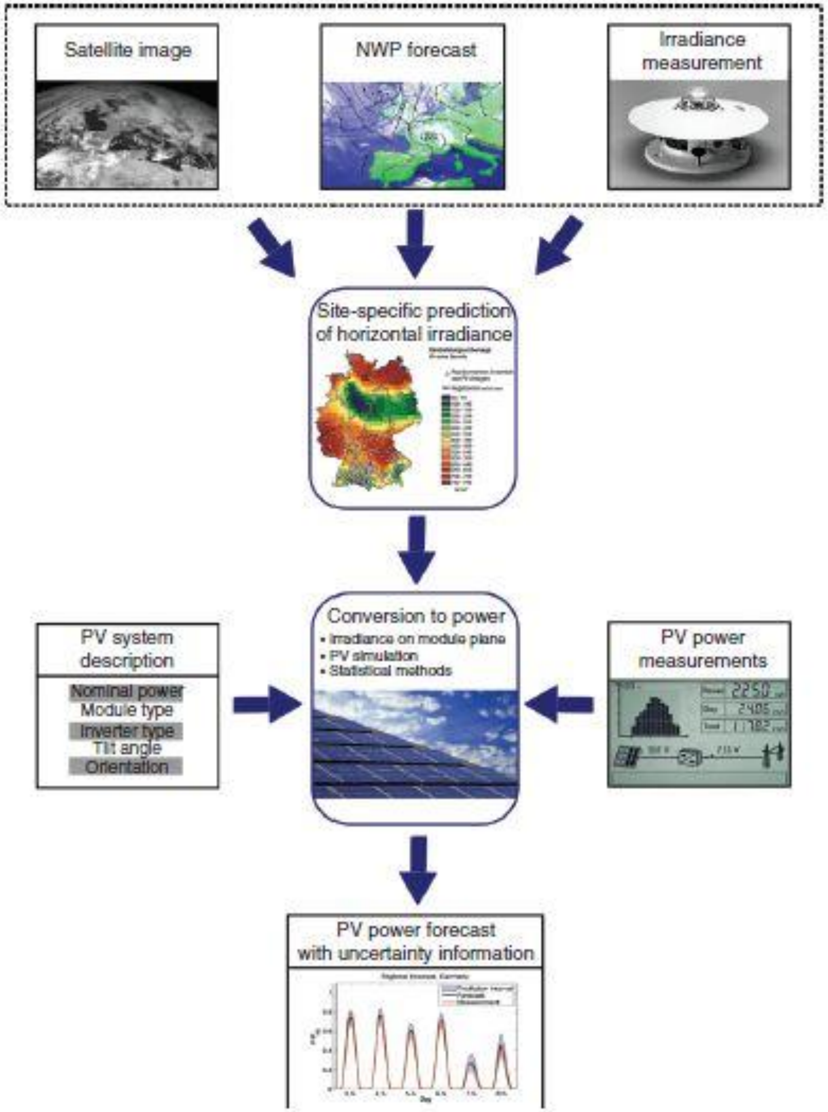
Solar Thermal Forecast

Weather Forecast

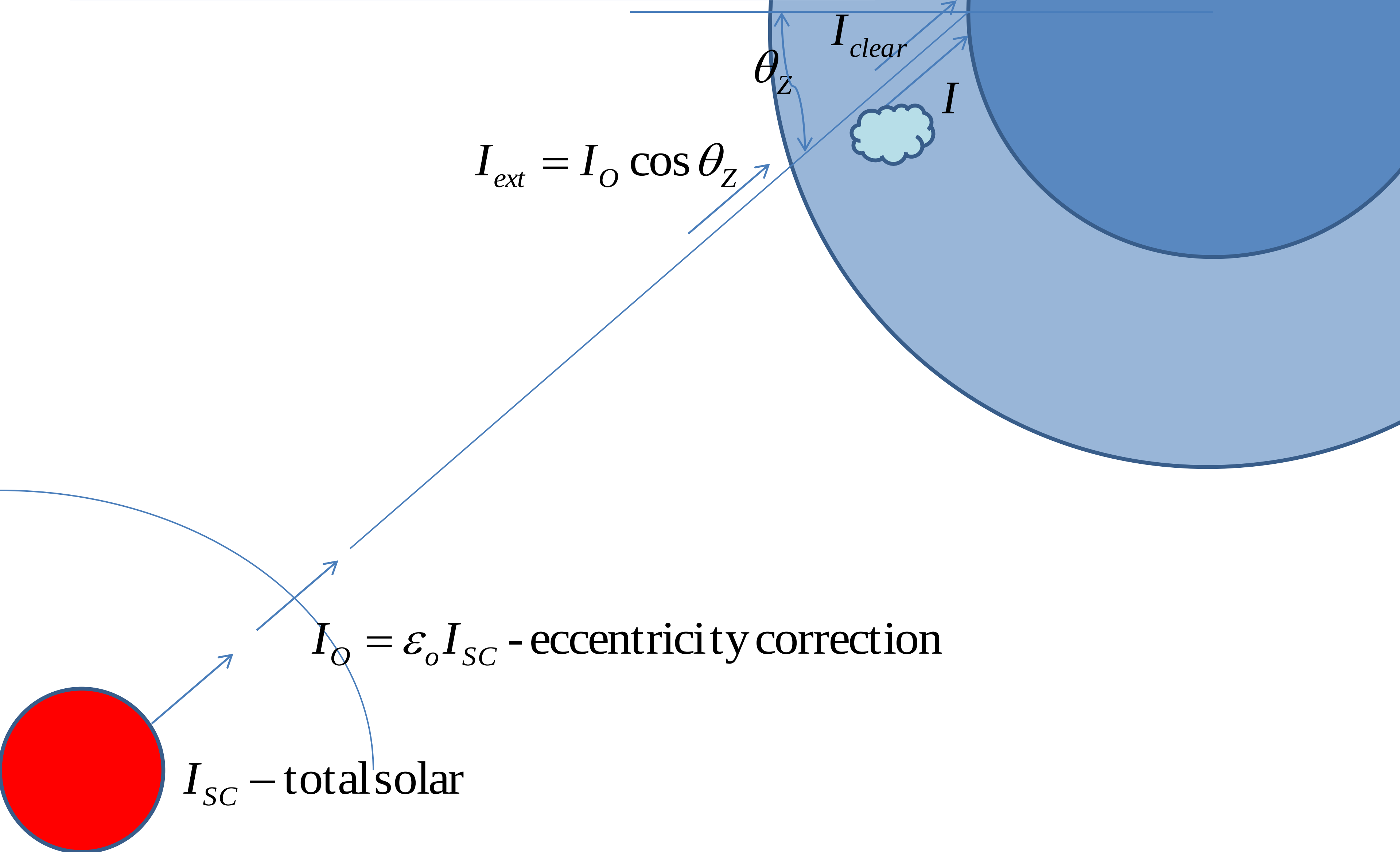
Agriculture Forecast

Load Forecast

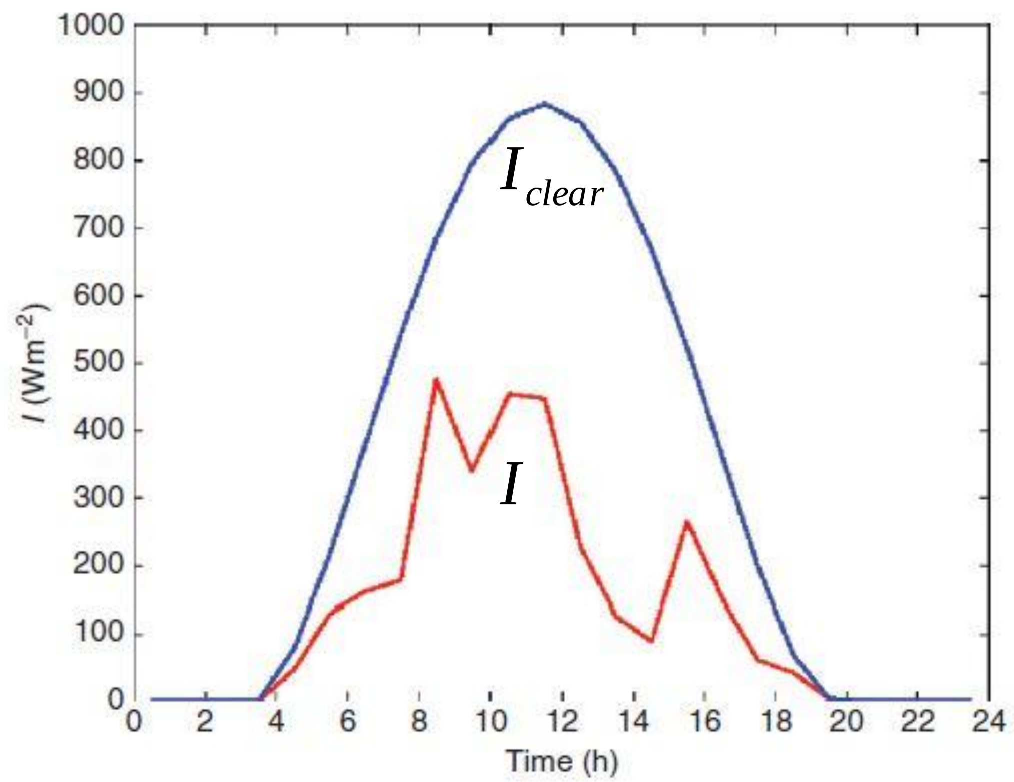
PV Power Forecast System

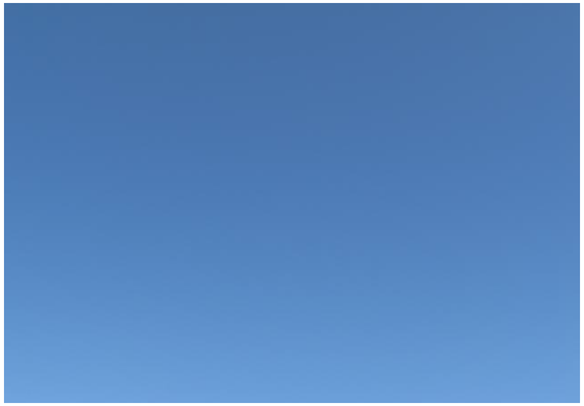


Basic Solar Irradiance



Basic Solar Irradiance (cont.)





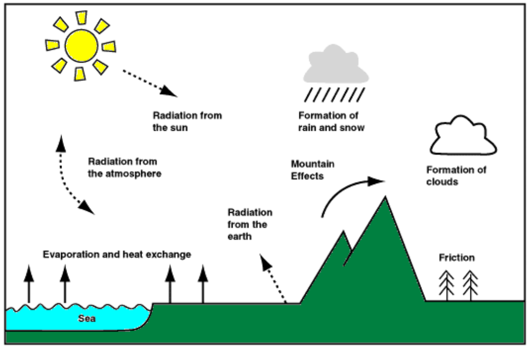
$$\text{Clear Sky Index}: k^* = \frac{I}{I_{clear}}$$

Basic Solar Irradiance Forecast

Time Series/Persistence
(good if no cloudiness change)

Satellite Imagers
(1-5 hr)

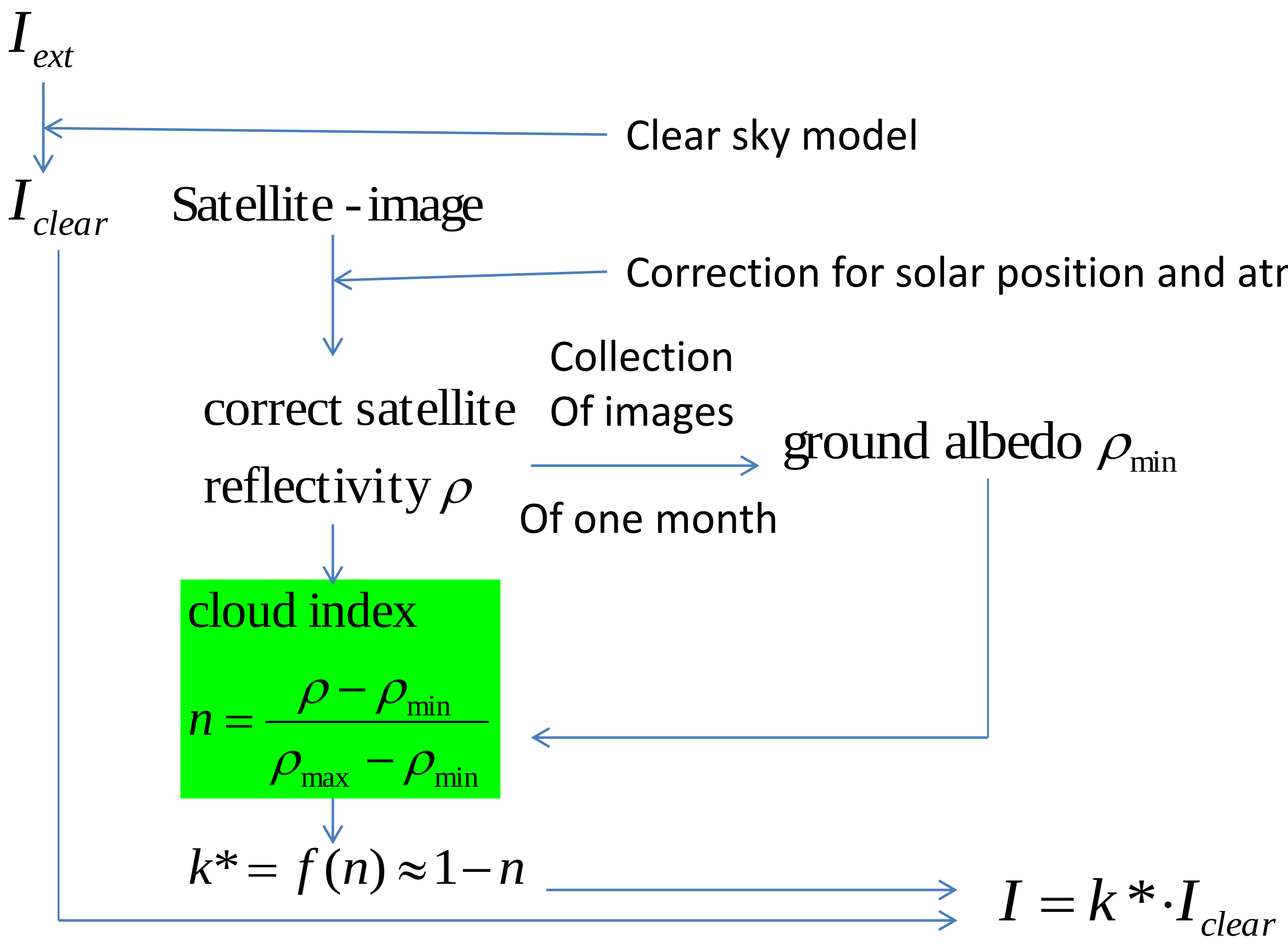
Ground-based Sky Imagers
(15-30 min)



Numerical Weather Prediction
(NWP) (> 5 hr)

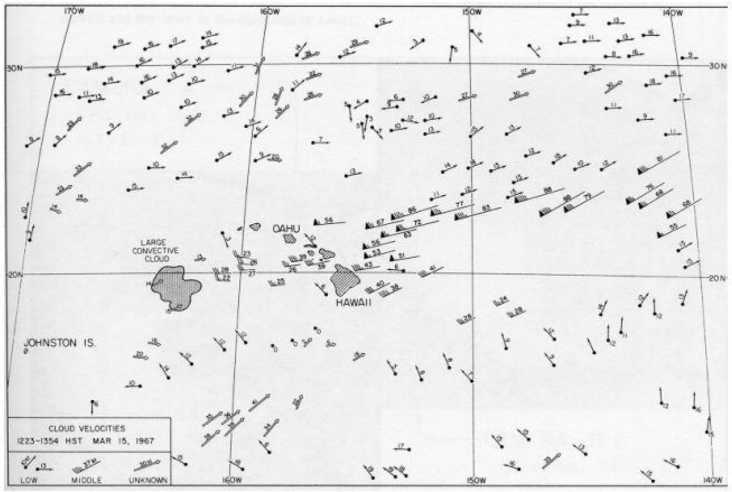
Irradiance from satellite data: HELIOSAT

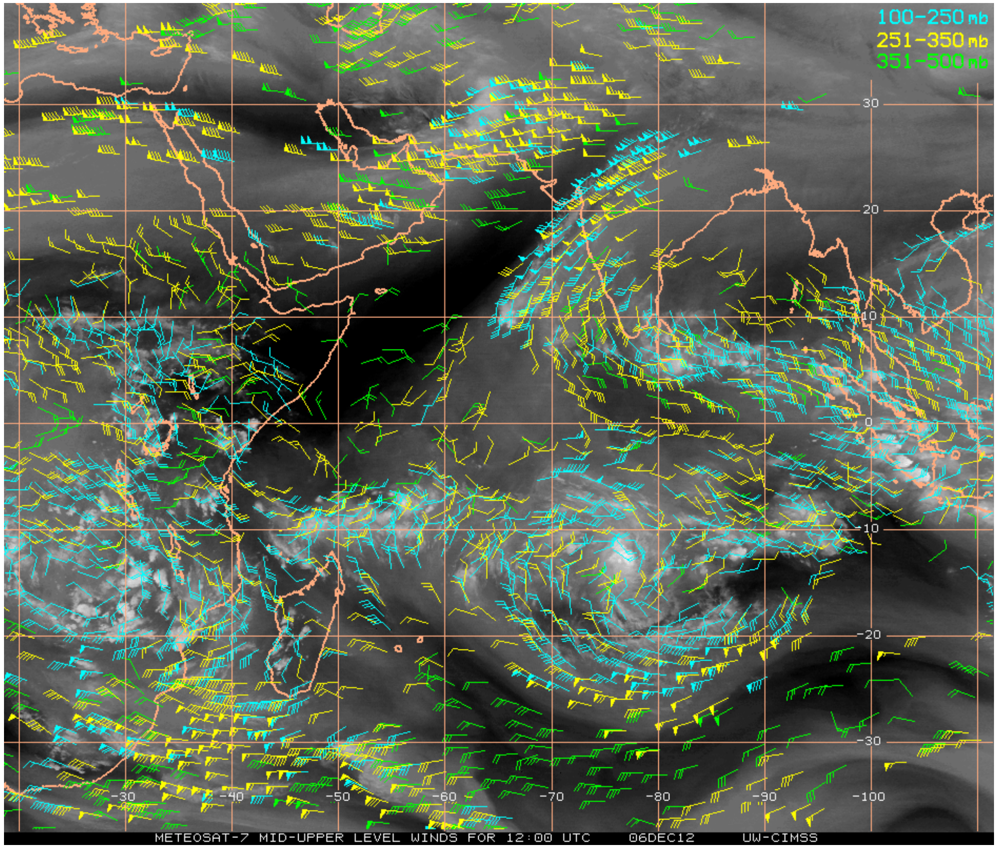
(simplified from Hammer et al 2003)



Cloud tracking

-Since 1960s (PV ~1970s)
-2001, National Environmental Satellite, Data and Information Service (NESDIS) – 3-hrly automatically generate winds





Cloud tracking (cont.)

Velocity Assessment –
small cloud ->
Tracer selection->
Spatial-correlation analysis

Height Assignment –
-> shadow
-> Infrared Window technique,
CO_2 slicing technique,
water vapor intercept technique

Properties–
-> cloud motion vectors not for all pixels
-> height assessment needed extra analysis
-> Constancy assumption

Cloud Motion Vectors I

- Statistical method for the estimation of motion (Hammer et al 1999, Konrad and Dubois 1992)
- Probabilistic model of random vector fields

vector field $d \in D$

image $g_0, g_1 \in G$

$$\text{maximize}_d \; P(D = d \mid g_0, g_1)$$

Bayes's Rule

$$\text{maximize} \; \frac{P(G_1 = g_1 \mid d, g_0) P(d \mid g_0)}{P(G_1 = g_1 \mid g_0)}$$

Cloud Motion Vectors I (cont.)

$$\text{Constancy}: \quad n_1(x+d) = n_0(x) \quad \longrightarrow \quad P(r) \approx \exp(\sum -r_i^{\,2} / 2\sigma^2): \quad r_i = n_1(x_i + d_i) - n_0(x_i)$$

$\mathrm{P}(\mathrm{G}_1 = \mathrm{g}_1 \mid d, g_0)$ Gaussian Random Surface w/ zero mean

$$\text{Gradient Constancy}: \quad \text{grad}(n_1)(x+d) = \text{grad}(n_0)(x) \quad \longrightarrow \quad P(r_g) \approx \exp(\sum -r_{g,i}^{\,2} / 2\sigma^2): \quad r_i = \text{grad}(n_1)(x_i + d_i) - \text{grad}(n_0)(x_i)$$

$\mathrm{P}(\mathrm{D} = \mathrm{d} \mid g_0)$ $\xrightarrow{\text{Theory of Markov Random Fields}}$

$$\mathrm{P}(\mathrm{D} = \mathrm{d} \mid g_0) = c_3 \exp(-U_d / \beta)$$

$$U_d = \sum_{i,j \in N} \left\| d(x_i) - d(x_j) \right\|^2$$

Cloud Motion Vectors I (cont.)

$$\text{maximize}_{\text{d}}\ P(D = d | g_0, g_1) \equiv \text{maximize}_{\text{d}} \frac{1}{Z} \exp(-U);$$

$$U = \lambda_1 U_n + \lambda_2 U_{grad(n)} + \lambda_3 U_d$$

$$U_n = \sum_{\text{i}} (n_1(x_i + d_i) - n_0(x_i))^2$$

$$U_{grad(n)} = \sum_{\text{i}} (\text{grad}(n_1)(x_i + d_i) - \text{grad}(n_0)(x_i))^2$$

Solved by Simulated Annealing: extend probability by ‘temperature’ T and do random search w/ scheme to escape from local minima

Comment: Constancy, Gradient Constancy, Continuous flow, Initial condition Problem

Cloud Motion Vectors II

- Optical Flow computation (Koltakov et al. 2012)
- Lucas-Kanade Algorithm (1961)
- Constancy assumption

$$\text{Constancy}:$$

$$n(x_1, x_2, t) = n(x_1 + \delta x_1, x_2 + \delta x_2, t + \delta t)$$

↓ Taylor Expansion

$$\frac{\partial n}{\partial x_1}\delta x_1 + \frac{\partial n}{\partial x_2}\delta x_2 + \frac{\partial n}{\partial t}\delta t = 0$$

$$grad(n)^T V = -n_t$$

$$V = d \text{ in one time step}$$

One equations with 2 unknowns!

Cloud Motion Vectors II (cont.)

Assume a group of pixels has same velocity V

$$grad(n)^T V = -n_t$$

If number of pixels in group > 2,
Not simultaneously solvable

$$grad(n(x_1))^T V = -n_t(x_1)$$

$$\ldots$$

$$grad(n(x_k))^T V = -n_t(x_k)$$

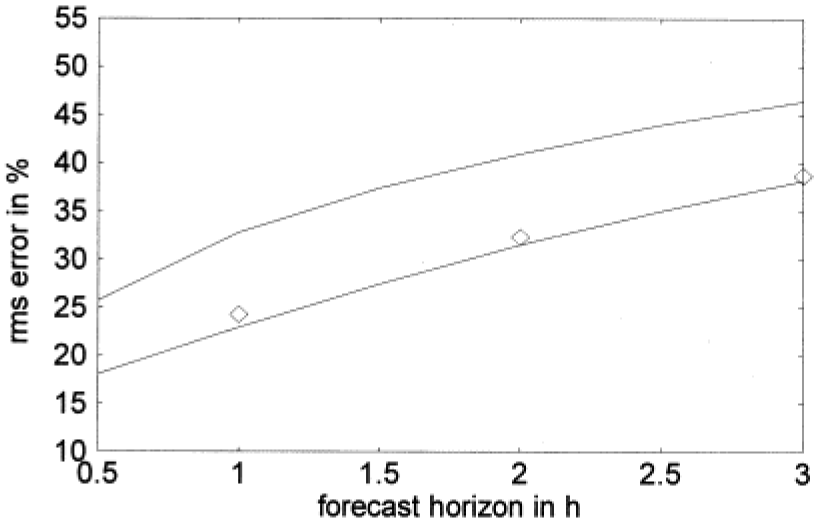
Convert it to weighted least-square problem

$$\min \sum_{x_i \in \Omega} W(x_i)[grad(n(x_i))^T V + -n_t(x_i)]^2$$

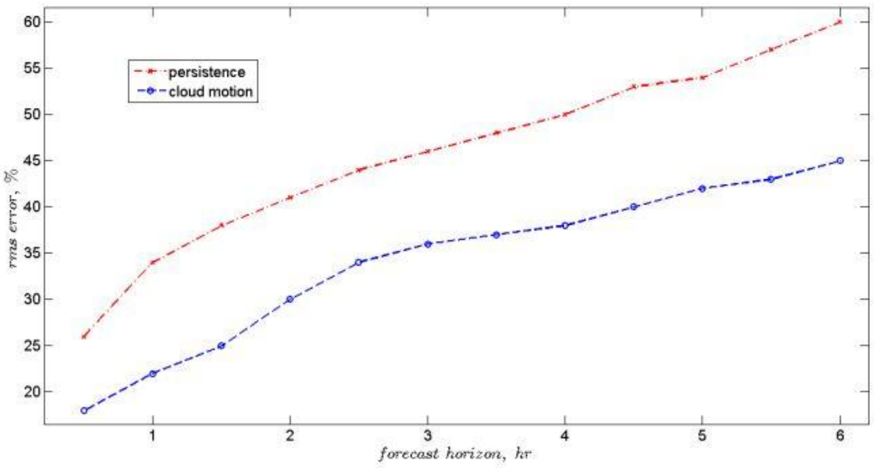
Comment: Constancy, Continuous flow, No Gradient constancy, Large Motion Problem (solved by multi-resolution image), Choice of group (nxn squares)

Cloud Cover Forecast

- Use velocity vector – simply first order equation of motion



Hammer et al (1999)



Koltakov (2012)

Comment: Same Accuracy, Better computation efficiency

Constancy assumption

Some Thoughts

- Constancy assumption
- Height, thickness of clouds
- Correlation between pixels
- Vector Calculus
- Other forms of optimization problem
- Utilization of Cloud Tracking Techniques
- How to cooperate with other prediction methods & other parameters