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www.vit.ac.in

## *Cambridge Particle Meeting 2018*

# Turbulent mixing and generation of short lived climate forcers from an Asian Mega City: The Soot and Black Carbon Conundrum

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4Mechanical Engineering, Saintgitis College of Engineering- Kerala, India

# Outline

- Overview
- Why are Soot and Black Carbon particles termed ‘’short lived climate forcers”?
- SLCF from *Indian Slums* and *Vehicular Traffic*
- Linking fruits of University Research to Operational models
- Solutions

# Overview- Indian cities dominate world air pollution list

Eight-Fold Levitation of Air Pollution across City during Weekend!

http://www.livechennai.com/detailnews.asp?newsid=11771


Cases of respiratory problems increasing in Chennai due to rising pollution levels.

**IBN** Live

*"Thou knowst all, I cannot see,*
*I trust I shall not live in vain"*

*– Oscar Wilde*

# What are climate forcers?

# Black carbon or soot as a climate forcer…

- Soot particles are essentially elemental carbon particles with some amount of organic compounds adsorbed over them.

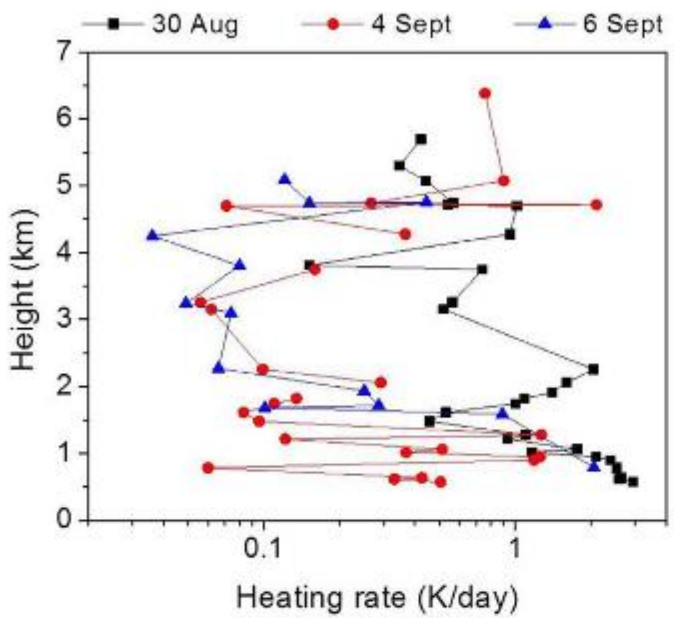
- Unlike carbon-dioxide (which would linger in our atmosphere for ages) soot remains in the air ***for just a few weeks*** – its short life span lends it the name 'Short-lived Climate Forcer' (SLCF).

- They are ephemeral and have insignificant falling speeds due to their light weight.

- They finally settle down under the effect of gravity or are washed away.

# Soot and Black Carbon affecting Climate- Studies conducted in India

- **Cloud Aerosol Interaction and Precipitation Enhancement Experiment (CAIPEEX)**




Atmospheric circulations associated with the ISM help in the formation of a second layer of black carbon in the upper atmosphere, which generates an upper atmospheric heating of 2 K/day

**Rahul et al. (2014)- *Scientific Reports***

- **Indian Ocean Experiment (INDOEX)**

**Main Findings:**

1. Plumes of sulphates, ***smoke particles***, and other anthropogenic aerosols blowing over the Indian Ocean was blocking sunlight and promoting cloud formation.
2. The amount of sunlight reaching the Earth's surface was reduced by 10%.

# Aerosol Particle Characterisation Over Chennai

- Why is this difficult to model?
- Why is the problem so intractable?

"Current models used by Central Pollution Control Board (CPCB) under-predict concentrations by over 50-60%"

**Causes of under-prediction**

1. ***Residual Pollution*** not accounted for!
2. ***Mass Transfer*** processes incompletely understood.
3. ***Aerosol Chemistry*** not incorporated into the pollution models.

Atmos. Chem. Phys., 13, 7199–7213, 2013
www.atmos-chem-phys.net/13/7199/2013/
doi:10.5194/acp-13-7199-2013

Atmospheric Chemistry and Physics
Open Access

**Identifying the sources driving observed $PM_{2.5}$ temporal variability over Halifax, Nova Scotia, during BORTAS-B**

M. D. Gibson[1], J. R. Pierce[2,3], D. Waugh[4], J. S. Kuchta[1], L. Chisholm[4], T. J. Duck[2], J. T. Hopper[1], S. Beauchamp[4], G. H. King[1], J. E. Franklin[2], W. R. Leaitch[5], A. J. Wheeler[6], Z. Li[7], G. A. Gagnon[8], and P. I. Palmer[9]

[1]Department of Process Engineering and Applied Science, Dalhousie University, Halifax, Nova Scotia, Canada
[2]Department of Physics and Atmospheric Science, Dalhousie University, Halifax, Nova Scotia, Canada
[3]Department of Atmospheric Science, Colorado State University, Fort Collins, Colorado, USA
[4]Environment Canada, Dartmouth, Nova Scotia, Canada
[5]Environment Canada, Toronto, Ontario, Canada
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[7]College of Environmental Science and Engineering, Ocean University of China, Qingdao, China
[8]Department of Civil and Resources Engineering, Dalhousie University, Halifax, Nova Scotia, Canada
[9]School of GeoSciences, University of Edinburgh, Edinburgh, UK

**Poor fit between modelled and observed PM values (Gibson et al. 2013)**

*Aerosol and Air Quality Research*, 17: 1925–1937, 2017
Copyright © Taiwan Association for Aerosol Research
ISSN: 1680-8584 print / 2071-1409 online
doi: 10.4209/aaqr.2016.06.0265

**Technical Note**

**Application of WRF Model for Air Quality Modelling and AERMOD – A Survey**

**Awkash Kumar[1*], Rashmi S. Patil[1], Anil Kumar Dikshit[1], Rakesh Kumar[2]**

*[1] Centre for Environmental Science and Engineering, Indian Institute of Technology, Bombay, Mumbai - 400 076, India*
*[2] Council of Scientific and Industrial Research-National Environmental Engineering Research Institute Mumbai Zone, Mumbai - 400 076, India*

**Under prediction by over 50 % (Kesarkar et al. 2007)**

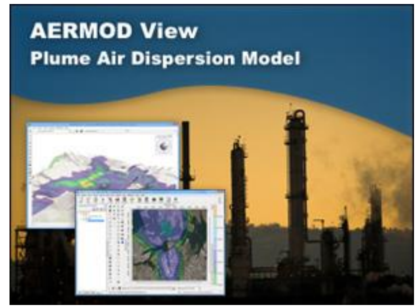
# Addressing the Problem

Our Recent research in VIT points to following course of action:

- Address why standard Air Quality models imported directly from the West are not applicable without amendment.

EPA United States Environmental Protection Agency

Preferred and Recommended Model




The Key is to quantifying **Residual Pollution!**

Pollution Pall in Delhi

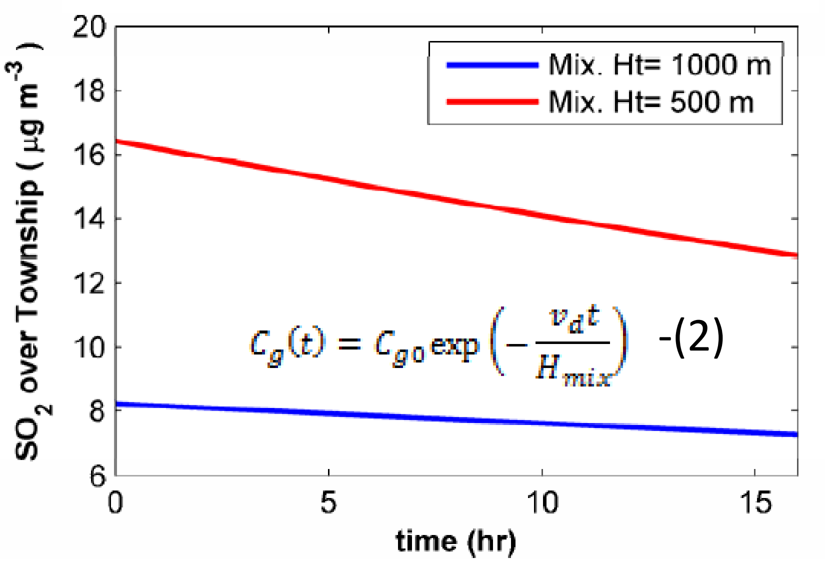
**-The Times of India**

# What is *Residual Pollution*?

***Left over pollution from a previous visit of the plume (transient sources)/transported from other affected areas/pall left behind due to changing wind direction.***

First pointed out by Picardo and Ghosh 2011- ***Air Pollution New Developments***

$$v_d = r_t^{-1} = (r_a + r_b + r_c)^{-1} \ (cms^{-1}) \quad \text{-(1)}$$




$$C_g(t) = C_{g0} \exp\left(-\frac{v_d t}{H_{mix}}\right) \quad \text{-(2)}$$

Residual pollution effects over NLC township in 15 hours.

A detailed study on *Asia's Largest Lignite based Power Plant*- Neyveli Lignite Corporation (NLC) located in the Cuddalore district of Tamil Nadu in South India conducted by Picardo and Ghosh

# Wind directions over Chennai- October 2011

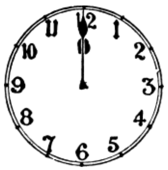
## 6 am to 8 am

# 8 am to 10 am

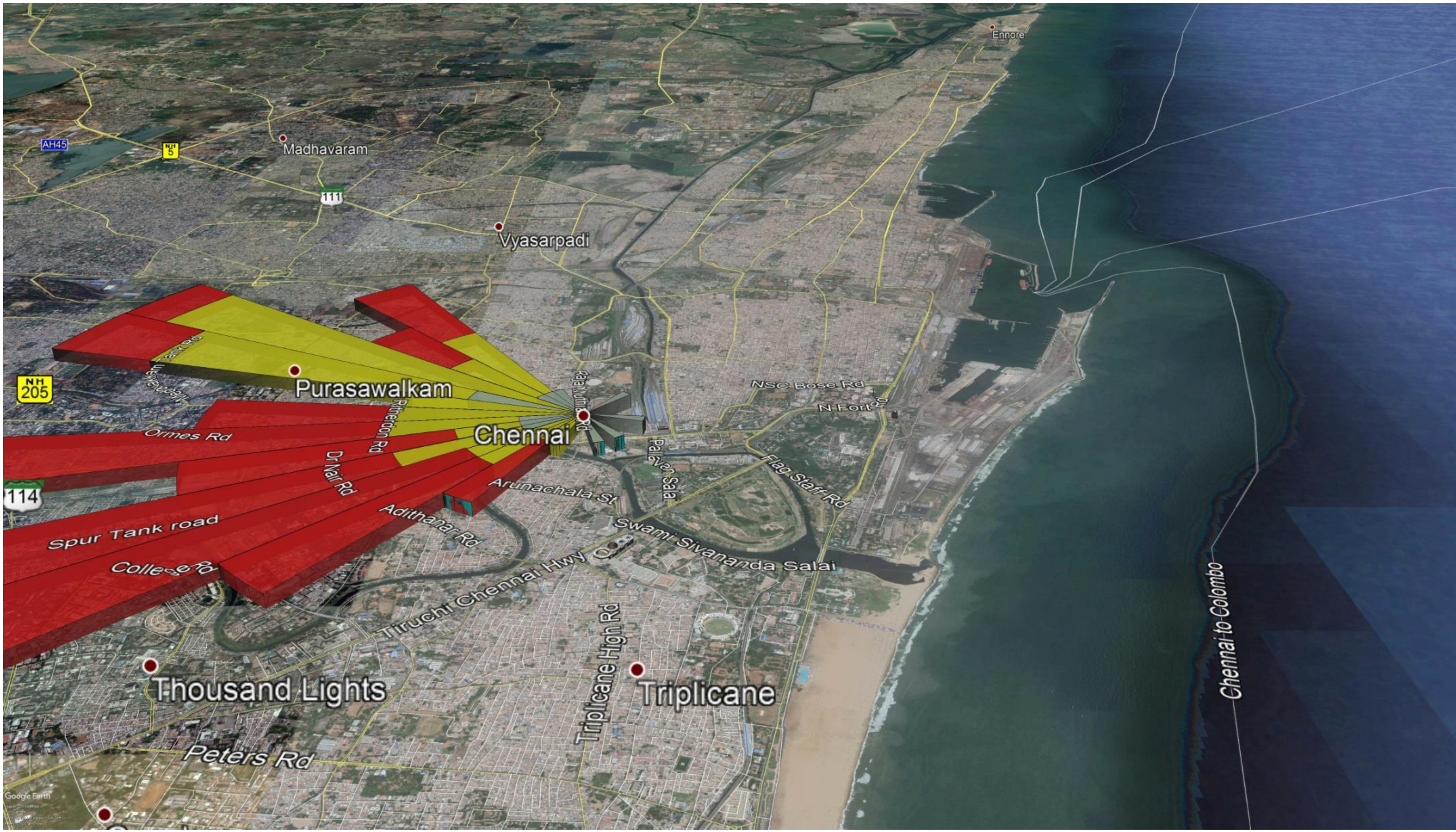

Ennore
AH45
NH 5
Madhavaram
111
Vyasarpadi
NH 205
Purasawalkam
Ritherdon Rd
Ormes Rd
Chennai
Dr Nair Rd
114
Spur Tank road
NSC Bose Rd
N Fort Rd
Pallavan Salai
Flag Staff Rd
Arunachala St
Adithanar Rd
College Rd
Swami Sivananda Salai
Tiruchi Chennai Hwy
Triplicane High Rd
Thousand Lights
Triplicane
Peters Rd
Chennai-to-Colombo
Google Earth

# 10 am to 12 noon

# 12 noon to 2 pm

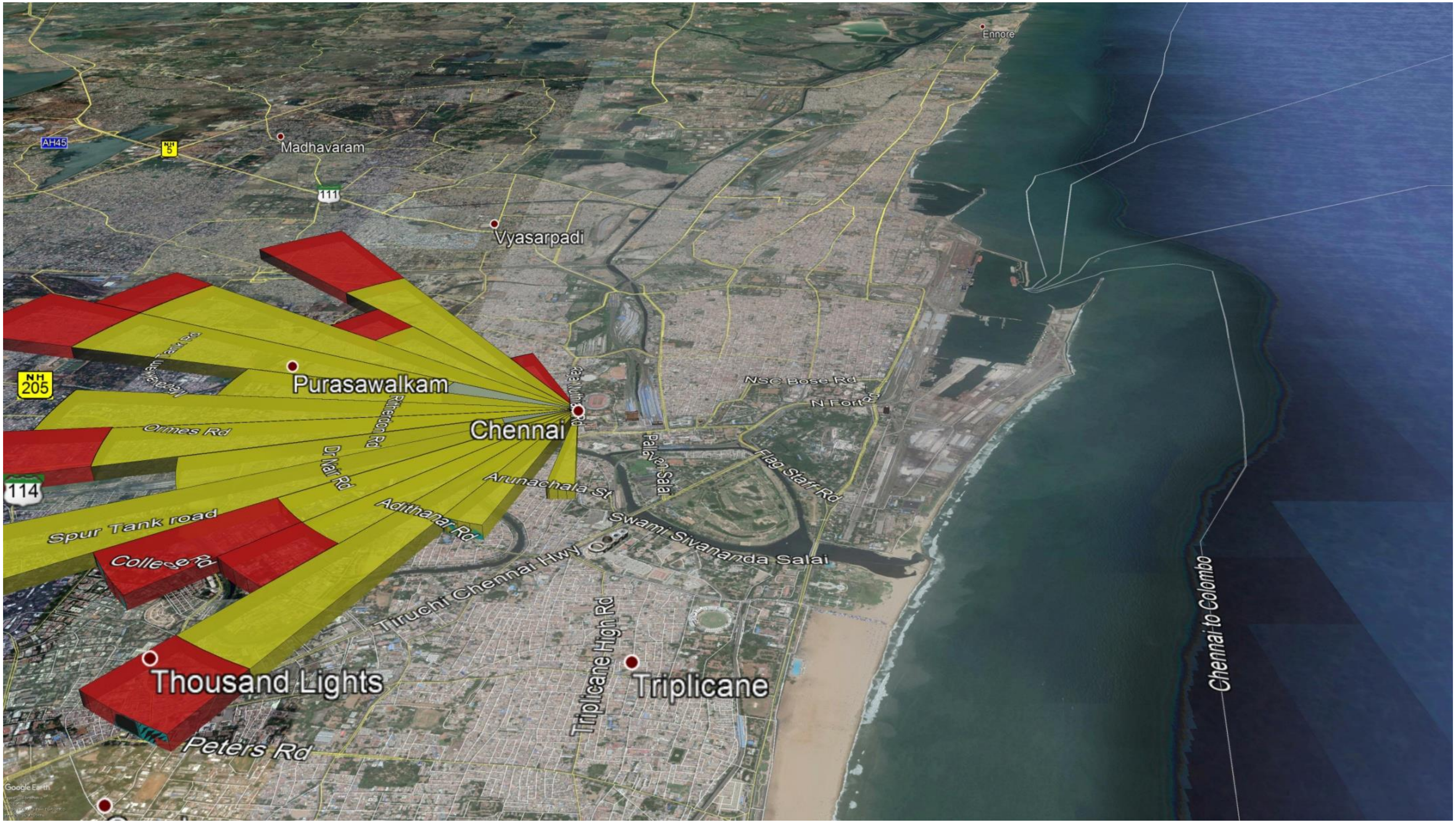


# 2 pm to 4 pm

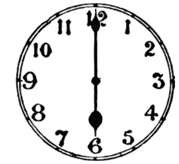


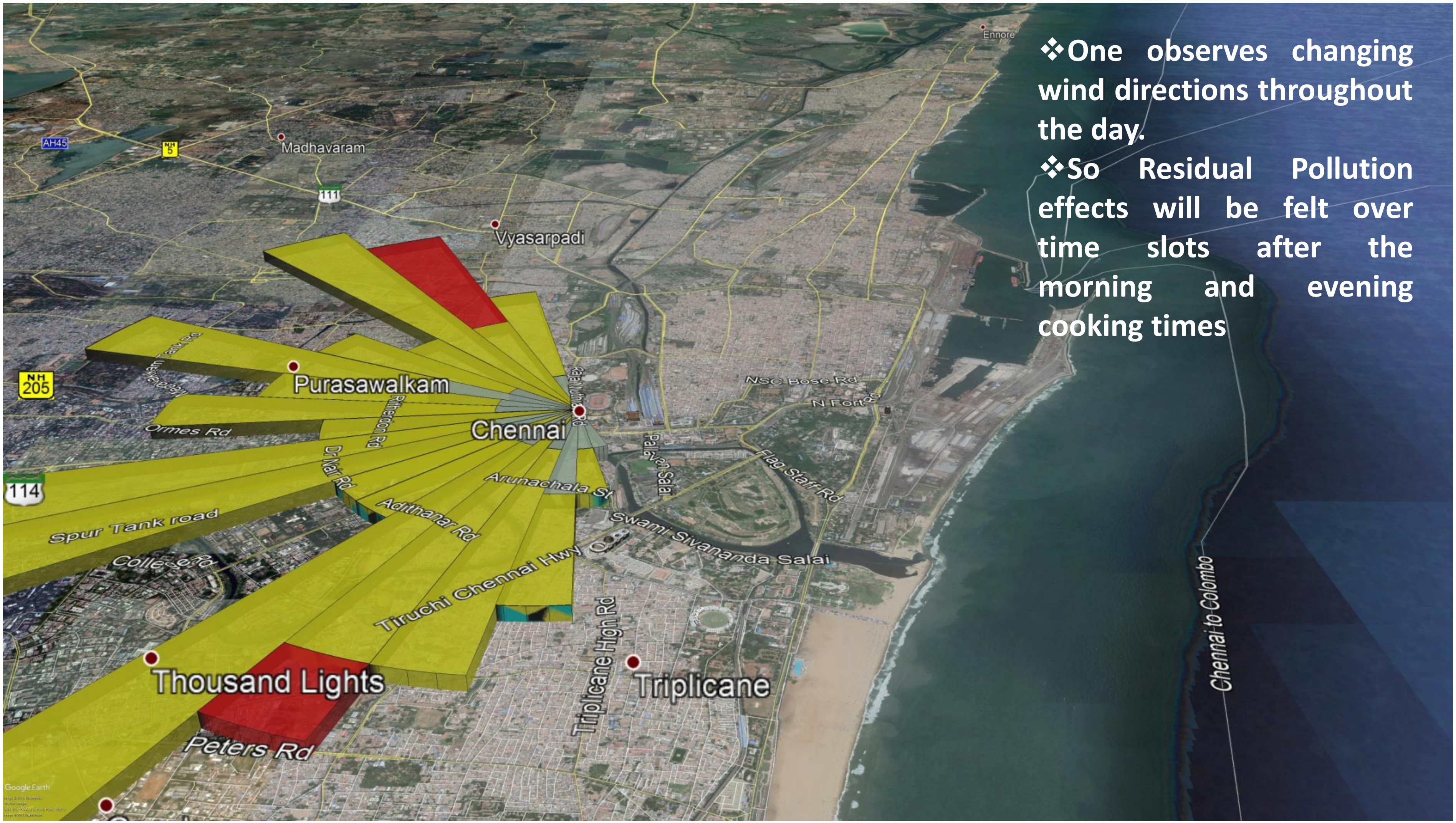
Ennore
AH45
NH 5
Madhavaram
111
Vyasarpadi
NH 205
Purasawalkam
Chennai
Ormes Rd
Dr Nair Rd
114
Spur Tank road
Adithanar Rd
Arunachala St
NSC Bose Rd
N Fort Rd
Flag Staff Rd
Swami Sivananda Salai
Tiruchi Chennai Hwy
Triplicane High Rd
Thousand Lights
Triplicane
Peters Rd
Chennai to Colombo
Google Earth

# 4 pm to 6pm


Ennore
Madhavaram
AH45
NH 5
111
Vyasarpadi
Purasawalkam
NH 205
Ormes Rd
Ritherdon Rd
Chennai
Dr Nair Rd
114
Arunachala St
Spur Tank road
Adithanar Rd
College Rd
NSC Bose Rd
N Fort Rd
Flag Staff Rd
Swami Sivananda Salai
Tiruchi Chennai Hwy
Triplicane High Rd
Thousand Lights
Triplicane
Peters Rd
Chennai to Colombo
Google Earth

# 6 pm to 8 pm






- ❖One observes changing wind directions throughout the day.
- ❖So Residual Pollution effects will be felt over time slots after the morning and evening cooking times

# Main Sources of Residual Pollution

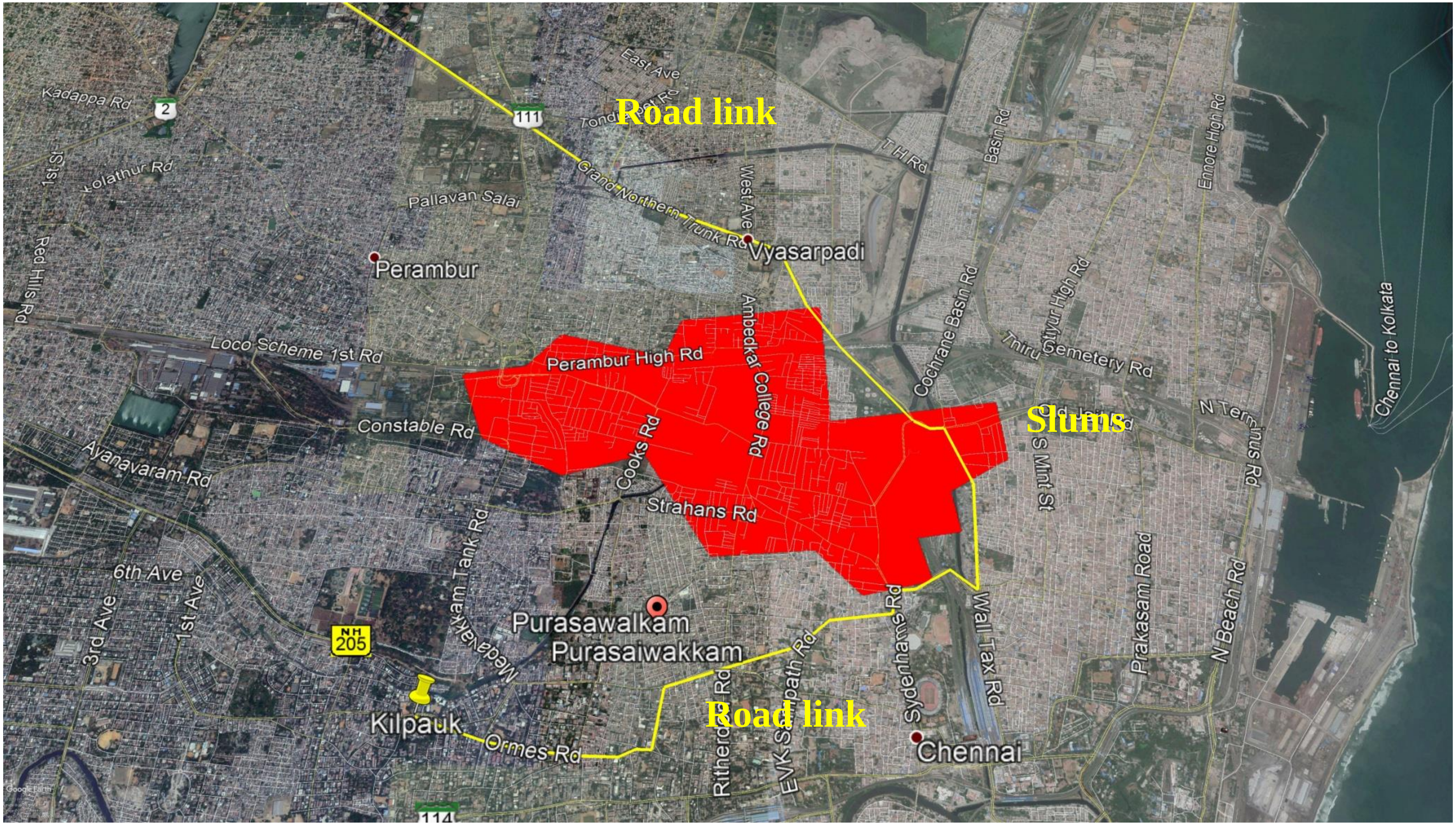
Smoking Auto rickshaws

Outdated Vehicles- HCV and LCV

Industrial Stacks

Traditional cooking methods

# Study zone- Road link and Slums

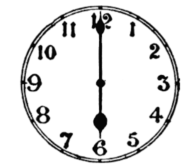


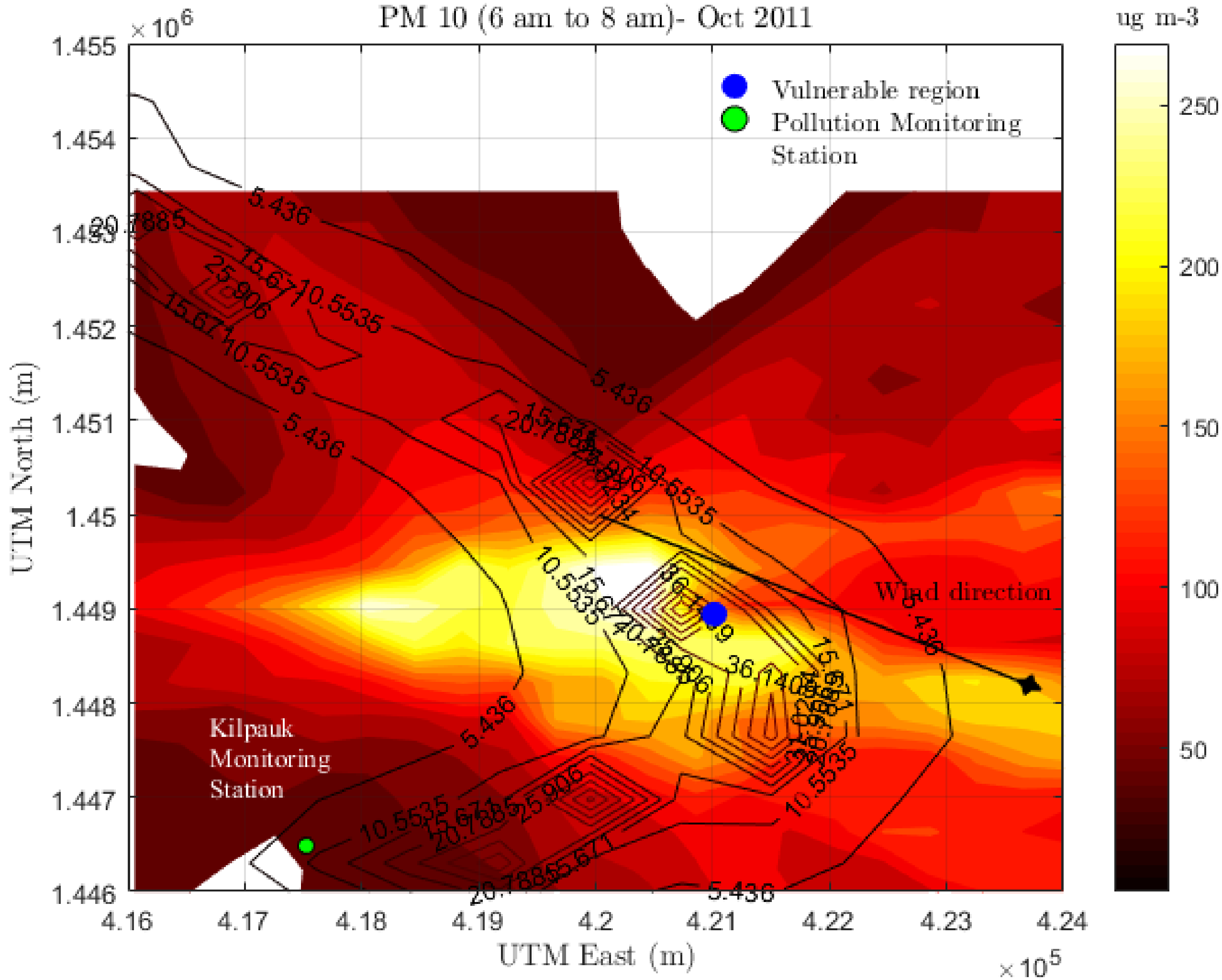
# Treatment of Transient Emissions

| Month | Observed Value in Vallalar Nagar TNPCB Monitoring Station in Northern Chennai 8 hrs Average $PM_{10}$ concentration in $\mu gm^{-3}$ | AERMOD Model Results for Slum Emissions over North Chennai 8 hrs Average $PM_{10}$concentration in $\mu gm^{-3}$ | AERMOD Model Results for traffic Emissions over North Chennai 8 hrs Average $PM_{10}$concentration in $\mu gm^{-3}$ | Prescribed standards by CPCB for 8 hrs Average $PM_{10}$ concentration in $\mu gm$-$^{3}$ |
|---|---|---|---|---|
| Feb-11 | **151** | 135.25-166.35 | 51.19-60.18 | 100 |
| May-11 | **133** | 100.01-114.29 | 15.64-20.98 | 100 |
| Aug-11 | **272** | 170.33-198.70 | 43.59-58.58 | 100 |
| Nov-11 | **217** | 163.57-190.69 | 58.39-78.79 | 100 |

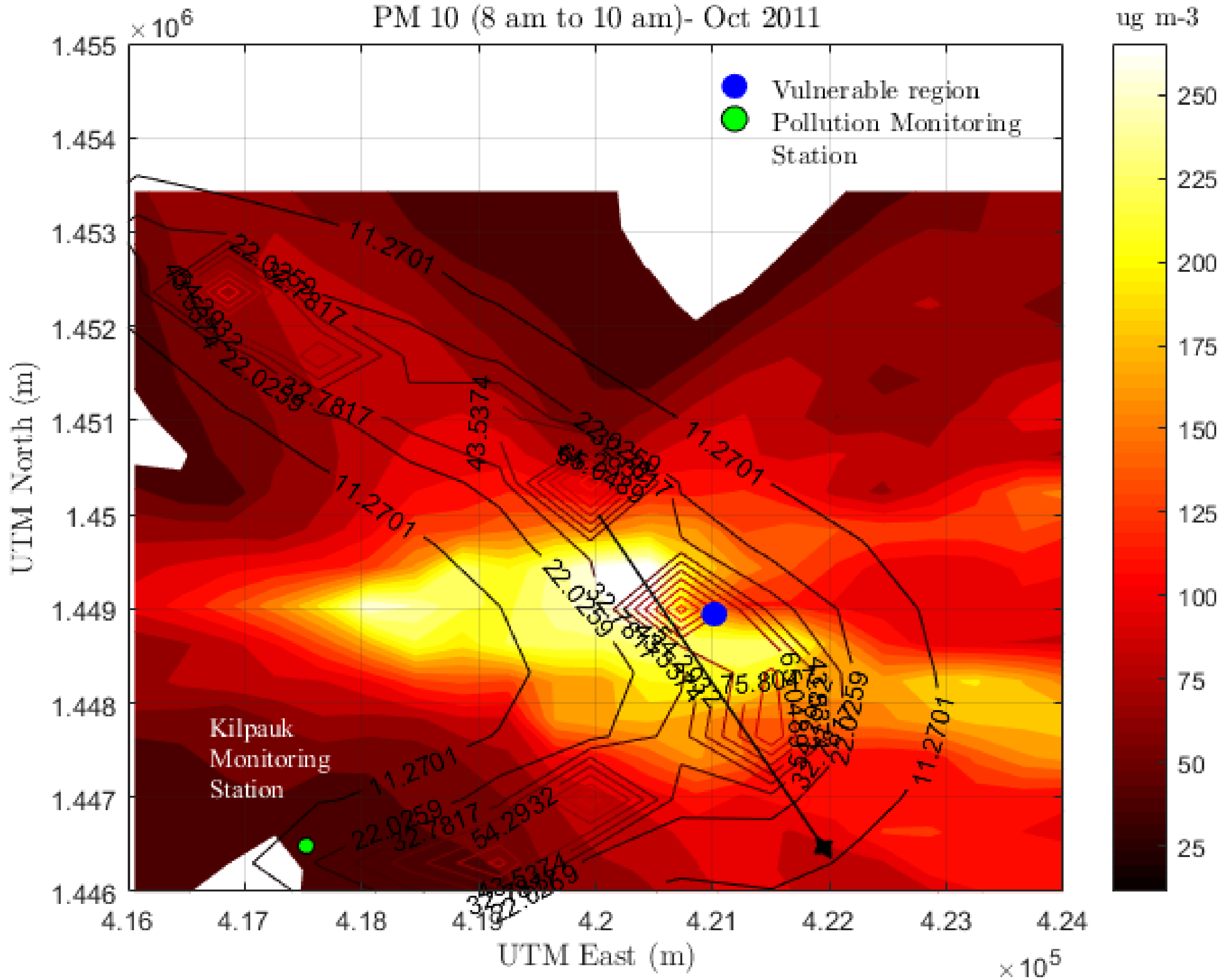
1. Even keeping slum emissions on for an entire month continuously- the numbers do not add up.
2. In reality, slum emissions peak only twice a day (Modelling studies have treated them as continuous sources)- proper treatment of transient sources necessary.

# Modelling PM10 at Receptor sites





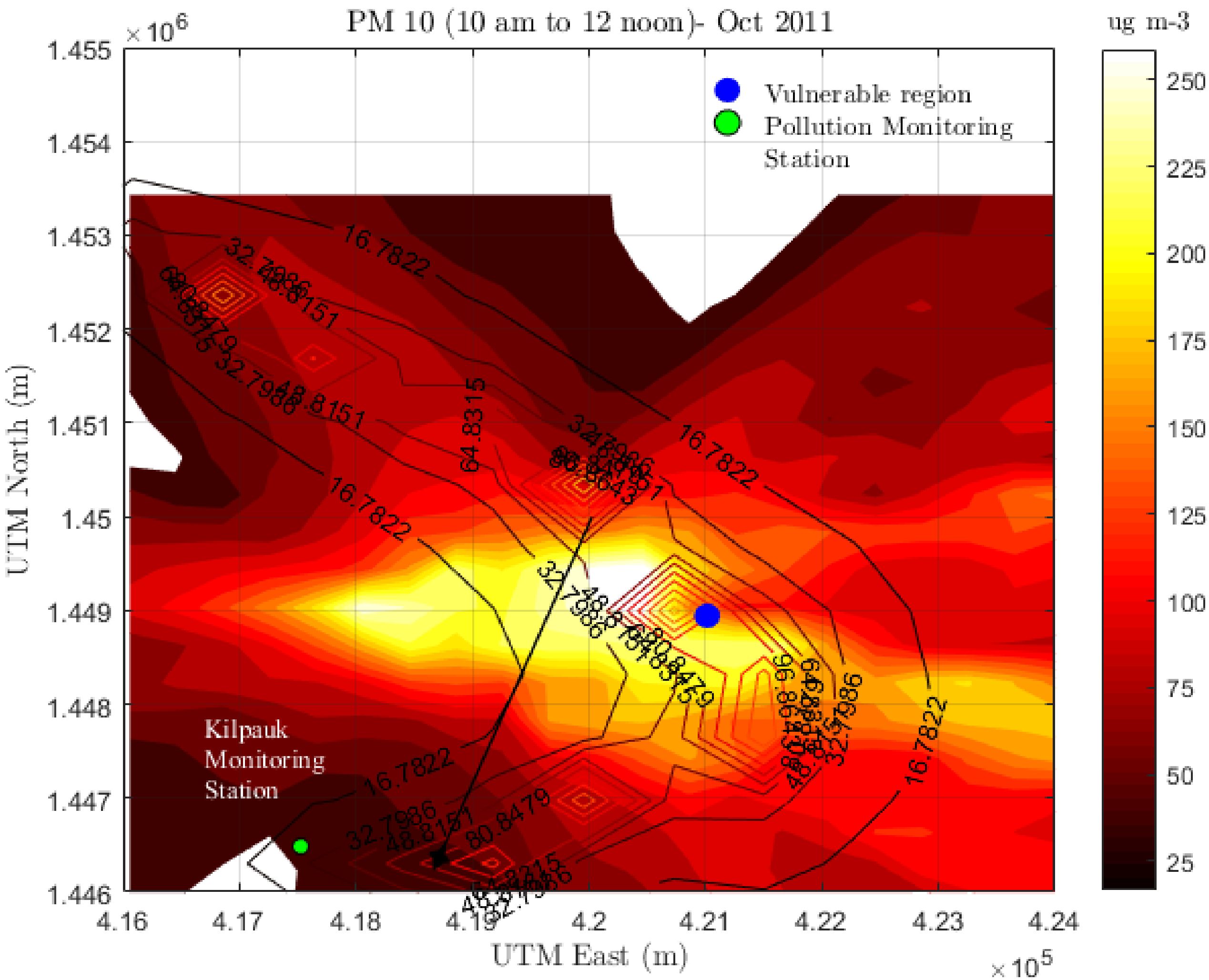

***Marked contours refer to traffic pollution***




○Morning slum pollution concentrations recede at the receptor.

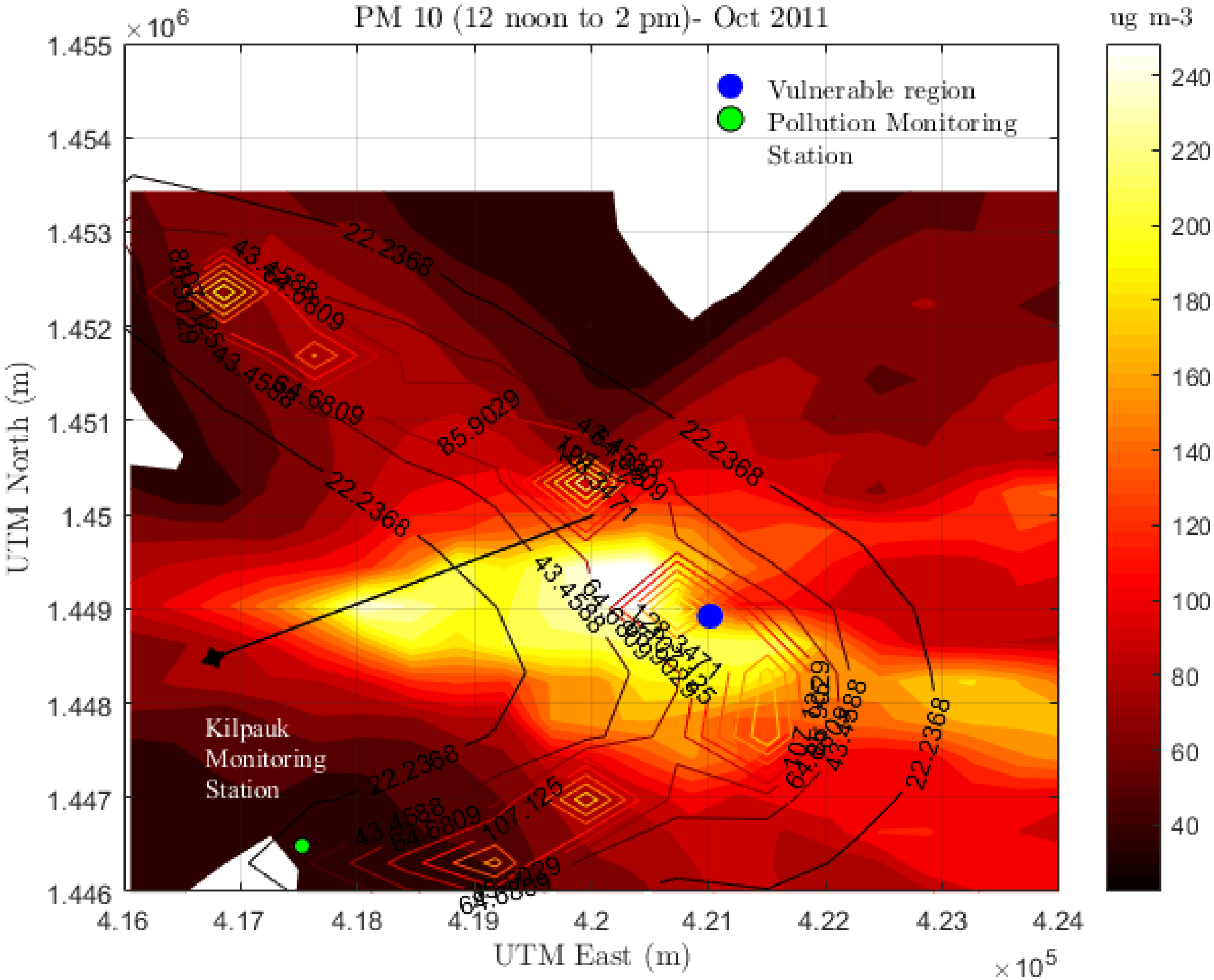
○Increase in traffic pollution concentrations at the receptor.

***Marked contours refer to traffic pollution***




- Morning slum pollution concentrations recede at the receptor.
- Further increase in traffic pollution concentrations at the receptor.

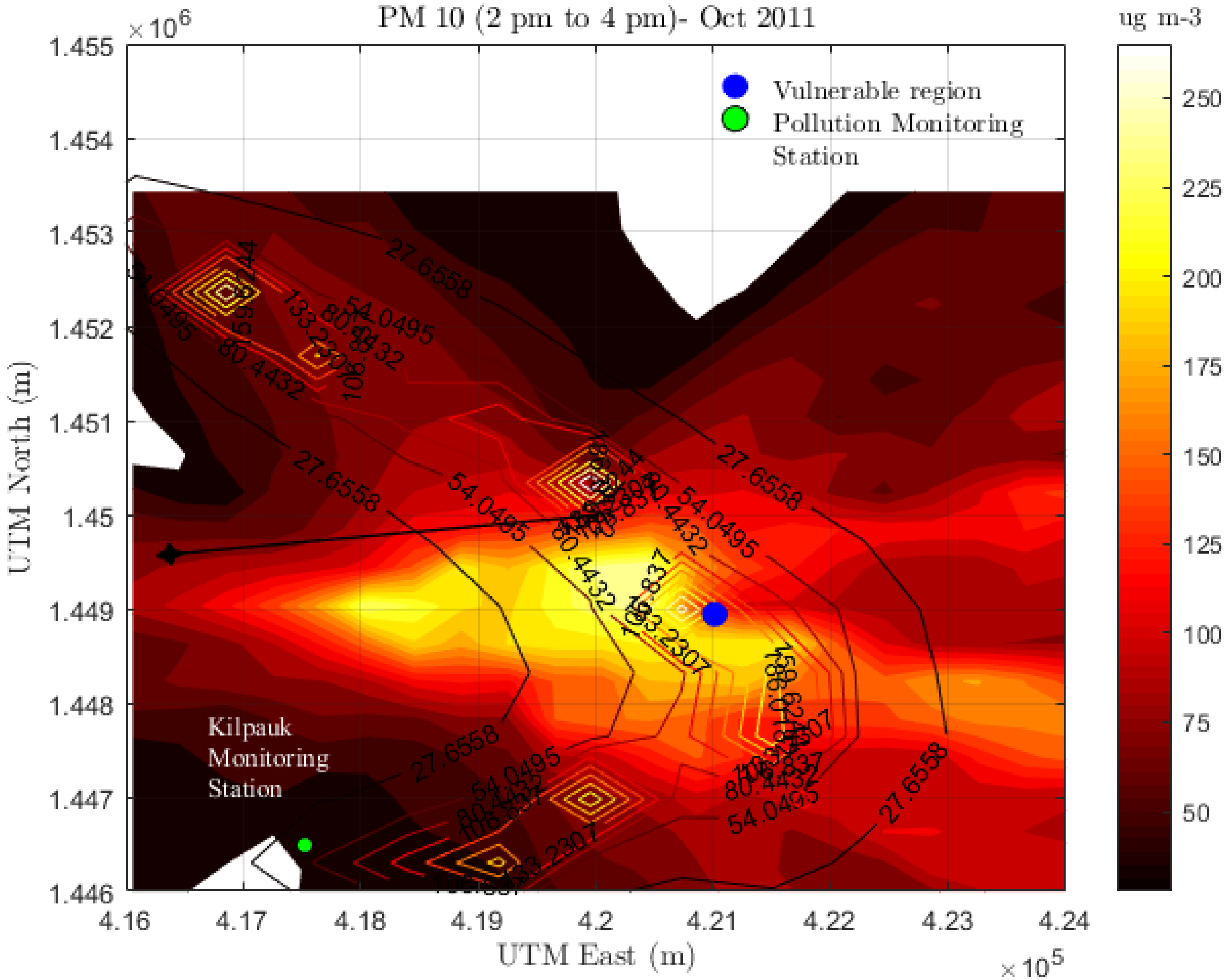
***Marked contours refer to traffic pollution***

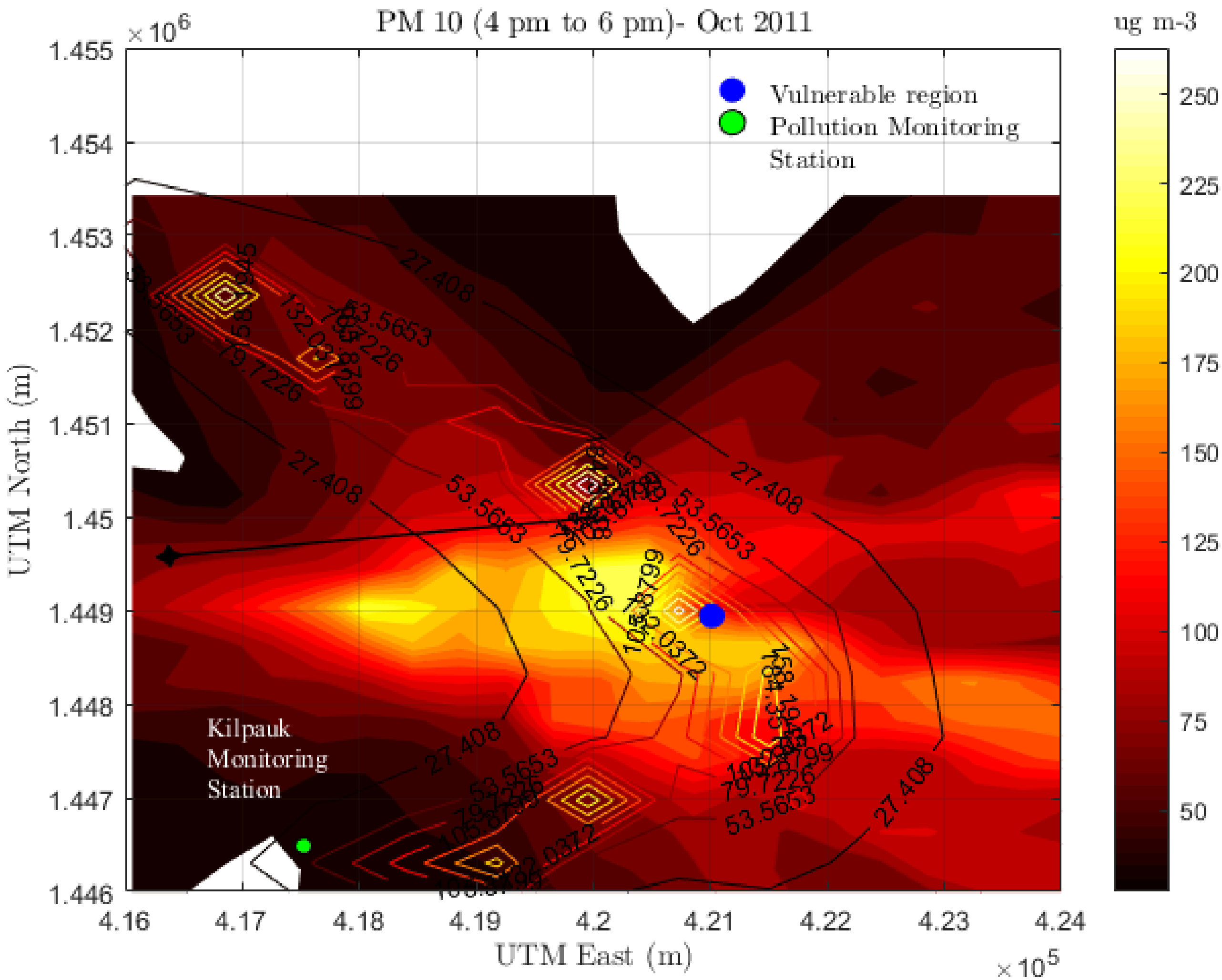

○Morning slum pollution concentrations recede at the receptor.

○Increase in traffic pollution concentrations at the receptor.

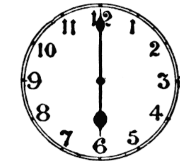
***Marked contours refer to traffic pollution***

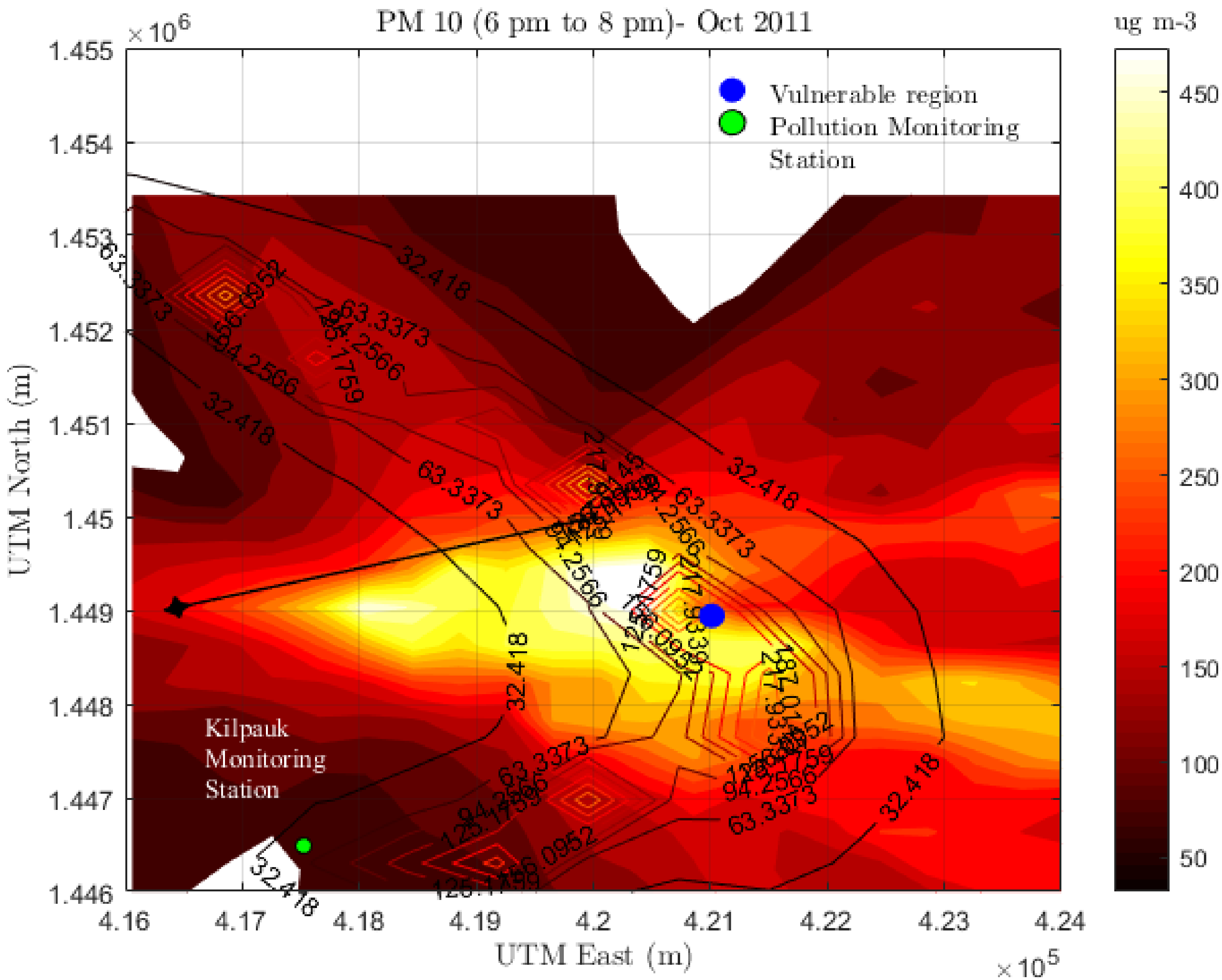



***Marked contours refer to traffic pollution***




***Marked contours refer to traffic pollution***



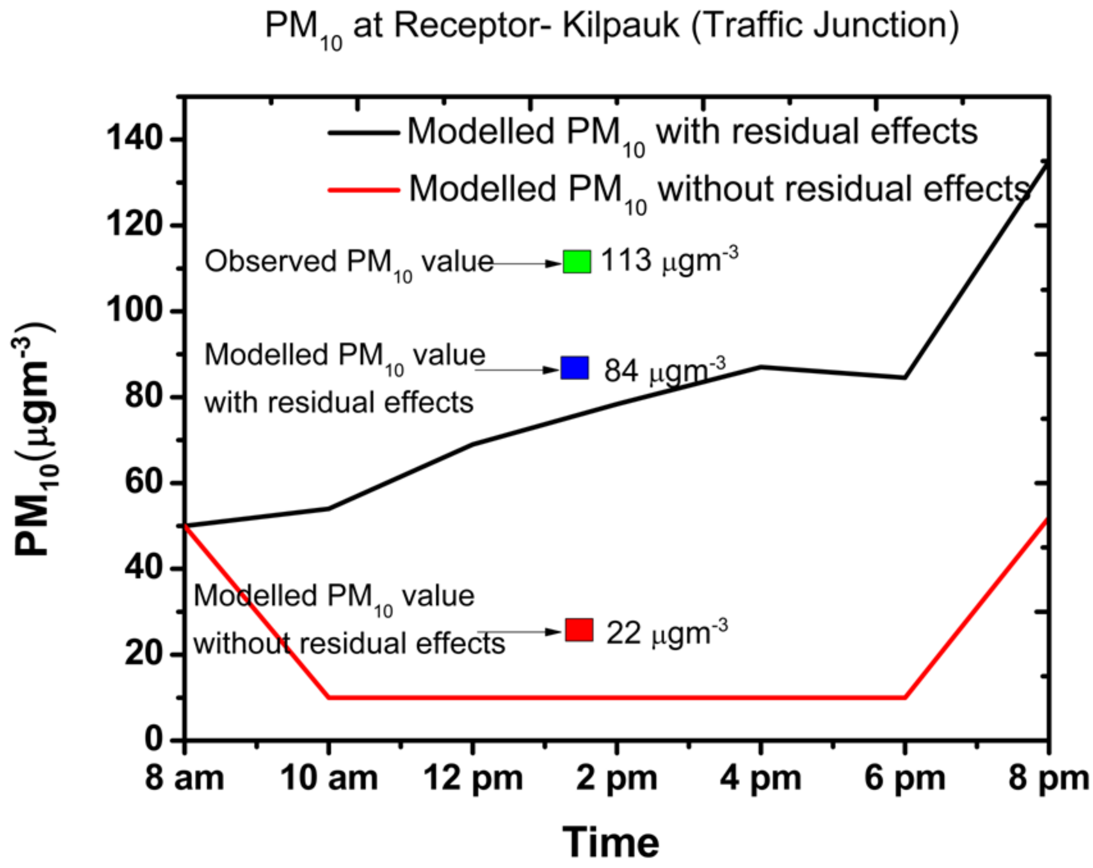



○Night-time slum pollution concentrations add up to the morning residual concentrations at the receptor.

○Increase in traffic pollution concentrations at the receptor.

***Marked contours refer to traffic pollution***

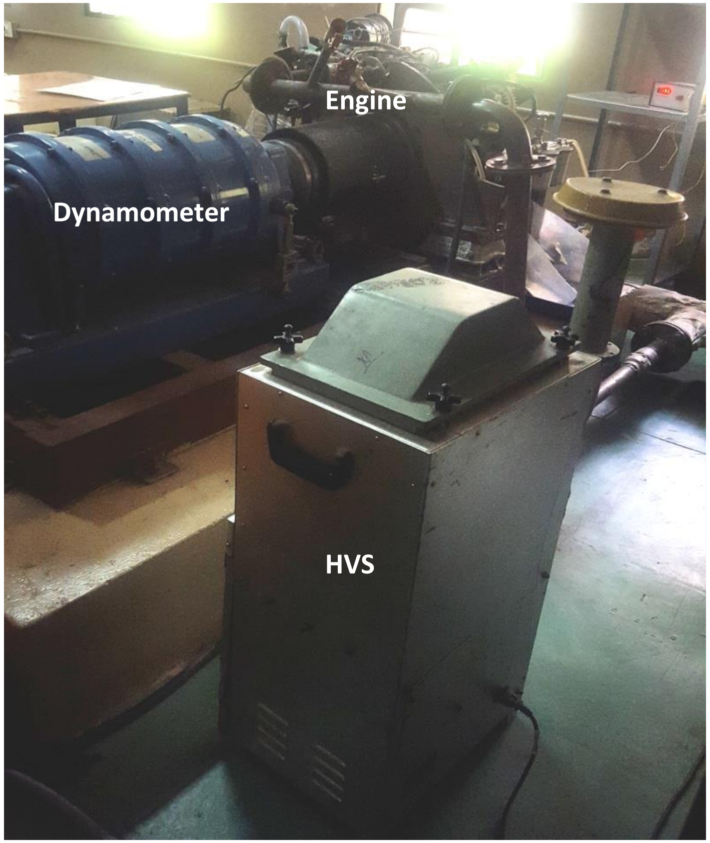
# Modelled PM10 at receptor- *Kilpauk Monitoring Station Chennai*




**Continued Research: Coupling University Generated Research Results To Operational Models**

# Coupling of Observational Research- Translation of *University research* to *Operational models*

- We address turbulence and mixing of climate forcers as they are released
  - Newer paradigms of model development in Indian city context- **cannot use European or American models verbatim.**

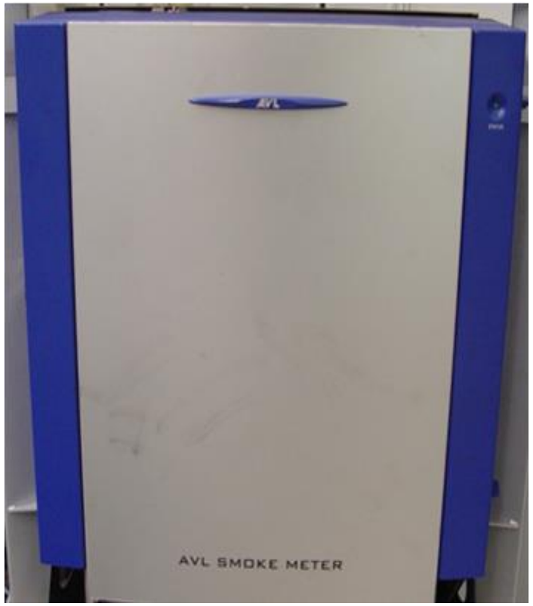



Dynamometer connected to the engine.

High Volume Sampler (HVS) Placed near the engine exhaust.

# Soot and Black carbon measurement

1. AVL Smoke Meter-415SE




| S. No. | Details | Particulars |
|---|---|---|
| 1 | Equipment name | AVL Smoke Meter-415SE |
| 2 | Measurement Range | 0 to 10 FSN |
| 3 | Sample Flow rate | 10 litre per minute |
| 4 | Filter Paper | PTFE Membrane Filter paper |

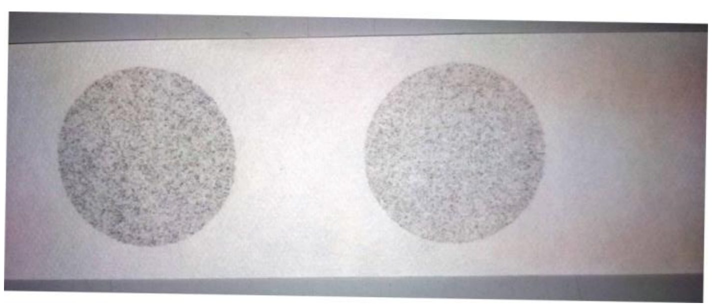
2. High Volume Sampler

| S. No. | Details | Particulars |
|---|---|---|
| 1 | Equipment name | Particulate Sampler (Aerovironment- FPS 9000) |
| 2 | Particle Collection Range | Less than 10µm |
| 3 | Flow rate | 1.5 litre per minute |
| 4 | Filter Paper | Glass Micro Fibre Filter, Size 20.3 x 25.4 cm |

# Experiment Configuration and Observations- Soot and Black Carbon Deposition

| Experimental variables and Apparatus configuration | |
|---|---|
| **Parameter** | **Value** |
| Engine Load | 25 N-m |
| Speed | 2250 rpm |
| Smoke | 11.41 mg.m-3 |
| FSN (Smoke Number) | 0.712 |

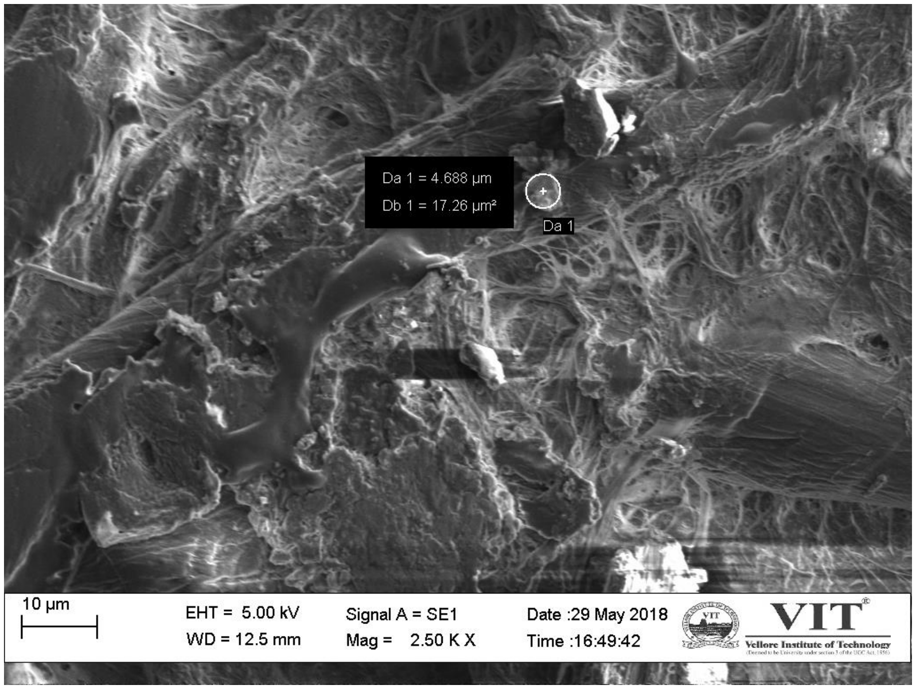
Observations



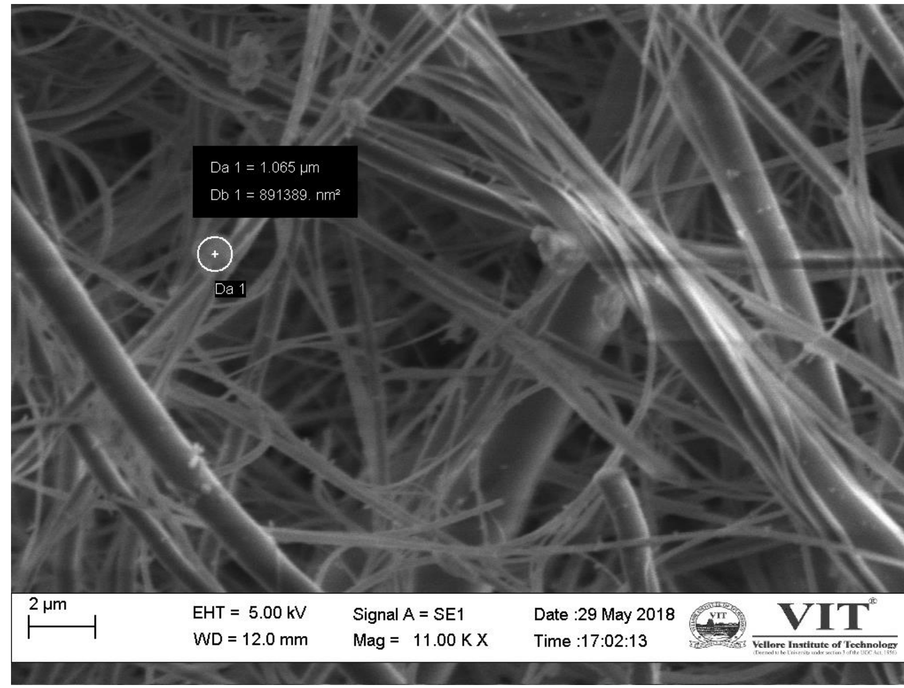
PTFE Membrane filter

Glass micro-fibre filter

# Particle Characterisation- *SEM*




PTFE Membrane from Smoke Meter




Glass micro-fibre filter paper from HVS

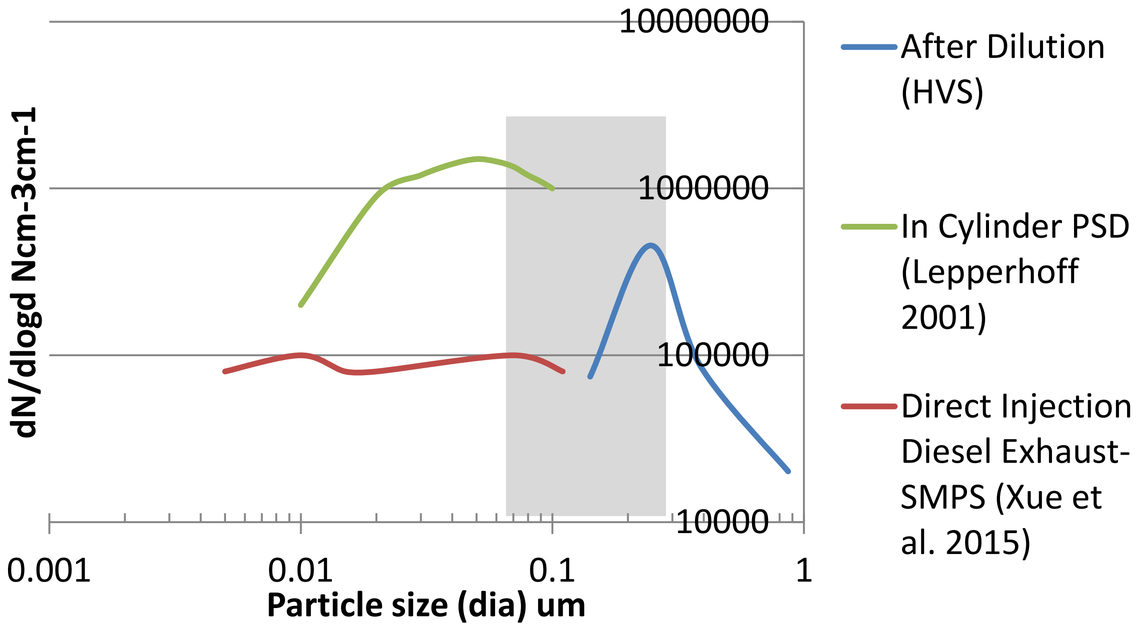
1. We observe submicron size- it ensures *low Stokesian settling velocities*.
2. These add to Residual Pollution Loads when there is a change in wind direction.
3. When aged in Sulphur-rich environment, they become CCN.

# Purpose of Experimental Analysis

We are trying to attack the problem- It's only possible if we model *turbulent transport* and *dispersion* as these particles are released.

Objectives:

1. To obtain *Particle Size Distribution* (PSD)- Chennai is home to dysfunctional gasoline/diesel operated vehicles emitting copious amounts of soot and black carbon into the atmosphere.




**Particle numbers from a 4-stroke diesel engine.**

*Auto rickshaws have the highest deterioration factor*

**Results pertain to a single engine. How do the numbers add up for Chennai?**

# Statistics of Vehicles plying in Chennai-

*A continuous source*

| Vehicular Emission Characterisation in Chennai for a Single Road Link | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| **SI. No** | Category of Vehicles | $X_i$ PM 10 | $T_n$ (No. of Veh. /24) | T (Det. Fac.) (0-5) | L (km) | $R_1$ | Pollution Load (g $km^{-1}day^{-1}$) | Pollution Load (g $km^{-1}s^{-1}$) |
| **1** | Heavy vehicles (Bus, etc.) | 0.56 | 2434.04 | 1.35 | 1 | 1 | 1840 | **0.021** |
| **2** | Heavy Vehicles (Trucks/ Tractors/ Goods vehicles | 0.28 | 4320.42 | 1.59 | 1 | 1 | 1923 | **0.022** |
| **3** | Light vehicles (Cars/Taxis, etc.) | 0.08 | 3103.40 | 1.28 | 1 | 1 | 318 | **0.004** |
| **4** | Three wheeler (Tempo, Auto-Rickshaw) | 0.05 | 11014.03 | 1.7 | 1 | 1 | 936 | **0.011** |
| **5** | Two-wheelers (Motor cycle, Scooter, moped) | 0.02 | 24401.25 | 1.3 | 1 | 1 | 634 | **0.007** |

# Sprinklers not a solution!

**Anti-smog guns fails CPCB's test to control pollution in Delhi, board declares machine ineffective!**

**New Delhi**: The Delhi government's experiment with anti-smog guns to control pollution has failed the test of Central Pollution Control Board (CPCB), which on Thursday declared the machine ineffective in open areas and on fine particles.

# Remedial Measures

- ***Green*** Facades (On the Air Cleansing Efficiency of an Extended Green Wall: A CFD Analysis of Mechanistic Details of Transport Processes- ***Journal of Theoretical Biology*** *Joshi and Ghosh 2014*)

Green Facade draped with *V. elaeagnifolia*

Journal of Theoretical Biology 361 (2014) 101–110

Contents lists available at ScienceDirect

Journal of Theoretical Biology

journal homepage: www.elsevier.com/locate/yjtbi

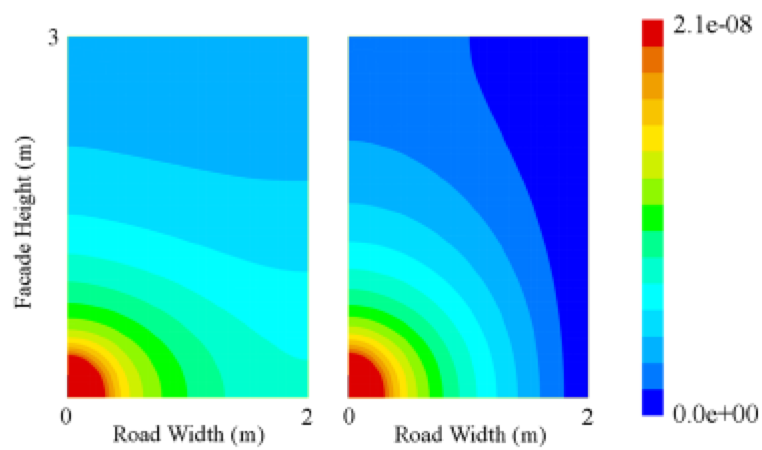
On the air cleansing efficiency of an extended green wall: A CFD analysis of mechanistic details of transport processes

Saumitra V. Joshi[a], Sat. Ghosh[a,b,*]

[a] School of Mechanical and Building Sciences, VIT University, Vellore, India
[b] School of Earth and Environment, University of Leeds, UK

***How much will settle under gravity and how much will be lifted up by updraft?***

Contours of SO2 concentration on a passage way cross-section at t = 13 h
***Without the facade***




Contours of SO2 concentration on a passage way cross-section at t = 13 h
***With the facade***

# Remedial Measures

- *Washout* ( A Sensitivity Study of Diffusional Mass Transfer of Gases in Tropical Storm Hydrometeors- ***Theoretical and Applied Climatology*** *Ghosh et al. 2017*)

Strong updrafts lift these particles aloft for cloud processing- formation of CCN.

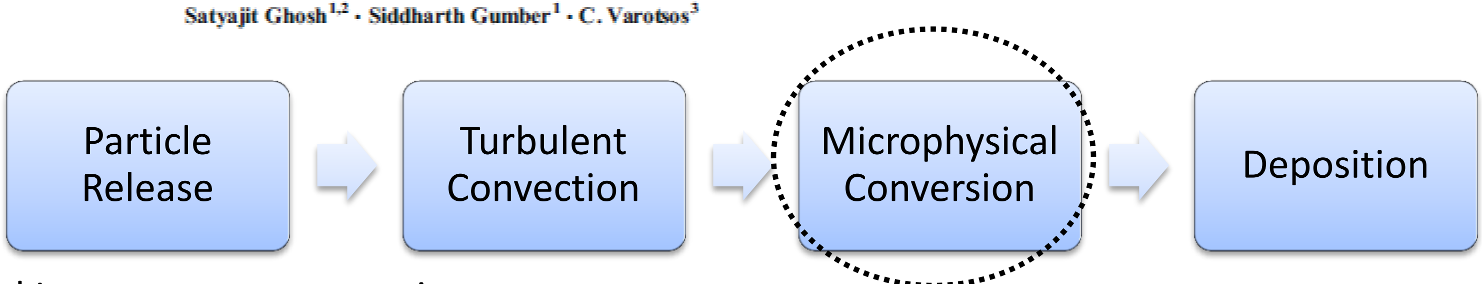
- Proper treatment of concentrated ionic solution droplets (***Models neglect these effects***).
- Detailed Mass Transfer Processing

Theor Appl Climatol
https://doi.org/10.1007/s00704-017-2321-4
CrossMark

ORIGINAL PAPER

**A sensitivity study of diffusional mass transfer of gases in tropical storm hydrometeors**

**Satyajit Ghosh**[1,2] **· Siddharth Gumber**[1] **· C. Varotsos**[3]

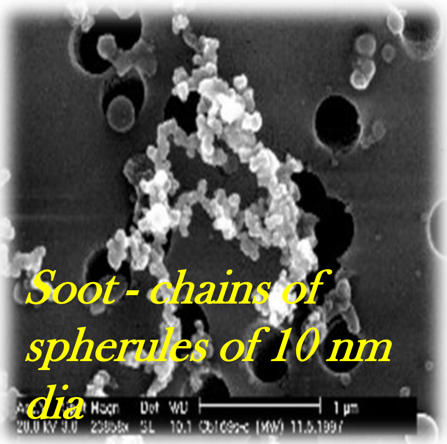



Model Improvements strategies:

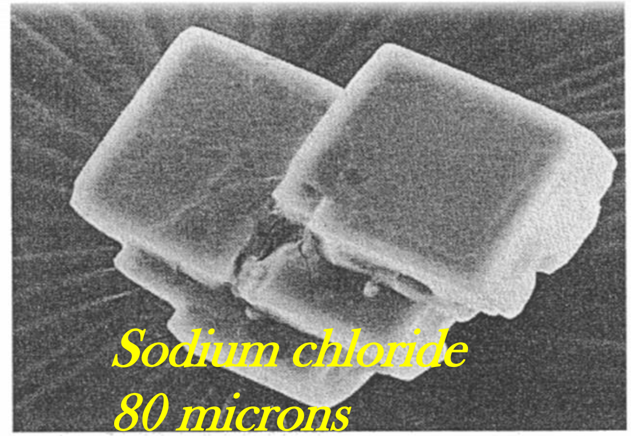
1. Quantifying how Residual Pollution is brought to cloud bases through strong updrafts.
2. How cities pollution help age the particle to form partially soluble sites.
3. Growth and activation of such particles in Cloud Condensation Nuclei
4. Ascertaining optimal updraft speeds, RH, Temp to promote high auto-conversion rates.

# The microstructures of some common aerosols

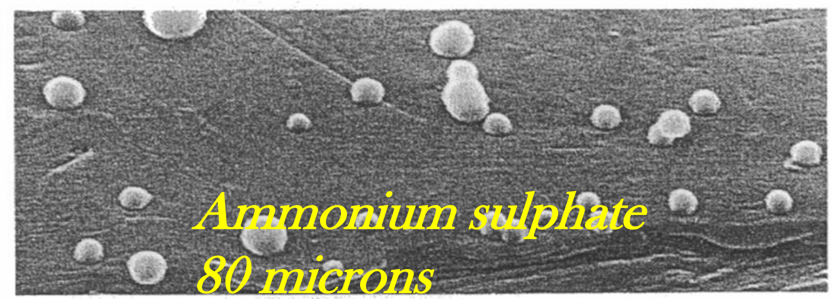
*Leaf debris (biomass)*



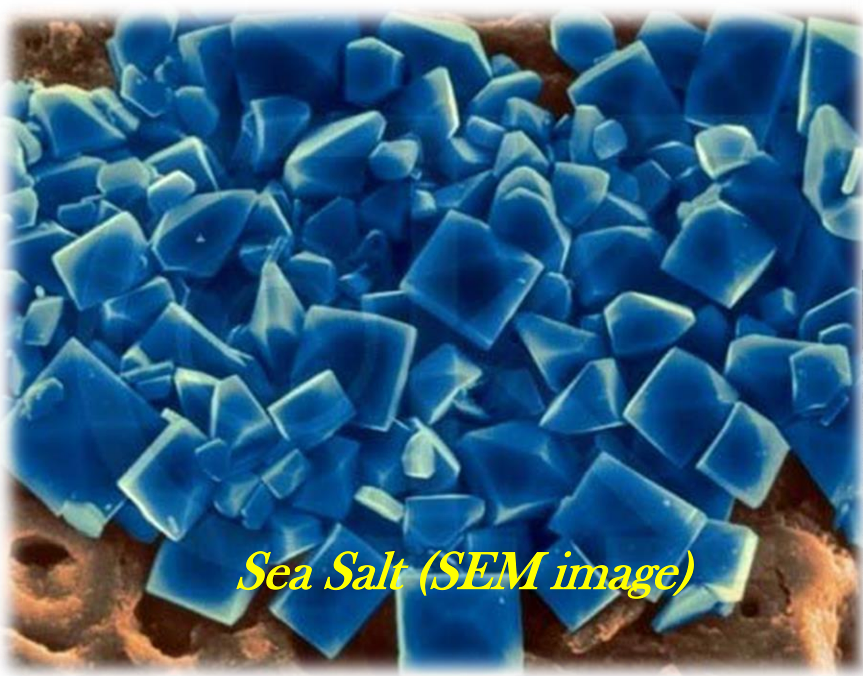
*Soot - chains of spherules of 10 nm dia*



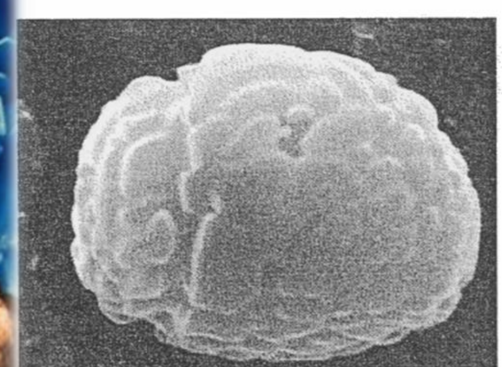
*Sodium chloride 80 microns*

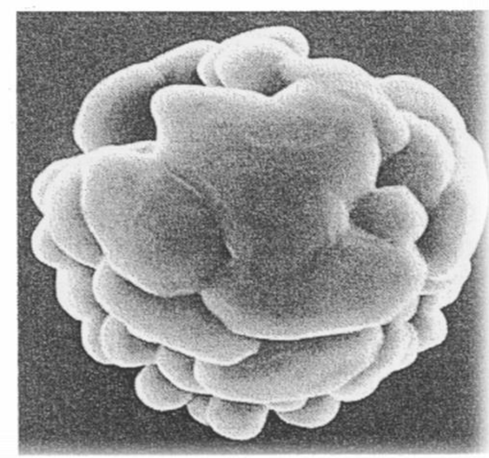


*Ammonium sulphate 80 microns*



*Sea Salt (SEM image)*





# Aerosol Particles as CCN: Complexities and Challenges

1. Atmospheric aerosol particles- hydrophobic, water-insoluble , possess hydrophilic sites.

2. Some water-soluble component- biomass aerosol internally mixed with sulphate aerosol.

3. Soluble gases- dissolve into a growing solution droplet prior to activation in cloud- this can decrease the critical super-saturation for activation.

4. In-cloud oxidation of $SO_{2.}$

# Aerosol Mixtures: Sulphate & Sea Salt

Adv. Geosci., 25, 51–54, 2010
www.adv-geosci.net/25/51/2010/


Advances in Geosciences

**The great Indian haze revisited: aerosol distribution effects on microphysical and optical properties of warm clouds over peninsular India**

**R. Ghanti[1] and S. Ghosh[1,2]**

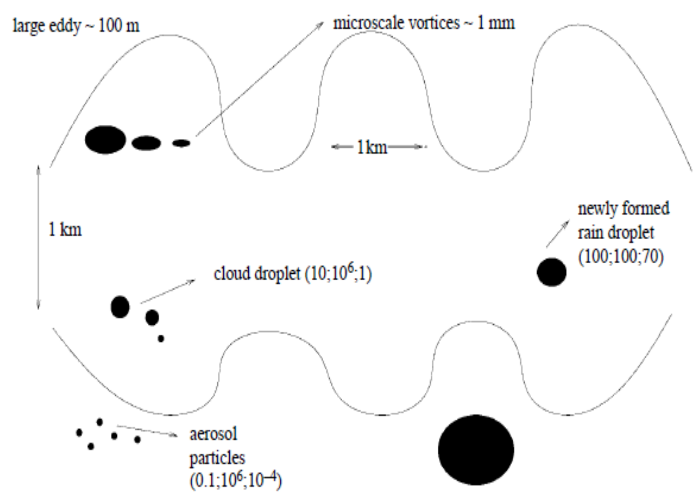



Figure 1. Schematic showing the diversity of spatial scales, vortices and particle number concentrations in cloud microphysical calculations. The numbers within brackets refer to radius in microns, number per litre and terminal velocity of droplets in cm $s^{-1}$, respectively.

# Science Questions to be answered

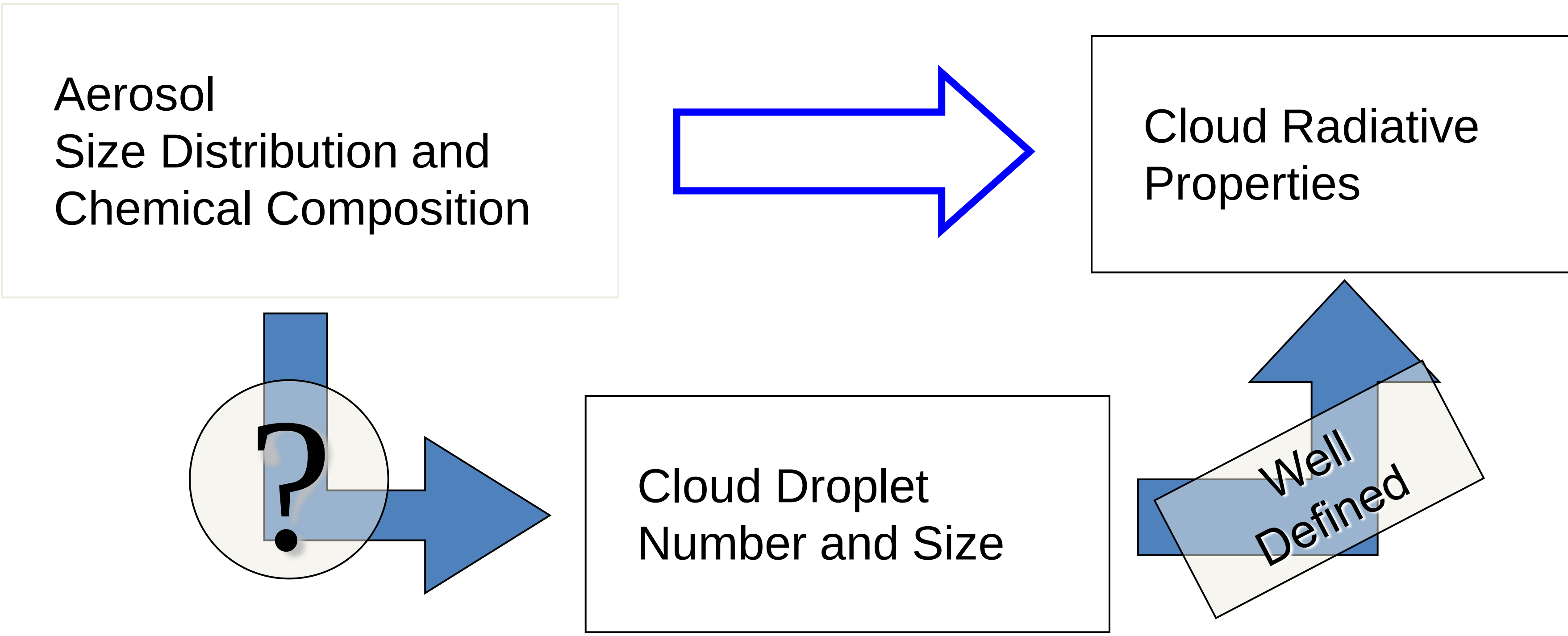
1. What are the regimes when the effect of microscale vortices on cloud droplet growth is important?

2. This research shows that this effect is pervasive ONLY in multi-component aerosol mixtures. (Rap et al. 2009)

3. Multi-component mixtures perturb the Aerosol-CDNC relationships over certain regimes.

4. It remains to be examined quantitatively the further perturbing effect of enhanced settling rates

# Quantification of the Indirect Effect




This problem has historically been reduced to finding the relationship between aerosol number concentration and cloud droplet number concentration. Empirical relationships are often used.

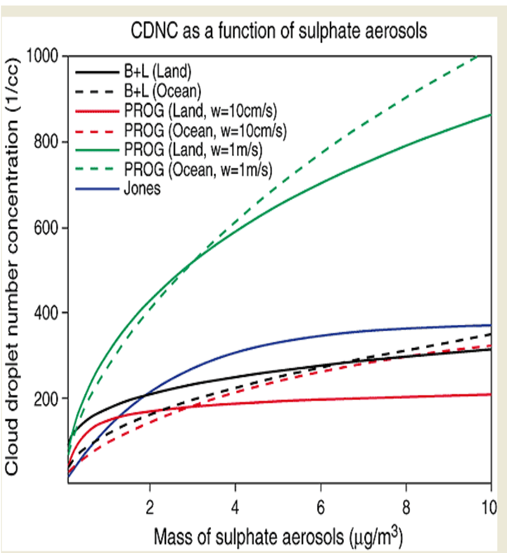
JANUARY 2009 RAP ET AL. 105

JOURNAL OF THE ATMOSPHERIC SCIENCES

**Shepard and Hardy Multiquadric Interpolation Methods for Multicomponent Aerosol–Cloud Parameterization**

ALEXANDRU RAP, SATYAJIT GHOSH,* AND MICHAEL H. SMITH

( CDN = $N_0$ (1 − exp[$-AN_a$]) with the coefficients $N_0$ and A (375 and −0.0025 ( Jones et al. 1994) ; Na being the aerosol number concentration).




Mixed aerosols perturbs the CDN relationship

JANUARY 2009 RAP ET AL. 111

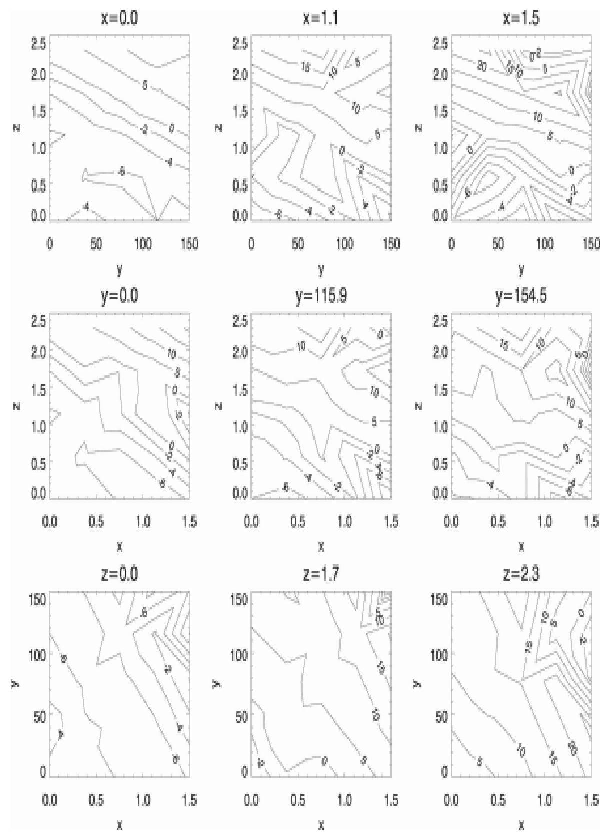
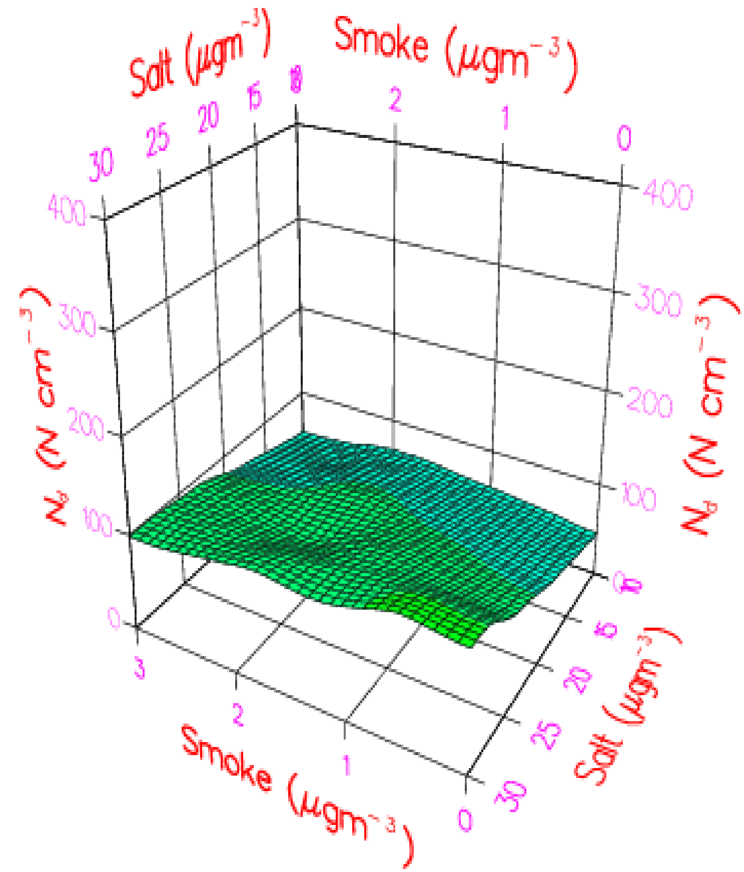



FIG. 1. Difference for the predicted CDNC (N cm$^{-3}$) between model results and the JRS94 parameterization.



PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY A

*Phil. Trans. R. Soc. A* (2007) **365**, 2659–2674
doi:10.1098/rsta.2007.2082
*Published online* 30 July 2007

# Integrating biomass, sulphate and sea-salt aerosol responses into a microphysical chemical parcel model: implications for climate studies

By S. Ghosh*, M. H. Smith and A. Rap

*School of Earth and Environment, University of Leeds, Leeds LS2 9JT, UK*

Table 2. Input aerosol spectral properties.

| spectral properties | median radius, $\overline{a}$ (nm) | s.d., $\sigma$ | density, $\rho$ (kg m$^{-3}$) |
|---|---|---|---|
| pure ammonium sulphate | 95 | 1.4 | 1769 |
| biomass smoke | 120 | 1.3 | 1350 |
| sea salt (film mode) | 100 | 1.9 | 2165 |
| sea salt (jet mode) | 1000 | 2.0 | 2165 |

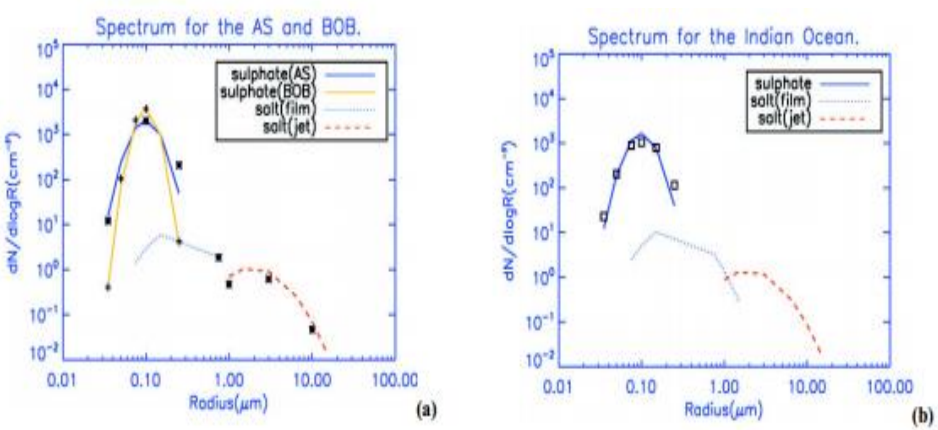
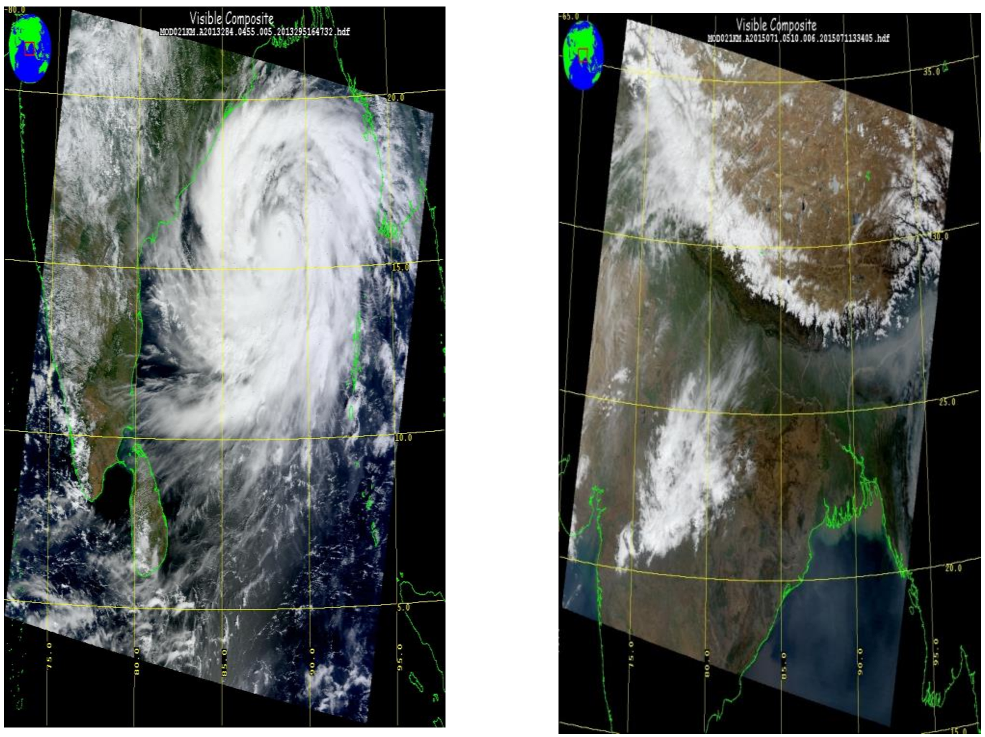



**Fig. 1.** Dry aerosol spectra for **(a)** AS and BOB (* and + represents the data observed by Jayaraman (2001) and Murugavel et al. (2008) respectively) and **(b)** Indian Ocean (represents the data observed by Murugavel et al., 2001). There were no observational data points for salt distributions for BOB and IO-wind-speed dependent estimates are shown.

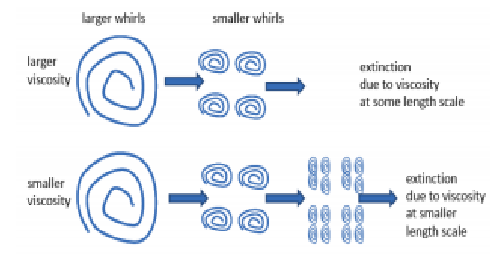
# New insights: Interaction of small cloud droplets grown from aerosol particles over the Bay of Bengal with micro-scale vortices in cumulus clouds




Length scales associated with cyclonic and normal convective activity: Retrieved form MODIS

*Richardson's picture of turbulence* (1922):

- a turbulent flow is composed by *'eddies'* of different size
- the large eddies are unstable and eventually break up into smaller eddies, and so on
- the energy is passed down from the large scales of the motion to smaller scales until reaching a sufficiently small length scale such that the viscosity of the fluid can effectively dissipate the kinetic energy.



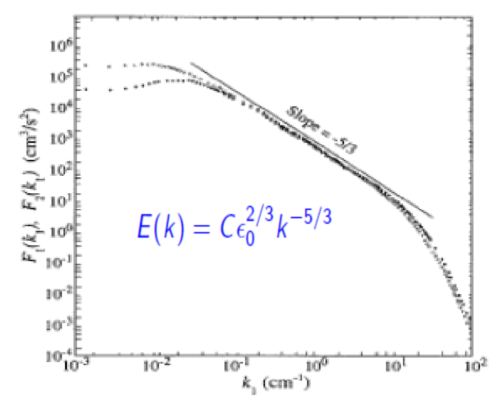




Fig. 5.7. log–log plot of the energy spectra of the streamwise component (white circles) and lateral component (black circles) of the velocity fluctuations in the time domain in a jet with $R_\lambda = 626$ (Champagne 1978).

***Can we expect micro-scale vortices?***

PROCEEDINGS OF THE ROYAL SOCIETY A

*Proc. R. Soc. A* (2005) **461**, 3059–3088
doi:10.1098/rspa.2005.1490
*Published online* 9 August 2005

# How turbulence enhances coalescence of settling particles with applications to rain in clouds

By S. Ghosh[1], J. Dávila[2], J. C. R. Hunt[3,4], A. Srdic[5], H. J. S. Fernando[5] and P. R. Jonas[6]

- From Ghosh et al. (2005), it can be inferred that the small inertial particles with density equal to β(>1) times that of the fluid, are 'centrifuged' out of the micro-scale vortices and eddies in turbulence.
- This process enhances the average sedimentation rate ($V_T$) of particles lying below a critical radius (~ 20 um) by about 80%.
- Thus, current forecasting models - which assume particle collision in still air – predict significantly lower precipitation rates.
- With this new insight, storm water drainage design can now be modified to accommodate the effect of turbulence enhancements on precipitation rates.

# Recent literature on the effect of turbulence on cloud settling rates


1. Falkovich et al. 2002. Acceleration of rain initiation by cloud by cloud turbulent. doi:10.1038/nature00983

2. Ghosh S., Davila, J., Hunt, J. C. R., Srdic, A., Fernando, H. J. S., and Jonas, P. 2005, How turbulence enhances coalescence of settling particles with applications to rain in clouds, Proc. Roy. Soc. London, 461A, 3059–3088.

3. Ghosh S., Jonas P.R, 2001, Some analytical calculations on the effect of turbulence on the settling and growth of cloud droplets, Geophysical Research Letters, Vol. 28, No. 20, Pages 3883-3886.

4. RA Shaw. 2003. Particle turbulence interactions in atmospheric clouds.

5. Grabowski WW, Wang LP. 2012. Growth of cloud droplets in a turbulent environment. DOI: 10.1146/annurev-fluid-011212-140750

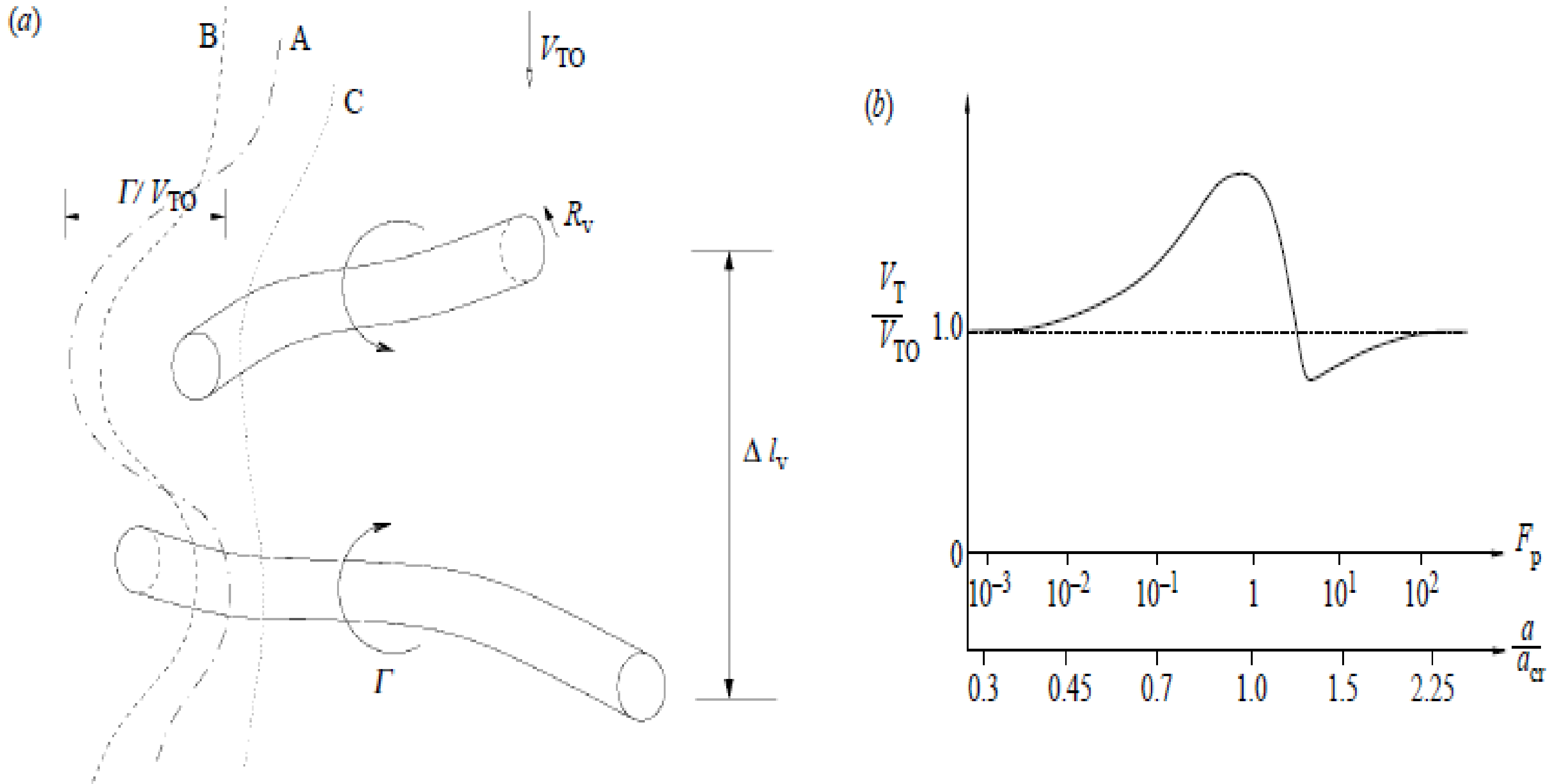



Figure 2. Mechanisms of particles falling near vortices: ($a$) typical trajectories of settling particles A, B, C moving around a vortex with strength $\Gamma$ and radius $R_v$ with increasing fall speed $V_{TO}$. Here, $\Delta l_v$ is the distance between vortices; ($b$) average settling velocity ratio $V_T/V_{TO}$ versus the particle Froude number $F_p$ and particle radius ratio $a/a_{cr}$;

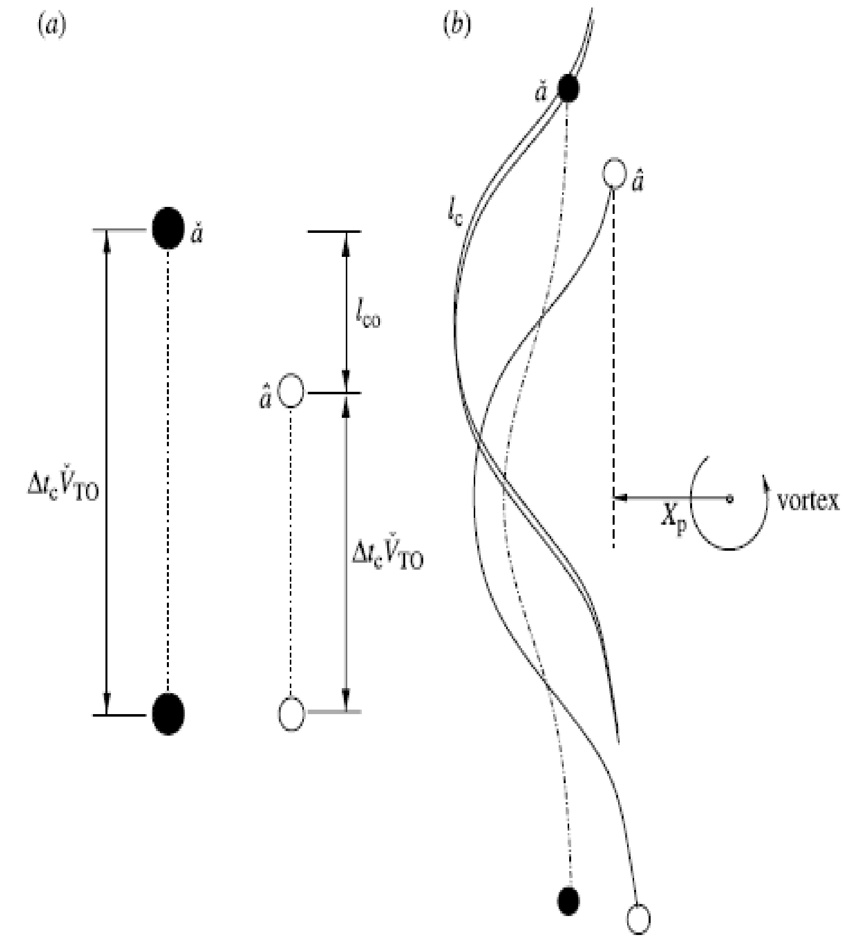



Figure 3. Collision mechanisms: ($a$) colliding droplets settling in still air in the absence of vortices with larger and smaller radii $\breve{a}$, $\hat{a}$. Note the vertical collision distance $l_{co}$; ($b$) colliding droplets descending near an isolated vortex. Note the curved collision line with length $l_c$; the large droplet collides with a smaller droplet both released at $t$=0, if they start on the curved collision line;

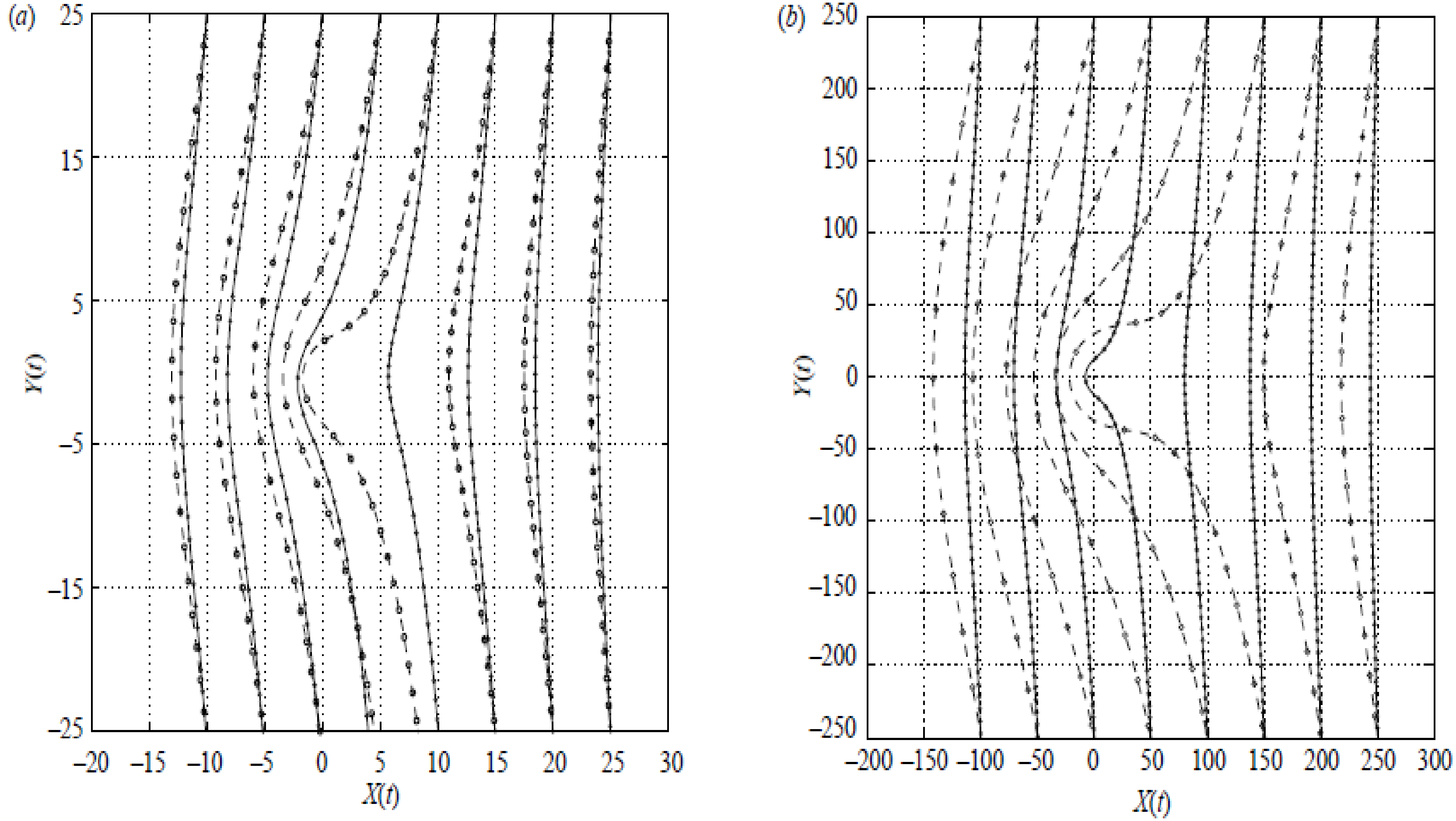



Figure 4. (*a*) Colliding droplet pairs with radii 20 and 25 μm descending near an isolated vortex with circulation $\Gamma = 1.5 \times 10^{-4}\ \mathrm{m^2\,s^{-1}}$ and radius $R_v = 1.5$ mm calculated from the Dávila & Hunt (2001) theory. Note the absence of collisions. (*b*) Colliding droplet pairs with radii 5 and 10 μm descending near an isolated vortex with circulation $\Gamma = 1.5 \times 10^{-4}\ \mathrm{m^2\,s^{-1}}$ and radius $R_v = 1.5$ mm calculated from the Dávila & Hunt (2001) theory. Note the presence of multiple collisions.

# Estimation of critical cloud droplet radius where micro-scale vortices impact settling rates

$$V_{\mathrm{TO}} \simeq g(\beta - 1)a^2/(9\nu/2), \tag{2.2}$$

$$\tau_{\mathrm{p}} = (2/9)(\beta - 1)a^2/\nu, \tag{2.3}$$

From 2.2 and 2.3

$$\Gamma(R) \sim V_{\mathrm{TO}}^2 \tau_{\mathrm{p}} \sim \frac{a^6 g^2 (\beta - 1)^3}{(9/2)^3 \nu^3}. \tag{3.2}$$

At the micro-scales where $R = R_{\mathrm{k}}$, the circulation

$$\Gamma = \Gamma_{\mathrm{k}} \sim U_{\mathrm{k}} R_{\mathrm{k}} \sim (\epsilon\nu)^{1/4}(\nu^3/\epsilon)^{1/4} \sim \nu. \tag{3.3}$$

$$a_{\mathrm{cr}} \sim \nu^{2/3} g^{-1/3} (\beta - 1)^{-1/2}. \tag{3.5}$$

In air $a_{\mathrm{cr}} \sim 20\,\mu\mathrm{m}$, and in water, for $\beta = 2$, $a_{\mathrm{cr}} \sim 100\,\mu\mathrm{m}$.

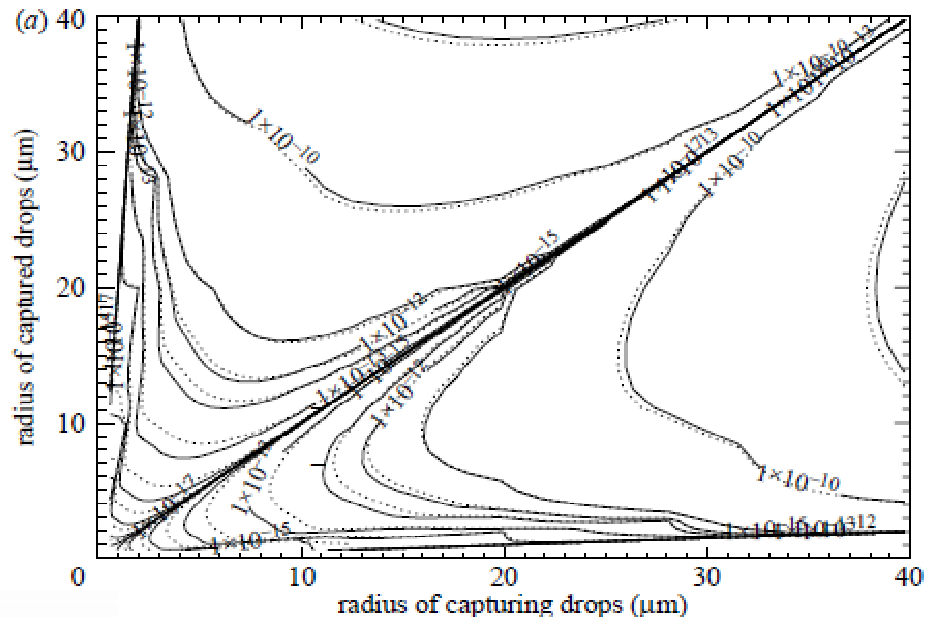
**IMP: This critical radius is independent of the turbulent kinetic energy dissipation rate**

# Estimating new fall velocity : effect of micro-scale vortices

- Droplets in cloud turbulence

$$P_{ij} = E(\breve{a}_i, \hat{a}_j)\pi(\breve{a}_i + \hat{a}_j)^2(V_{\mathrm{T}i} - V_{\mathrm{T}j}).$$

| Enhanced Velocities (ms-1) | Stokesian Velocities (ms-1) | Radii (um) |
|---|---|---|
| 2.14E+00 | 3.40E-01 | 5.28E+00 |
| 2.70E+00 | 4.27E-01 | 5.93E+00 |
| 3.40E+00 | 5.37E-01 | 6.66E+00 |
| 4.28E+00 | 6.76E-01 | 7.47E+00 |
| 5.40E+00 | 8.51E-01 | 8.39E+00 |
| 6.80E+00 | 1.07E+00 | 9.42E+00 |
| 8.57E+00 | 1.34E+00 | 1.06E+01 |
| 1.08E+01 | 1.69E+00 | 1.19E+01 |
| 1.36E+01 | 2.12E+00 | 1.33E+01 |
| 1.71E+01 | 2.66E+00 | 1.49E+01 |
| 2.16E+01 | 3.34E+00 | 1.68E+01 |
| 2.72E+01 | 4.19E+00 | 1.88E+01 |
| 3.43E+01 | 5.24E+00 | 2.11E+01 |
| 4.32E+01 | 6.55E+00 | 2.37E+01 |
| 5.44E+01 | 8.15E+00 | 2.66E+01 |



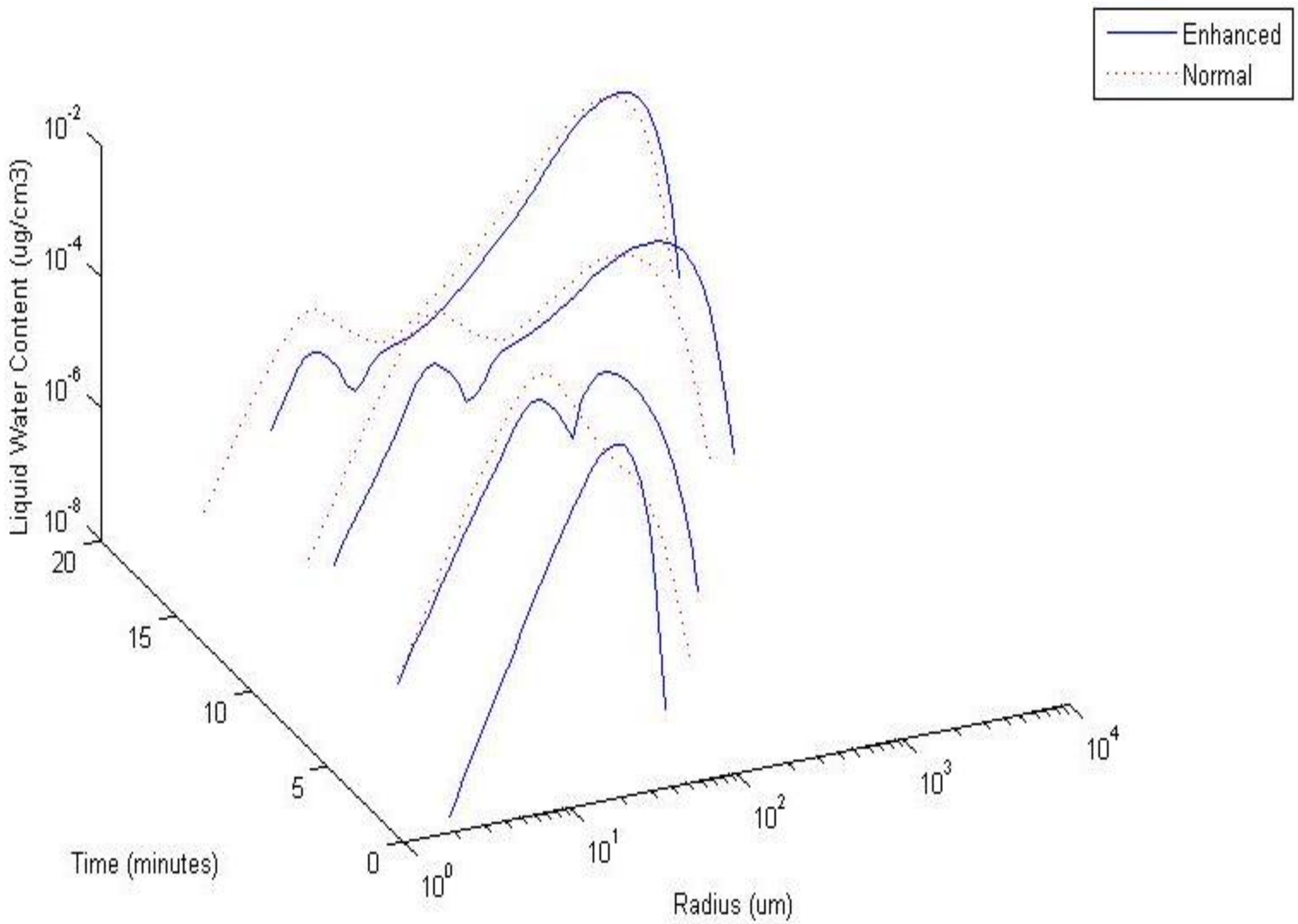

GEOPHYSICAL RESEARCH LETTERS, VOL. 28, NO. 20, PAGES 3883-3886, OCTOBER 15, 2001

**Some analytical calculations on the effect of turbulence on the settling and growth of cloud droplets**

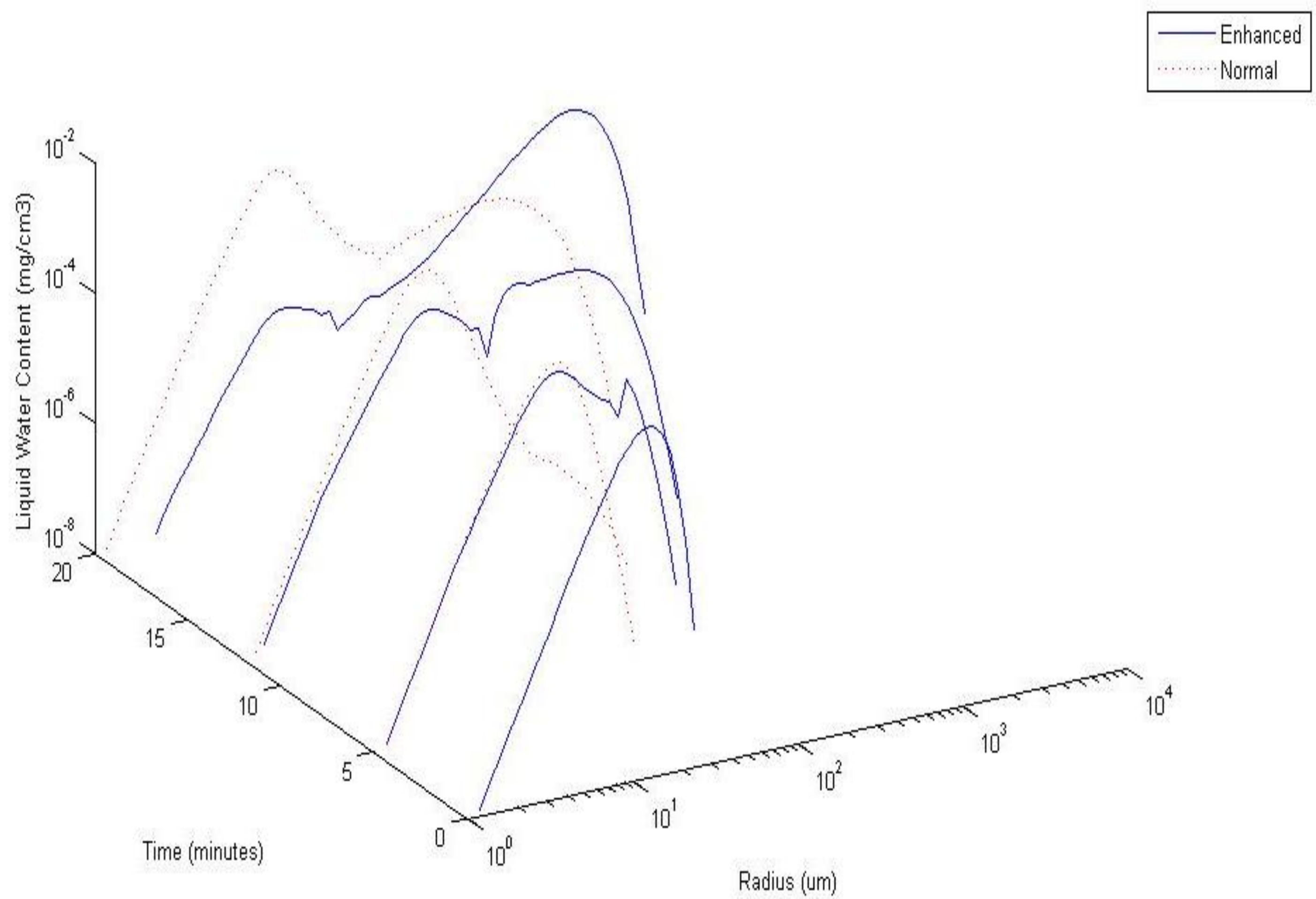
S.Ghosh
School of the Environment, University of Leeds, Leeds, England

P.R. Jonas
Department of Physics, UMIST, Manchester, England

Ghosh, Hunt , Fernando, Davilla, Srdic, Jonas Proc. Roy. Soc. A (2007)

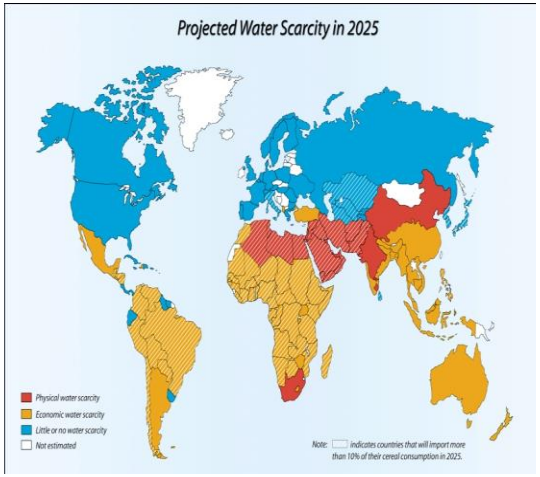


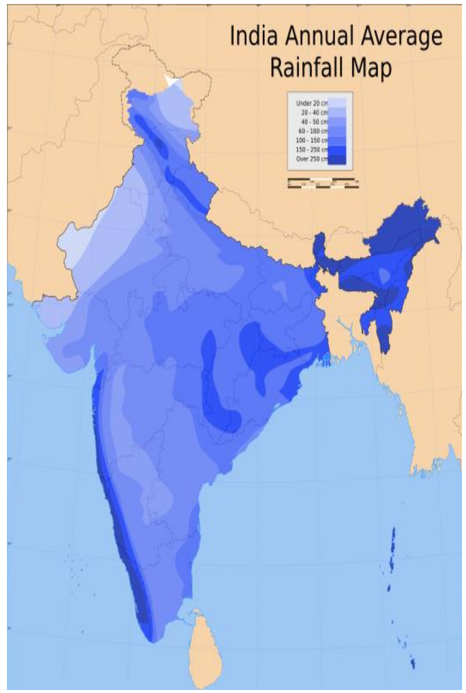

**Time evolution of liquid-water mass** for **Phailin** spectra (modal radius 15 um)
**[5 minutes difference]**




**Time evolution of liquid-water mass** for Normal day aerosol spectra with high convective activity (modal radius 12 um) **[10 minutes difference]**

# Real Time Applications: Streamlining Cloud Seeding : VIT-JNTU Collaboration



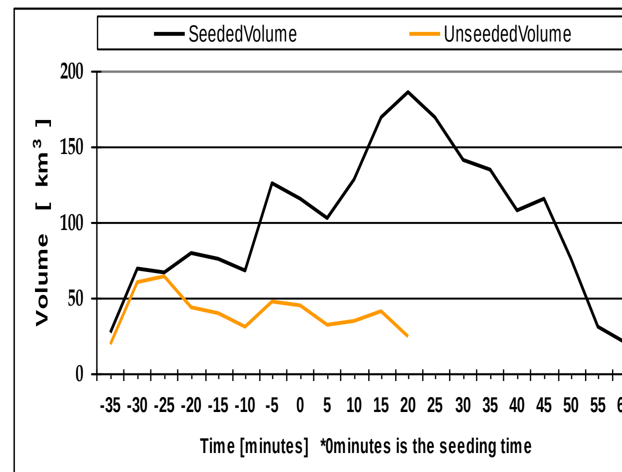




Geneares Publishing

Asian Journal of Water Environment Vol.1 No. 1 (2013) 1-8
Available online at www.geneares.org/ajwe.1.1.html

MICROPHYSICAL CHARACTERISATION OF CLOUD SEEDING EXPERIMENTS IN INDIA

A. Samaddar[*1], Y. Roohani[2], S. Ghosh[3, 4], B.V. Rao[5]




Variation of Volume of Seeded and Unseeded clouds on August 11, 2008

Geographical area of the country :322 M.ha about 60% of total area

Cultivable Area : 188 M.ha
10%-USSR
29%-U.K.
20% - U.S
26% - Pak.
10% - China

Cropped land at present :144 M.ha

Present area under irrigation : 78 M.ha

Likely irrigated area by the year 2025to meet food production :100 M.ha

Total utilisable Water Resources :114 M.ha.m

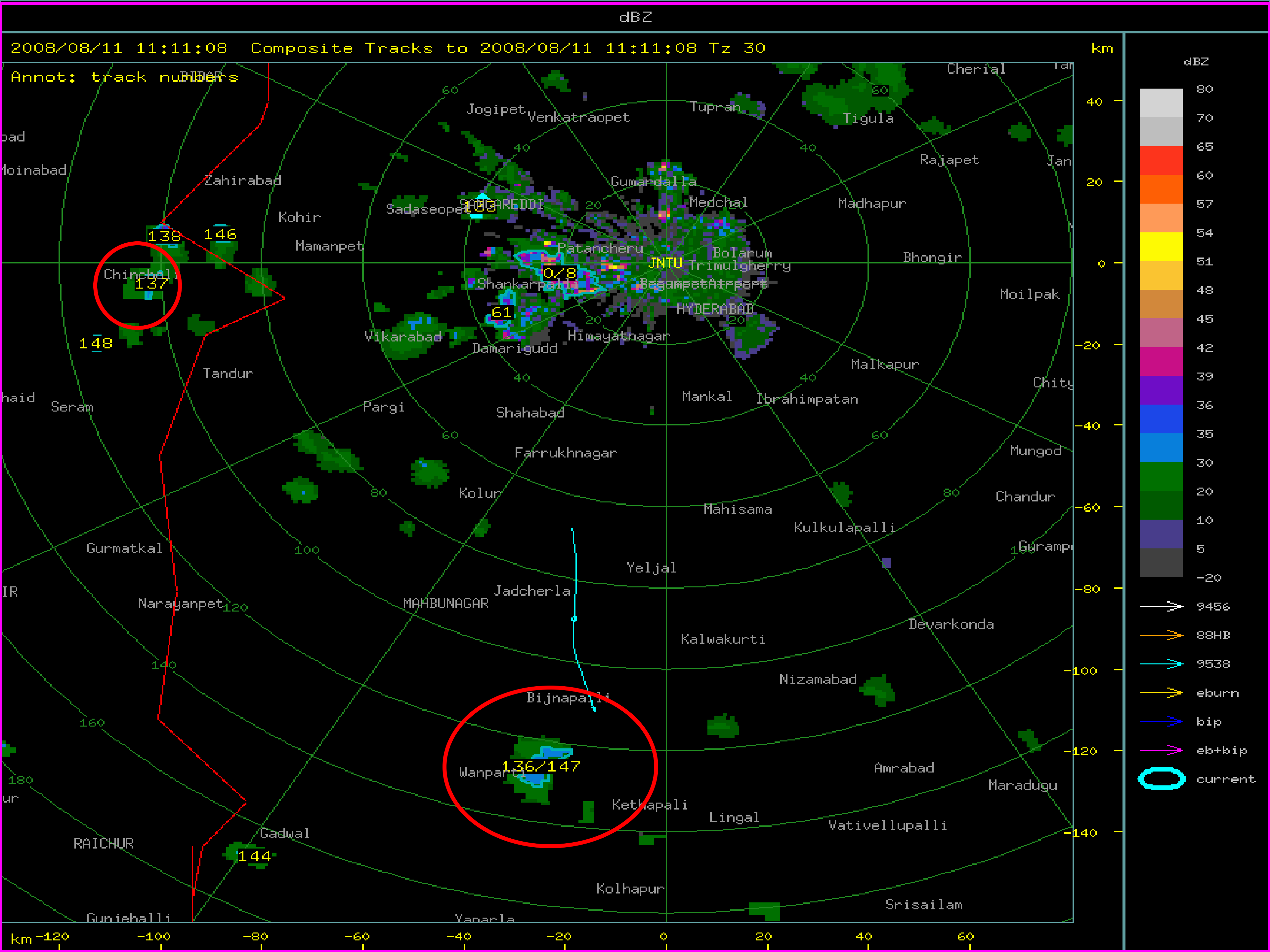
Present utilisation : 55 M.ha.m

Water required by the year 2025 : 105 M.ha.m

**PARTICLE SIZE NATURAL vs FLARE**

| S.No | HYDERABAD | | ANANTHAPUR | | FLARE | |
|---|---|---|---|---|---|---|
| | Particles Size (Microns) | % of Total | Particles Size (Microns) | % of Total | Particles Size (Microns) | % of Total |
| 1 | 0.2 | 41.60% | 0.1 | 41.60% | 0.8 | 28.50% |
| 2 | 0.4 | 33.30% | 0.3 | 33.30% | 1 | 12.50% |
| 3 | 0.6 | 16.60% | 0.5 | 16.60% | 0.2 | 14.60% |
| 4 | 0.8 | 8.30% | 0.7 | 8.30% | 0.4 | 10.20% |

CaCl


dBZ
2008/08/11 11:11:08 Composite Tracks to 2008/08/11 11:11:08 Tz 30
km
Annot: track numbers
Cherial
Jogipet
Venkatraopet
Tupran
Tigula
Zahirabad
Rajapet
Kohir
Sadaseopet
SANGAREDDI
Gumardalla
Medchal
Madhapur
Mamanpet
Patancheru
Bolarum
JNTU
Trimulgherry
Bhongir
Chincholi
Shankarpalli
HYDERABAD
Moilpak
Vikarabad
Damarigudd
Himayatnagar
Tandur
Malkapur
Seram
Pargi
Shahabad
Mankal
Ibrahimpatan
Farrukhnagar
Mungod
Kolur
Mahisama
Chandur
Kulkulapalli
Gurmatkal
Yeljal
Jadcherla
Narayanpet
MAHBUNAGAR
Devarkonda
Kalwakurti
Nizamabad
Bijnapalli
Wanparti
Amrabad
Maradugu
Kethapali
Lingal
Vativellupalli
Gadwal
RAICHUR
Kolhapur
Srisailam
Yanarla
138
146
137
148
108
0/8
61
136/147
144
80
70
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88HB
9538
eburn
bip
eb+bip
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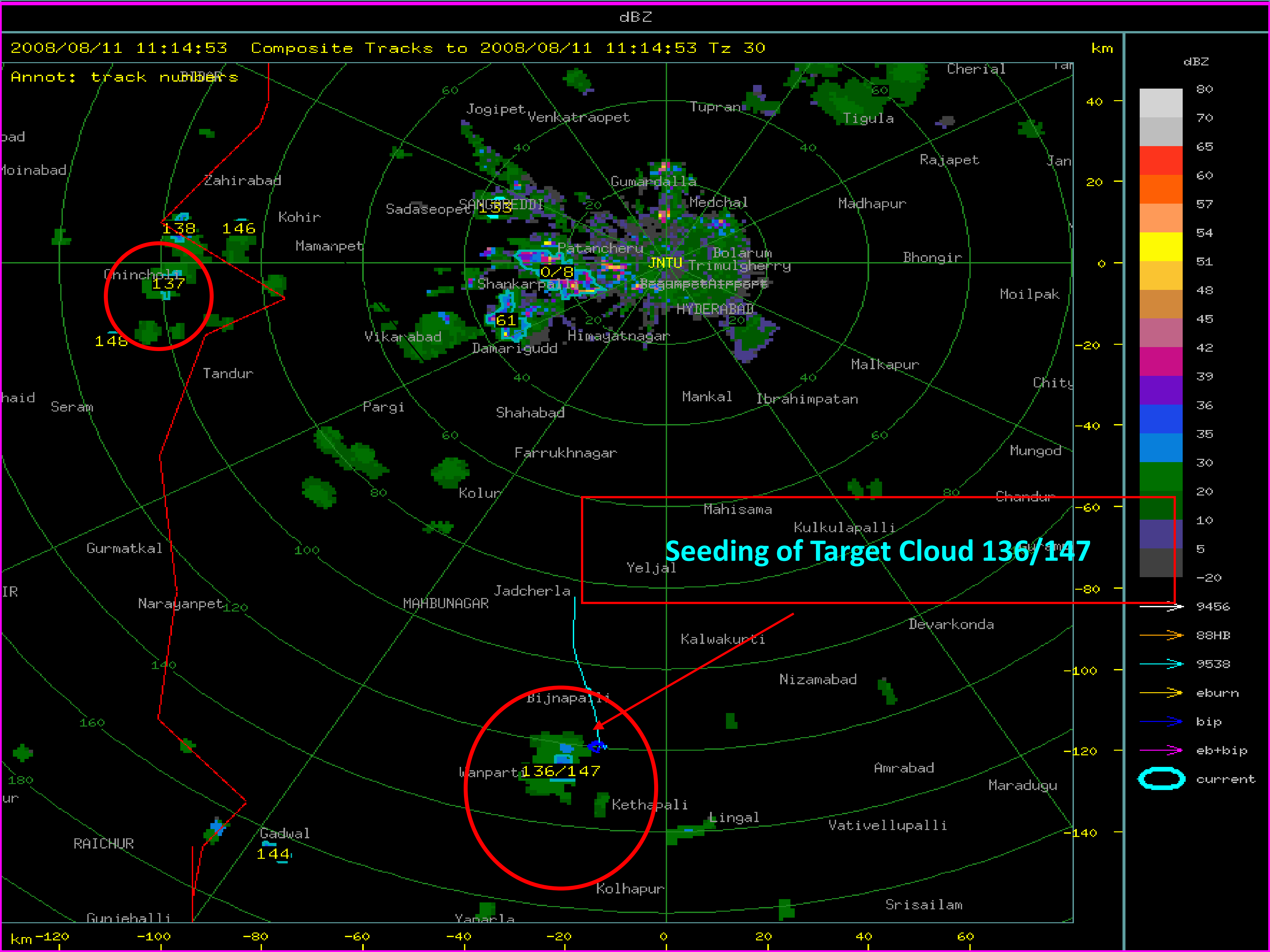
dBZ
2008/08/11 11:14:53 Composite Tracks to 2008/08/11 11:14:53 Tz 30
km
Annot: track numbers
Seeding of Target Cloud 136/147
138
146
137
148
133
0/8
61
136/147
144
JNTU
HYDERABAD
SANGAREDDI
MAHBUNAGAR
RAICHUR
Cherial
Jogipet
Venkatraopet
Tupran
Tigula
Rajapet
Zahirabad
Kohir
Mamanpet
Sadaseopet
Gumardalla
Medchal
Madhapur
Patancheru
Bolarum
Trimulgherry
Bhongir
Shankarpalli
Begampet Airport
Moilpak
Chinchpoli
Vikarabad
Damarigudd
Himayatnagar
Malkapur
Tandur
Mankal
Ibrahimpatan
Seram
Pargi
Shahabad
Farrukhnagar
Mungod
Kolur
Chandur
Mahisama
Kulkulapalli
Gurmatkal
Yeljal
Jadcherla
Narayanpet
Devarkonda
Kalwakurti
Nizamabad
Bijnapalli
Wanparti
Amrabad
Maradugu
Kethapali
Lingal
Vatívellupalli
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Kolhapur
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9456
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9538
eburn
bip
eb+bip
current

# August 11,2008 at 4:50PM

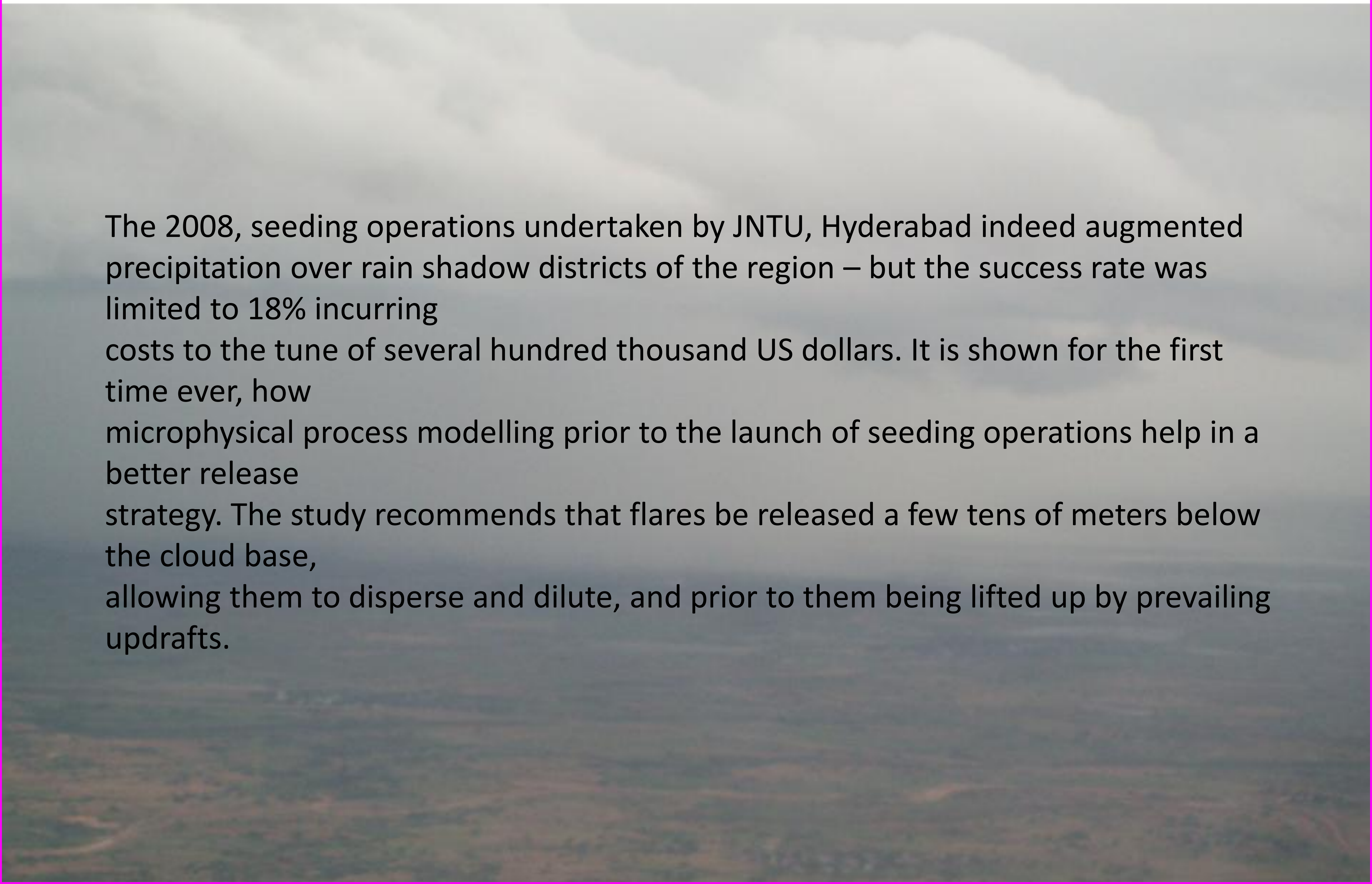
# August 11,2008 at 4:51PM

# August 11,2008 at 4:52PM

# August 11,2008 at 5:00PM

# August 11,2008 at 5:01PM

# August 11,2008 at 5:02PM



The 2008, seeding operations undertaken by JNTU, Hyderabad indeed augmented precipitation over rain shadow districts of the region – but the success rate was limited to 18% incurring
costs to the tune of several hundred thousand US dollars. It is shown for the first time ever, how
microphysical process modelling prior to the launch of seeding operations help in a better release
strategy. The study recommends that flares be released a few tens of meters below the cloud base,
allowing them to disperse and dilute, and prior to them being lifted up by prevailing updrafts.

# Improved mass accommodation calculations : implications

Theor Appl Climatol
https://doi.org/10.1007/s00704-017-2321-4

CrossMark

ORIGINAL PAPER

## A sensitivity study of diffusional mass transfer of gases in tropical storm hydrometeors

Satyajit Ghosh[1,2] · Siddharth Gumber[1] · C. Varotsos[3]

- Ghosh et al. (2018)

Received: 22 August 2017 / Accepted: 2 November 2017

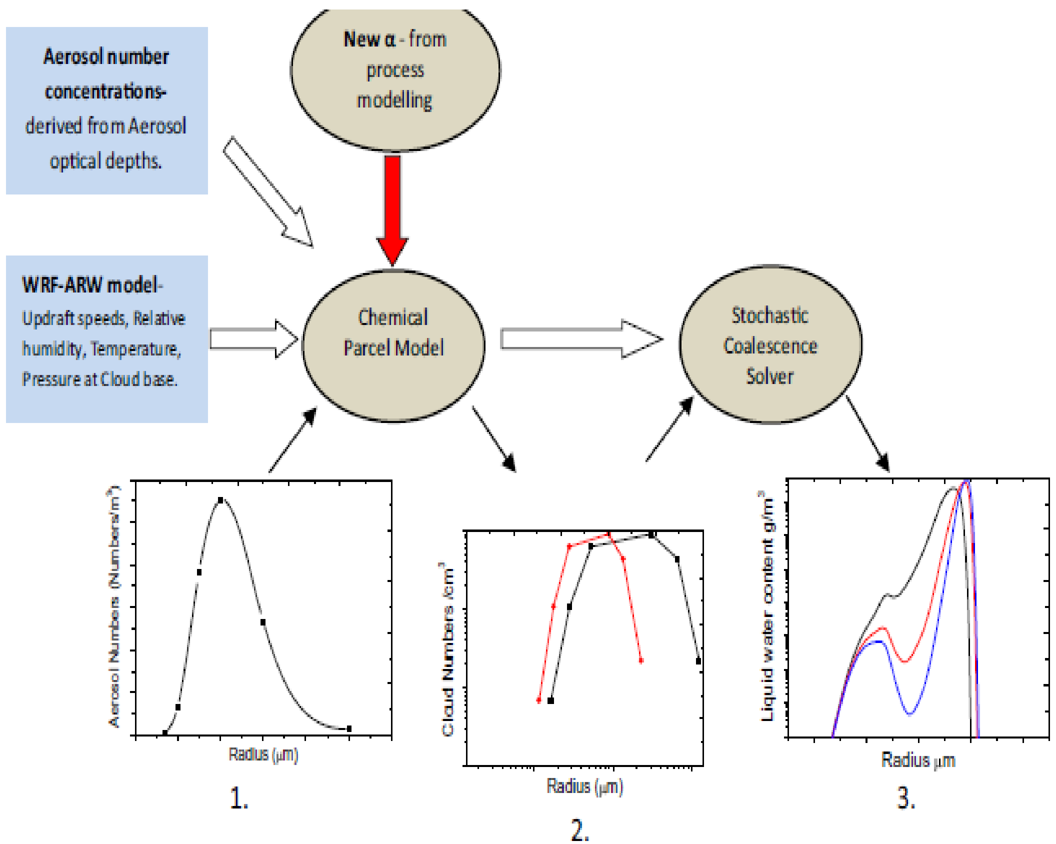



Fig. 1 Schematic representation of the processes involved. In stage 1, dry aerosol spectral data and updraft speeds are fed to the CPM. In stage 2, aerosol particles grow into activated cloud droplets through a detailed configuration of the CPM using dynamical variables from a WRF-ARW run. In stage3, the cloud droplets grow into rain droplets through a stochastic coalescence model. $\alpha$ is the mass accommodation coefficient

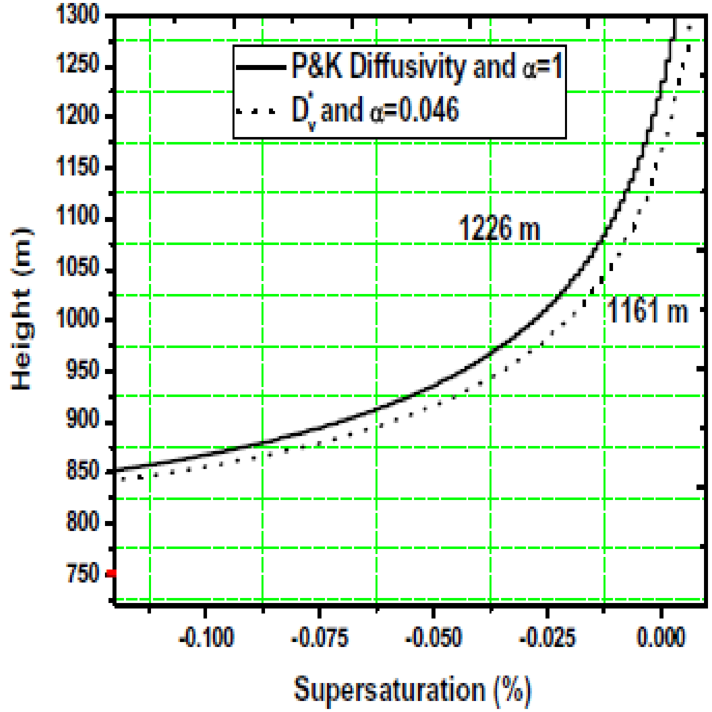



Fig. 7 Cloud base heights obtained from super saturation profiles using the CPM. Standard diffusivity values (labelled P & K (Pruppacher and Klett 1998)) and for $\alpha = 1$ yields a cloud base height of 1226 m. Using the corrected values for $D_v^*$ and $\alpha$ yields a cloud base at 1161 m for all three modes

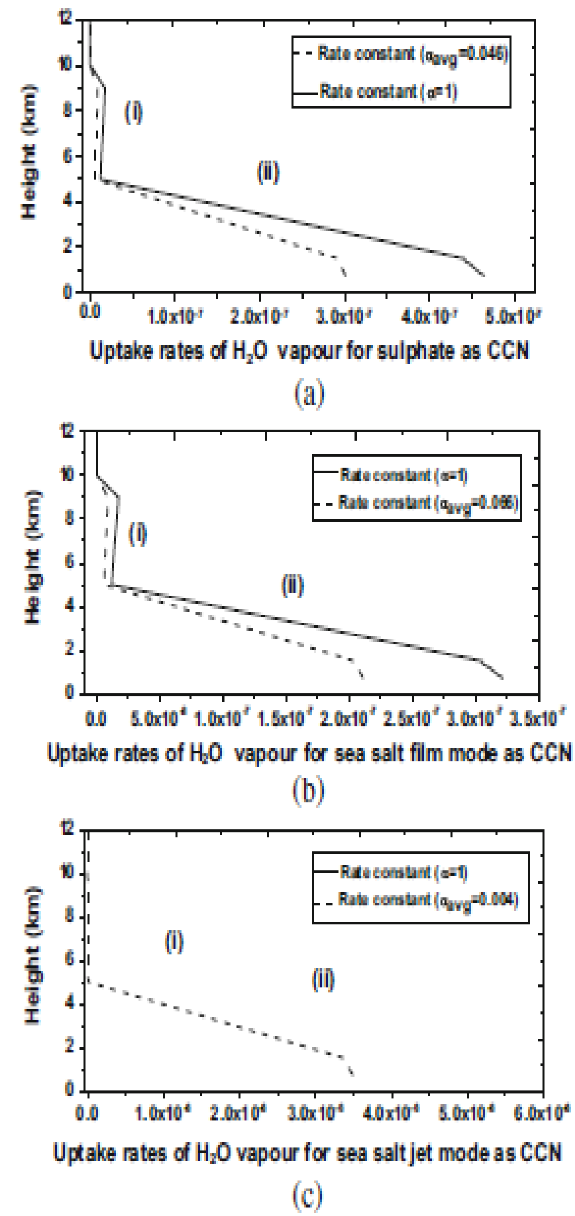



Fig. 13 Uptake rates ($s^{-1}$) for water vapour diffusing into cloud hydrometeors—liquid droplets and ice crystals for Chapala's cloud structure. Rate constants in ice crystals for $l = 30$ μm and $\alpha_{ice} = 0.013$

# Concluding Remarks

1. Particle retention times for residual pollution are long- of the order of 12 hours. A slow ascent rate of an updraft eddy will ensure sufficient diffusional mass transport.

2. Green facades are known to work well in cleansing Residual Pollution. (Ghosh and Joshi 2014)

3. Vernonia *elaeagnifolia*- easy to maintain- adds aesthetic appeal.

4. Since the median size is biased towards the sub-micron range, anti smog guns failed. Artificial injection of liquid droplets through carefully controlled experiments can bias the growth to exceed 20 um radii. This will foster rapid onset of stochastic coalescence (Proc. Royal Met. Soc. Ghosh)

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## *Cambridge Particle Meeting 2018*

# Thank You