Urban PBL Seminar Series
Part 1 of 3: Observations of urban climate, weather, and air quality

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My Research Interests

- Observation, analysis, & simulation of polluted coastal urban boundary layers (today's lectures)
  - How urbanization & pollution create new urban climate
  - How new urban climate controls spread of pollution within & downwind of city
- Emergency response facility for NYC
  - Meso- and canyon- met networks
  - Meso- and canyon met and air quality models
- Obs of climate change in coastal areas

Seminar Series

- Part 1: Observations of urban PBLs
- Part 2: Meso met-models of PBLs
  - Formulations
  - Problems
- Part 3: Meso met-models of uPBLs
  - Formulations
  - Applications

OVERVIEW OF PART 1

- WHY STUDY URBAN AREAS
- CAUSES OF URBAN CLIMATE
- URBAN CLIMATE ELEMENTS
  - TEMP
  - WIND: MEAN & TURBULENCE
  - MOISTURE & STORMS
- AIR QUALITY IMPACTS
  - MESOSCALE
  - MICROSCALE

HUMAN-HEALTH IMPACTS OF URBAN CLIMATE

- UHI → THERMAL STRESS
- PRECIP ENHANCEMENT → FLOODS
- URBAN-INDUCED INVERSIONS → POLLUTED LAYERS
- TRANSPORT & DIFF PATTERNS FOR
  - POLLUTION EPISODES
  - EMERGENCY RESPONSE

uPBL sub-layers

- Urban mixing layer
  - Non-homogeneous
  - Non-stationary
- Urban SfcBL: has several sub-layers
- Urban surface: where is it (in our models)?
  - ground
  - roughness length, z_o
  - displacement height, d
  - rooftop
  - Top of roughness sub-layer (see next slide)
- Urban sub-surface: consists of
  - ground
  - walls
  - roofs

uSBL sub-layers (next slide)

- Canyons (UCL)
  - Between buildings (extends from 0-h)
  - Flow is f(W/H ratio) → skimming, vortex, or isolated-obstacle flow
- Canopy layer (or roughness sub-layer)
  - Flux-blending layer (extends from h to 3h)
  - M-O theory not valid → $u_*(z)$
- Inertial sub-layer
  - Fluxes have blend (> 3h)
  - M-O theory is valid → u_* not f(z)

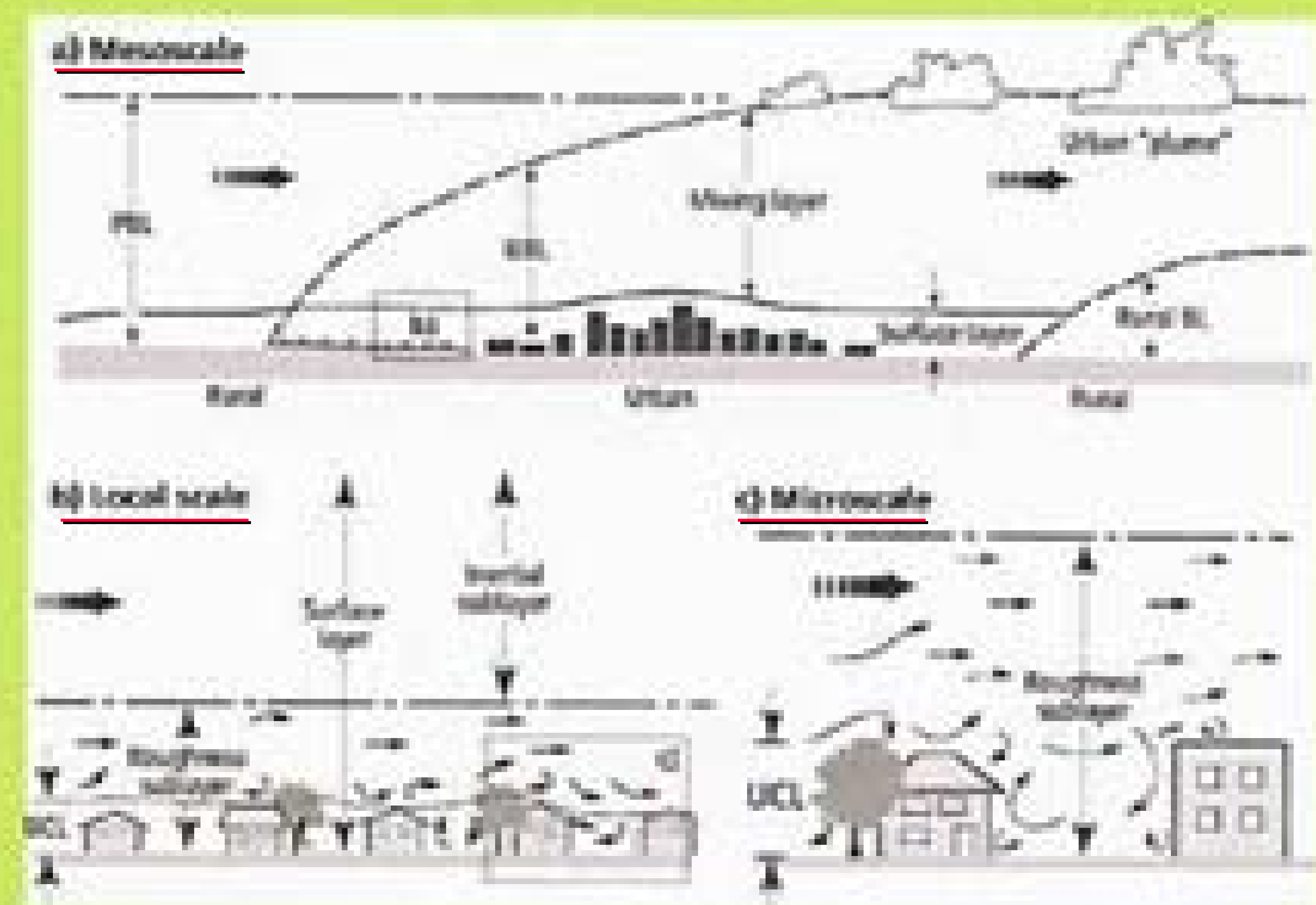


Figure 1. Schematic of climatic scales and vertical layers found in urban areas.

IMPORTANT THEME 1: URBAN WX ELEMENTS

- Battles b/t conflicting effects
- Long-term climo-averages →
  small- Δs b/t 2 large conflicting-effects → confusion in literature
- Must ask right-question →
  intelligent data-segmentation →
  better understanding of phy-processes

URBAN Wx-ELEMENTS

Monatomic effects

- VISIBILITY: decreased
- PBL NIGHT STABILITY: neutral
- TURBULENCE: increased (both mechanical & thermal)
- FRONTAL SPEED (synoptic & sea breeze): slowed

More-complex effects

- TEMP & PRECIP: increased (UHI) or decreased (UCI)
- WIND SPEED: increased or decreased
- WIND DIRECTION: con- & divergence
- THUNDERSTORMS: triggered or split

URBAN HEAT ISLAND (UHI)

- Most-studied urban climate impact
- Causal factors (previous slide) → reduced nocturnal urban-cooling → urban areas remain-warmer than rural areas → UHI forms
- Mostly studied at: 2 m, night, mid-lat
- uPBL can be plume (windy atm) or dome (calm V)
- Satellite obs of radiative sfc-T → strong daytime sfc-UHIs

NEW URBAN-CLIMATE: CAUSES

- GRASS/SOIL → CONCRETE/BUILDINGS →
  NEW SOIL MOISTURE CONTENT →
  NEW THERMAL INERTIA →
  ALTERED SFC HEAT & MOSITURE FLUXES
- FUEL CONSUMPTION (next slide)→
  ATM POLLUTION, HEAT, AND MOISTURE
- BUILDINGS (LOWER SKY-VIEW FACTORS) &
  ATM POLLUTION→
  ALTERED (SOLAR & IR) RADIATIVE FLUXES

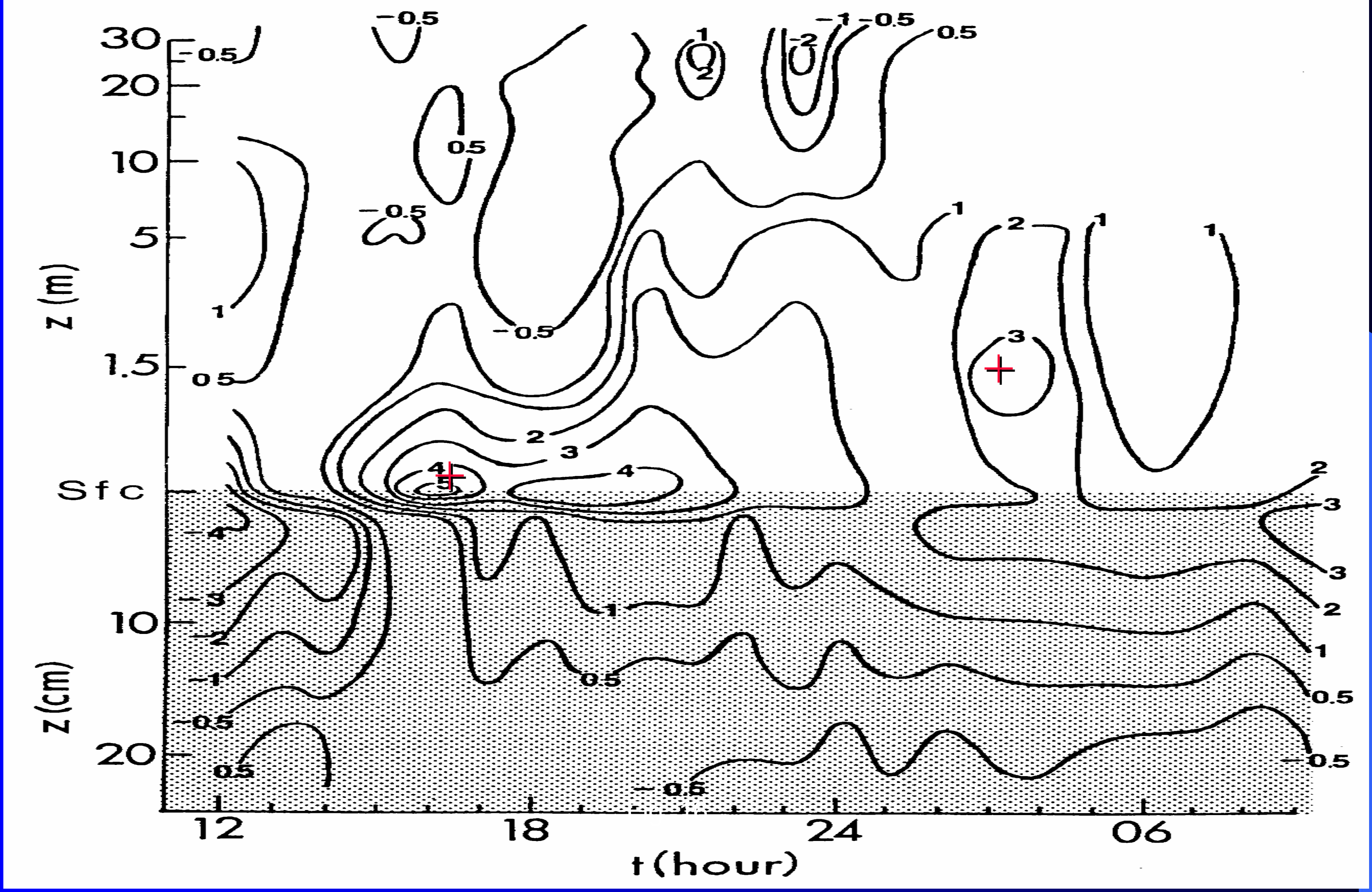
Ratio (r) of anthro heat-flux to sfc net-radiation: some cold-cites in winter have r > 1

Average Annual Anthropogenic Heat Flux Densities (Q_F) Of Urban Areas[1]

Urban Area	Year	Population Density (persons $km^{-2} \times 10^3$)	Per Capita Energy Use ($GJ\ y^{-1}$)	Q_F ($W\ m^{-2}$)	Q_N ($W\ m^{-2}$)	Q_F/Q_N
Manhattan (40°N)	1965	29.8	169	159	93	1.71
Moscow (56°N)	1970	7.3	530	127	42	3.02
Montreal (45°N)	1961	14.1	221	99	52	1.90
Budapest (47°N)	1970	11.5	118	43	46	0.93
Hong Kong (22°N)	1971	37.2	28	33	~110	0.30
Osaka (35°N)	1970-74	14.6	55	26		
Los Angeles (34°N)	1965-70	2.0	331	21	108	0.19
West Berlin (52°N)	1967	9.8	67	21	57	0.37
Vancouver (49°N)	1970	5.4	112	19	57	0.33
Sheffield (53°N)	1952	10.4	58	19	56	0.34
Fairbanks (64°N)	1967-75	0.55	314	6	18	0.33

Sources: Bowling and Benson (1978); Kalma and Newcombe (1976); Ojima and Moriyama (1982); Oke (1978b); SMIC (1971).

Sacramento (sub-sfc, sfc, & atm) obs by Imamura (1992): max-UHI at 2-m at night & Sfc during day (largest value)



Daytime Sacramento-UHIs:

2 m (left) UHI (2^{0}C) << sfc (right) UHI (20^{0}C)

Note: Irrigated urban treed-park (inner square) is cool area

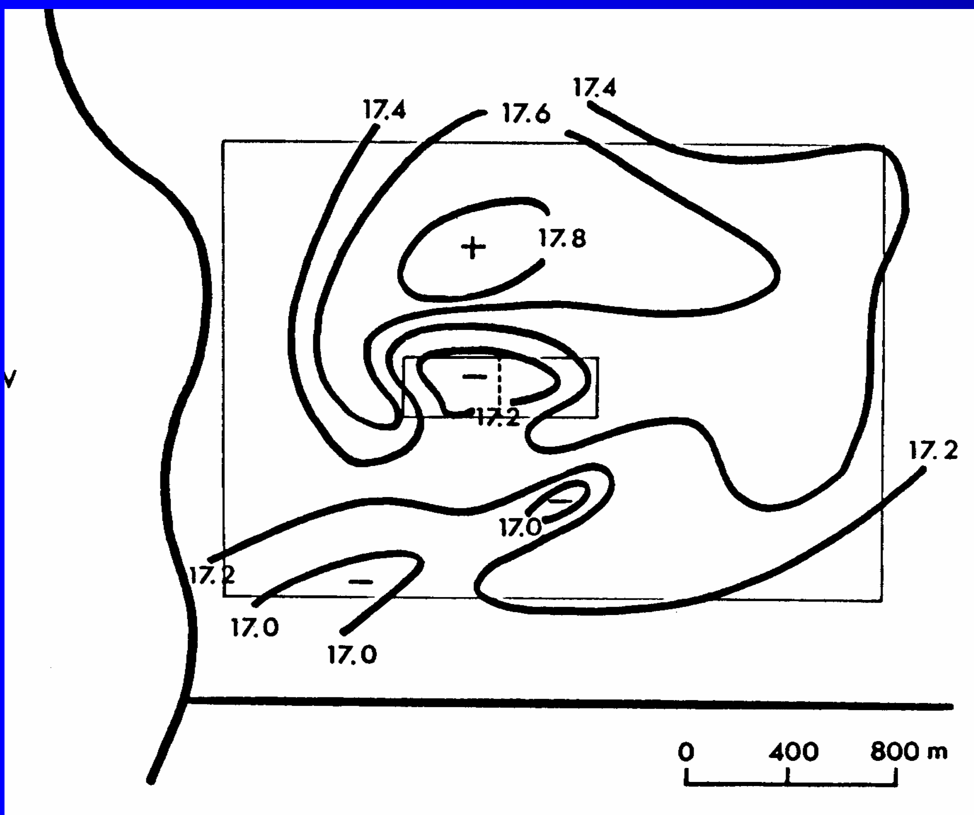


Fig. 15

NYU/NYC uPBL-STUDY

- 10 IOPs
  - FIVE DAYS EACH (DAY AND NIGHT)
  - ALL SEASONS
- 80 10-m V-SITES → HOURLY V-CHARTS
- PIBALS:
  - 1- 4 THEODOLITES (1OR 2 BALLOONS)
  - 15 SEC OBS → 37.5 m z-RESOLUTION
- HELICOPTER SOUNDINGS (ABOUT 1000)
  - T (next 2 slides), q, & SO_2
- NOAA TETROONS: ABOUT 200
- EMISSIONS
  - 1 KM X 1 KM
  - SO2, HEAT, & MOISTURE

NYC nocturnal UHI-dome (V into page):

Note: > warm, neutral, polluted uPBL

> no urban sfc-inversion

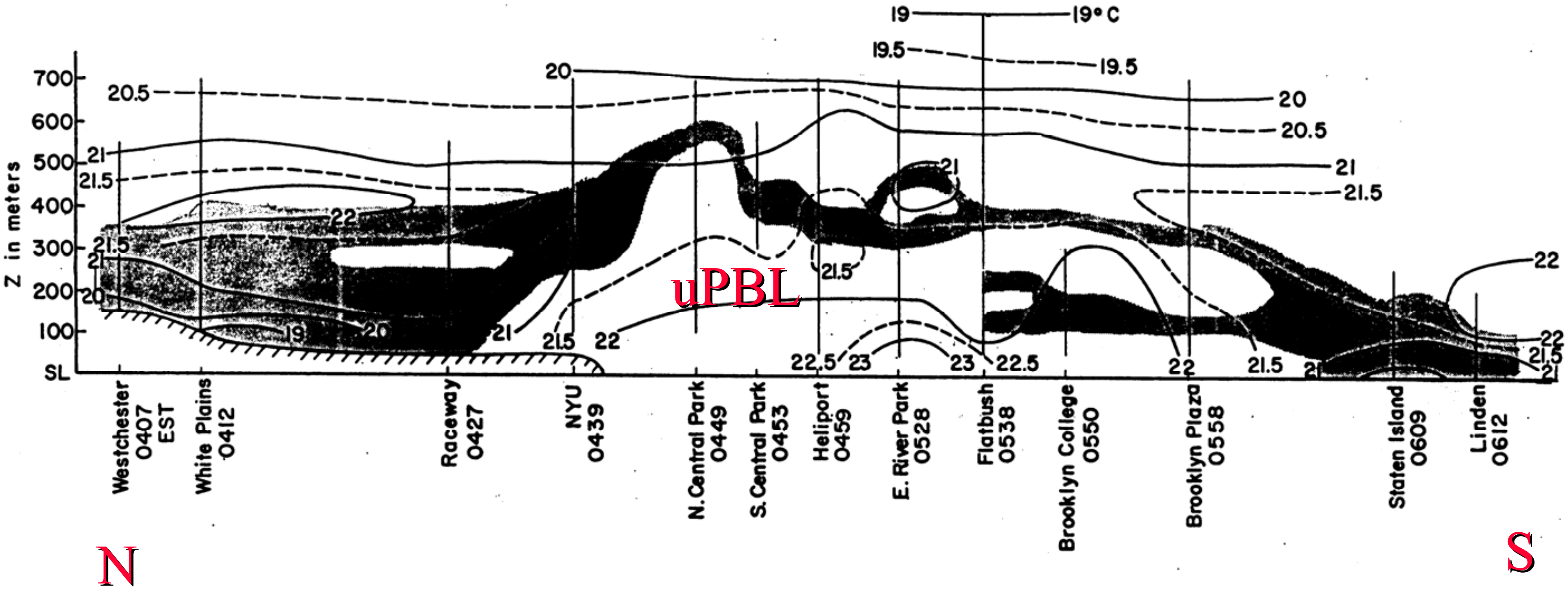


Fig. 5 Vertical temperature cross section (°C) over New York City area (NYU to Brooklyn) on 16 July 1964. Shaded areas indicate isothermal and inversion layers (from Bornstein, 1968).

NYC AVERAGE NOCTURNAL UHI (z):

note cross-over layer (UHI < 0) aloft due to RFD, sinking rural air, ??

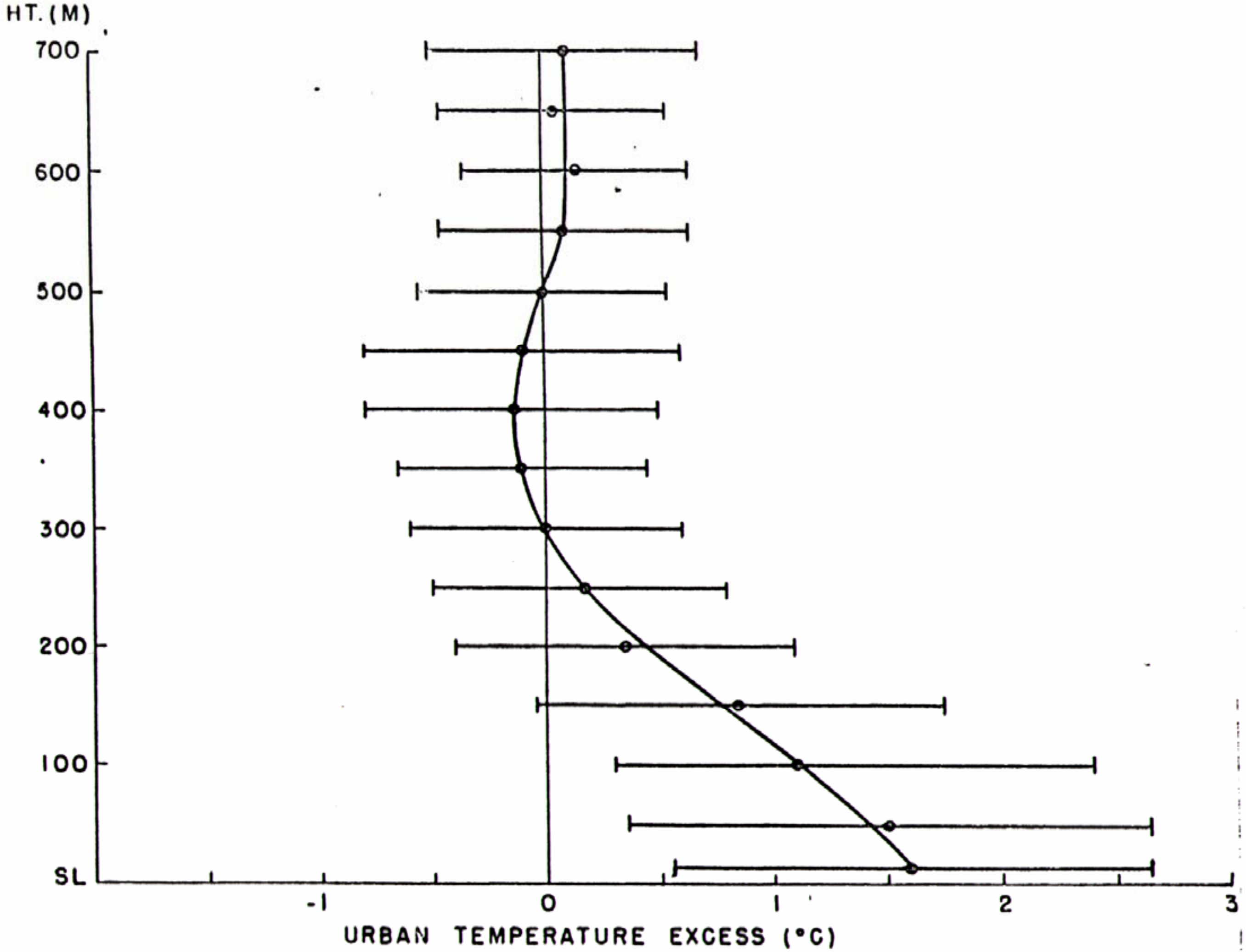


Fig. 7 Average urban heat island over New York City as function of height. Horizontal bars show plus and minus one standard deviation (from Bornstein, 1968).

vs. St. Louis nocturnal urban-plume

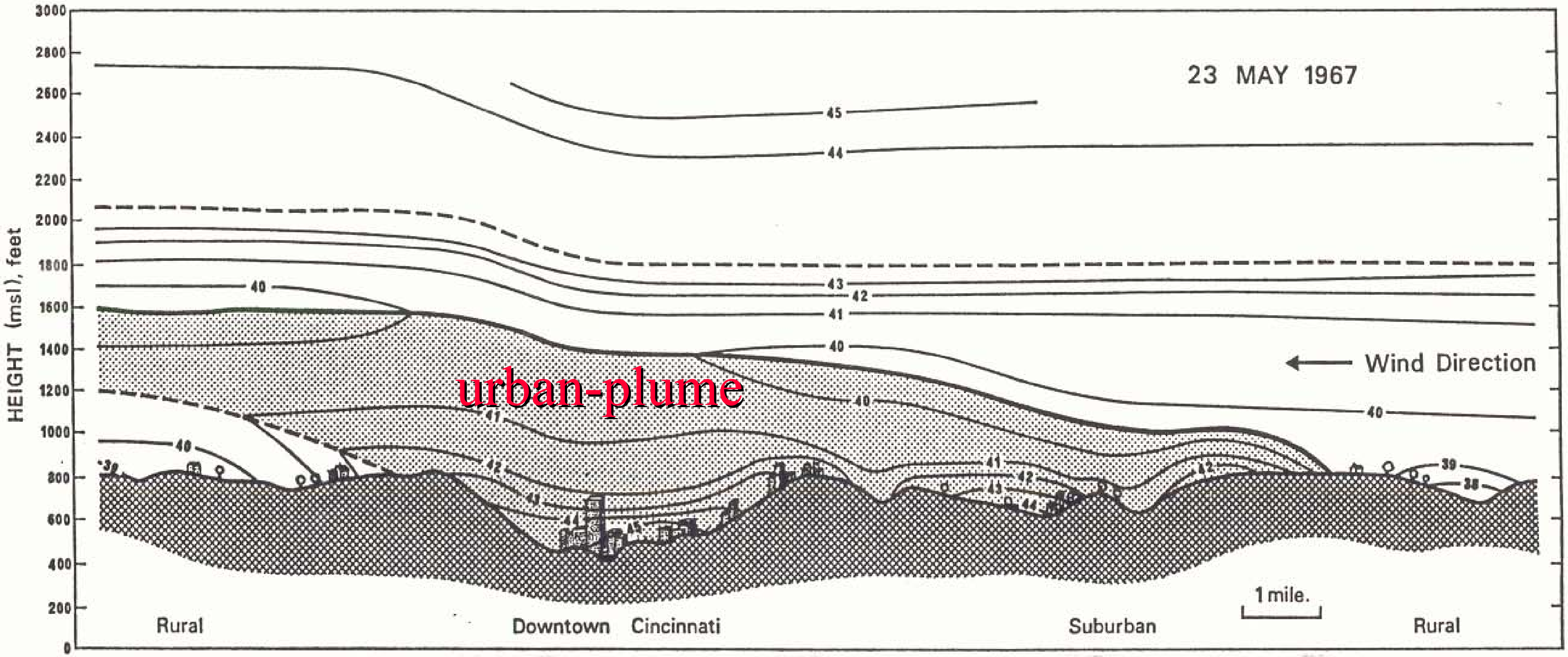
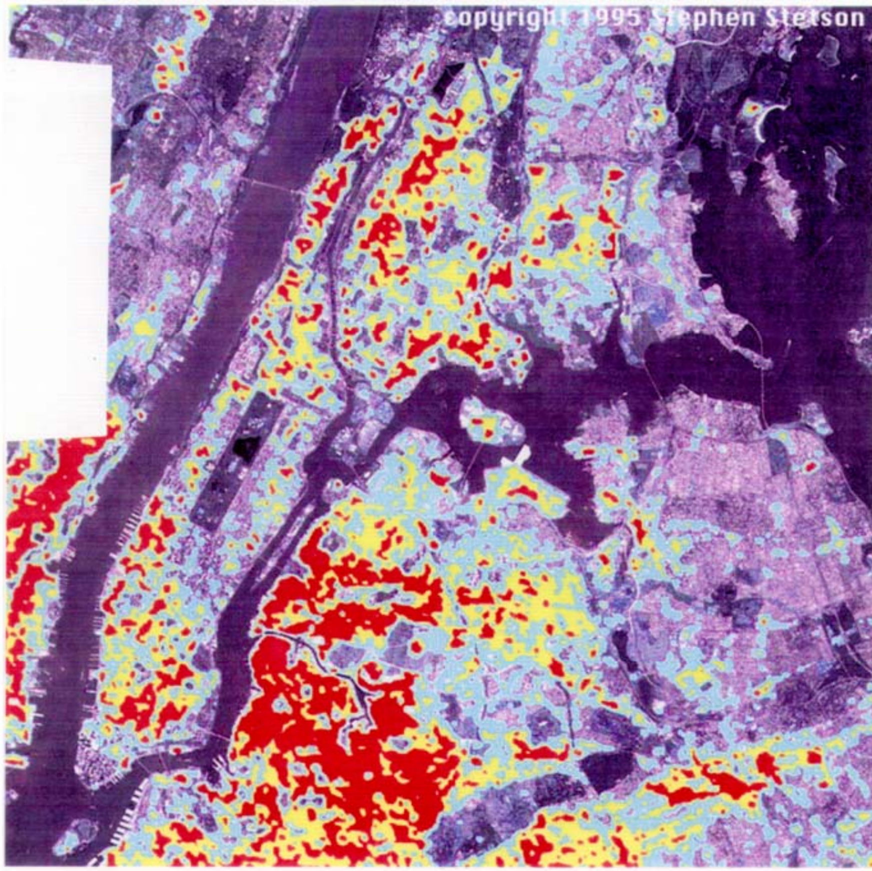


Fig. 6 Vertical temperature cross section (°F) over Cincinnati area on 23 May 1967 (from Clarke and McElroy, 1970).

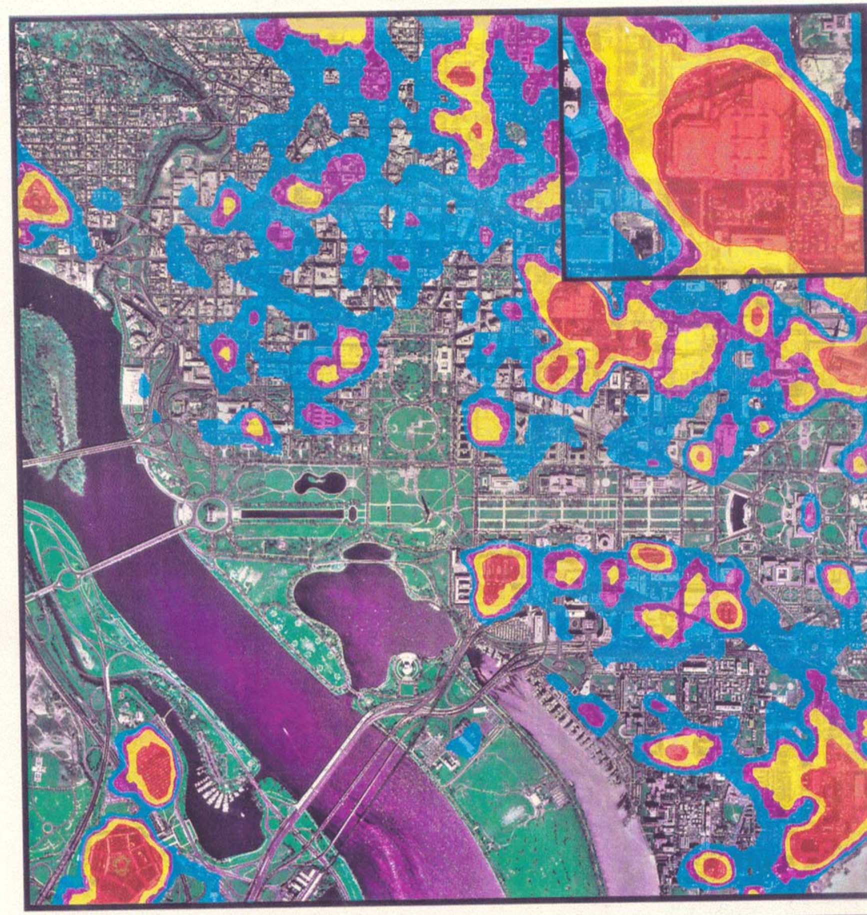
DAYTIME uPBL

- NEUTRAL STABILITY
  IN BOTH URBAN & RURAL PBLs
- WEAK ATM-UHIs
- BUT:
  - REGIONAL ELEVATED-INVERSIONS BOW-UPWARDS DUE TO ENHANCED URBAN CONVECTION
  - STRONG SFC-UHIs (next slide)

SATELLITE-DERIVED DAYTIME UHIs (sfc radiative-T) for NYC (left) & Washington, DC (right) (from S. Stetson)



Landsat Thermal Map of New York City Region, June 22, 1994
Red = hottest 5%, Yellow = 5-10%, Blue = 10-20%
Scale = 1: 118,000. Base map produced from TM bands 3,2,1 with 25 meter ground cell resolution



- > 12° F above median
- > 8° F above median
- > 6° F above median
- > 3° F above median

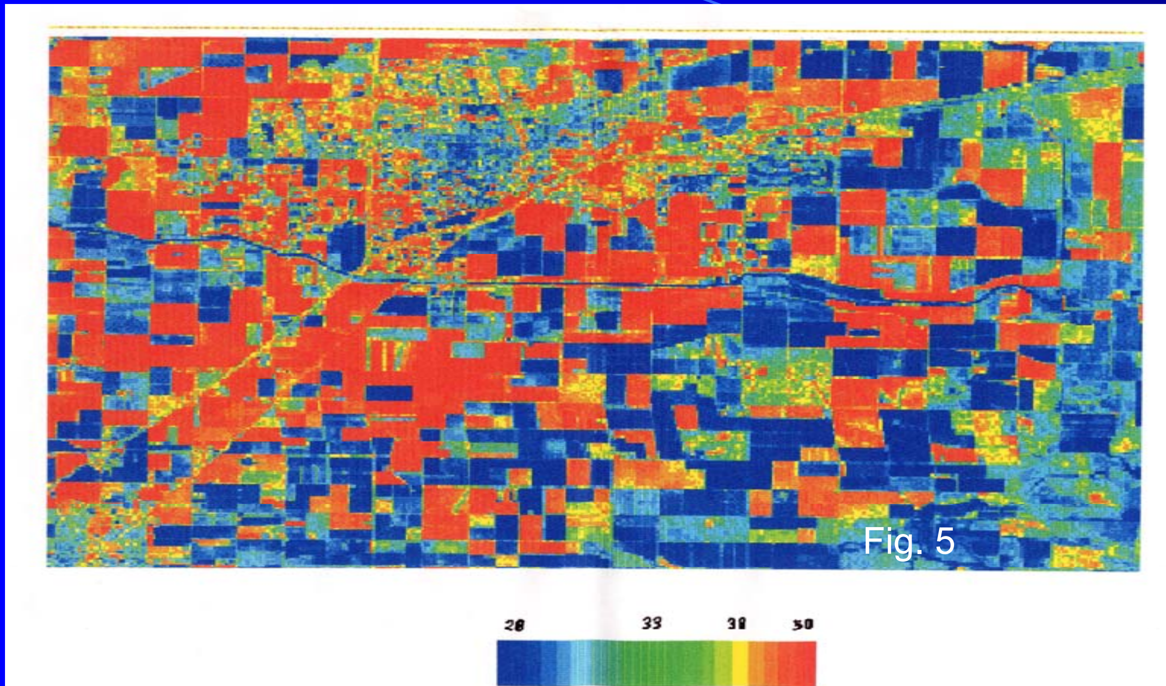
Inset in upper right corner is a detail view of the Convention Center and the hottest area in Washington.

Temperature data from LANDSAT's thermal band is combined with an aerial photograph to illustrate the heat island characteristics of Washington, DC. In the picture vegetation appears ~~of~~ green. Red, yellow, violet and blue areas denote temperature variation in the hottest 25% of the city. Red represents the hottest 1%, yellow-5%, violet-10% and blue-25%.

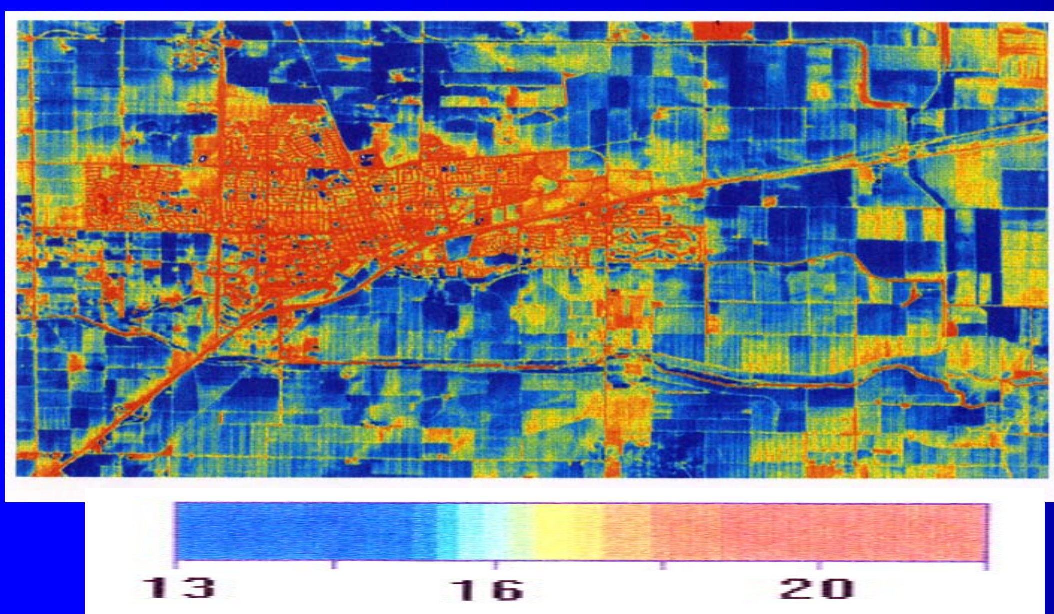
Theme 2: Role of rural soil-moisture in UHI formation (Imamura 1992)

- Thermal inertia (or emitance): (TI) = $(\rho\ c\ k)^{1/2}$
- High-TI → slow nite-cooling & day-warming → nighttime UHI
- Vice versa for low-TI materials
- Wet rural-soil TI > urban TI > dry rural-soil TI
- This cities surrounded by wet rural-soils have max nighttime UHIs
- Vice versa for cities surrounded by dry rural-soils
- See next 2 slides

NASA SFC RAD-T (C) OBS: DAY & NIGHT



DAY:
- HOT RED = DRY SOIL
- COOL BLUE = WET SOIL
- URBAN AREAS:: IN BETWEEN T
  (WITH WARM ROOFS)
- UHI ?: DEPENDS WHERE RURAL
  OBS TAKEN

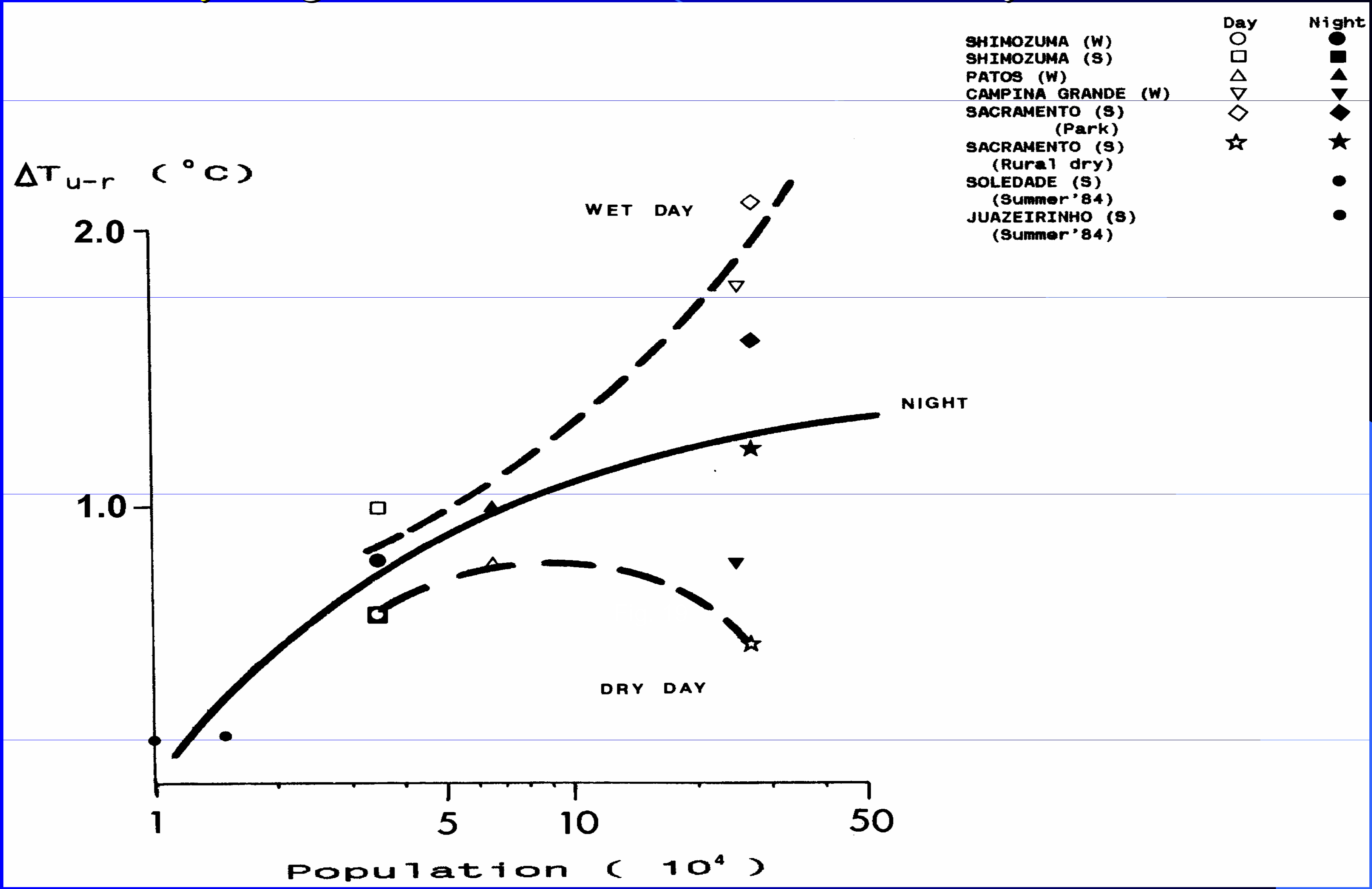


NIGHT:
- HOT RED = URBAN ROADS
- WARM YELLOW = WET SOIL
- COOL BLUE =DRY SOIL
- UHI: YES

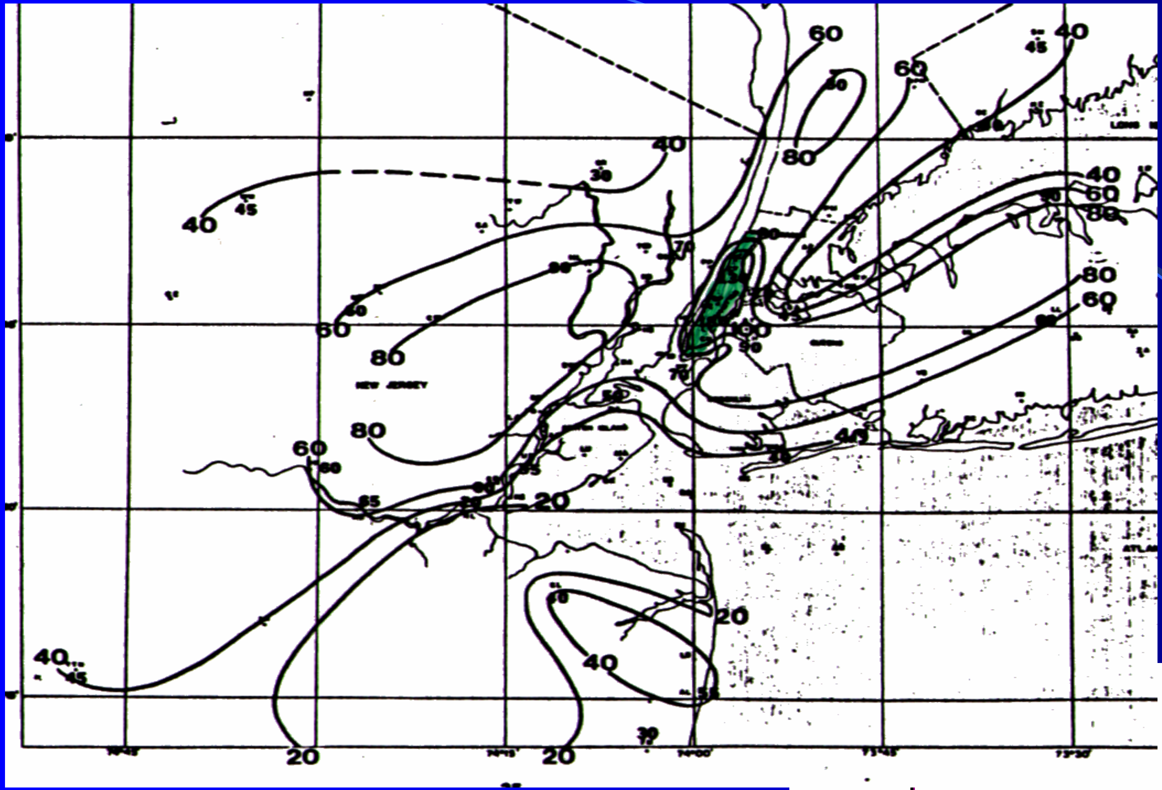
2-m UHI AS FUNCTION OF POPULATION (Imamura 1992)

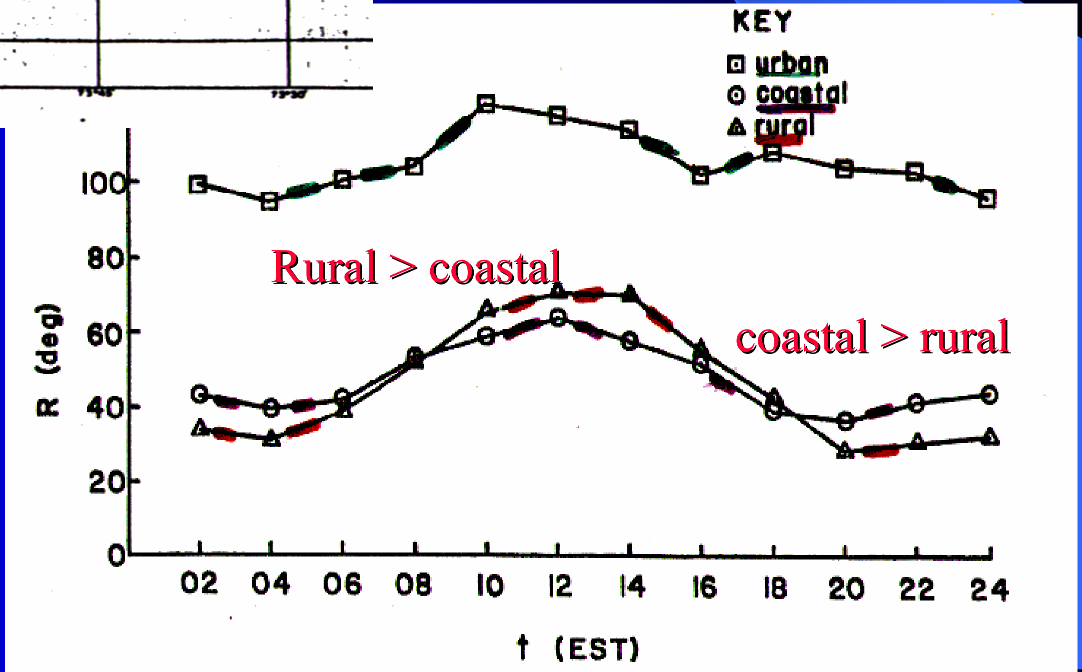
> Night: only one-line

> Day: large for wet rural- soils & small for dry rural-soils



NYC TURBULENCE: ESTIMATED BY WIND DIR RANGE (deg)



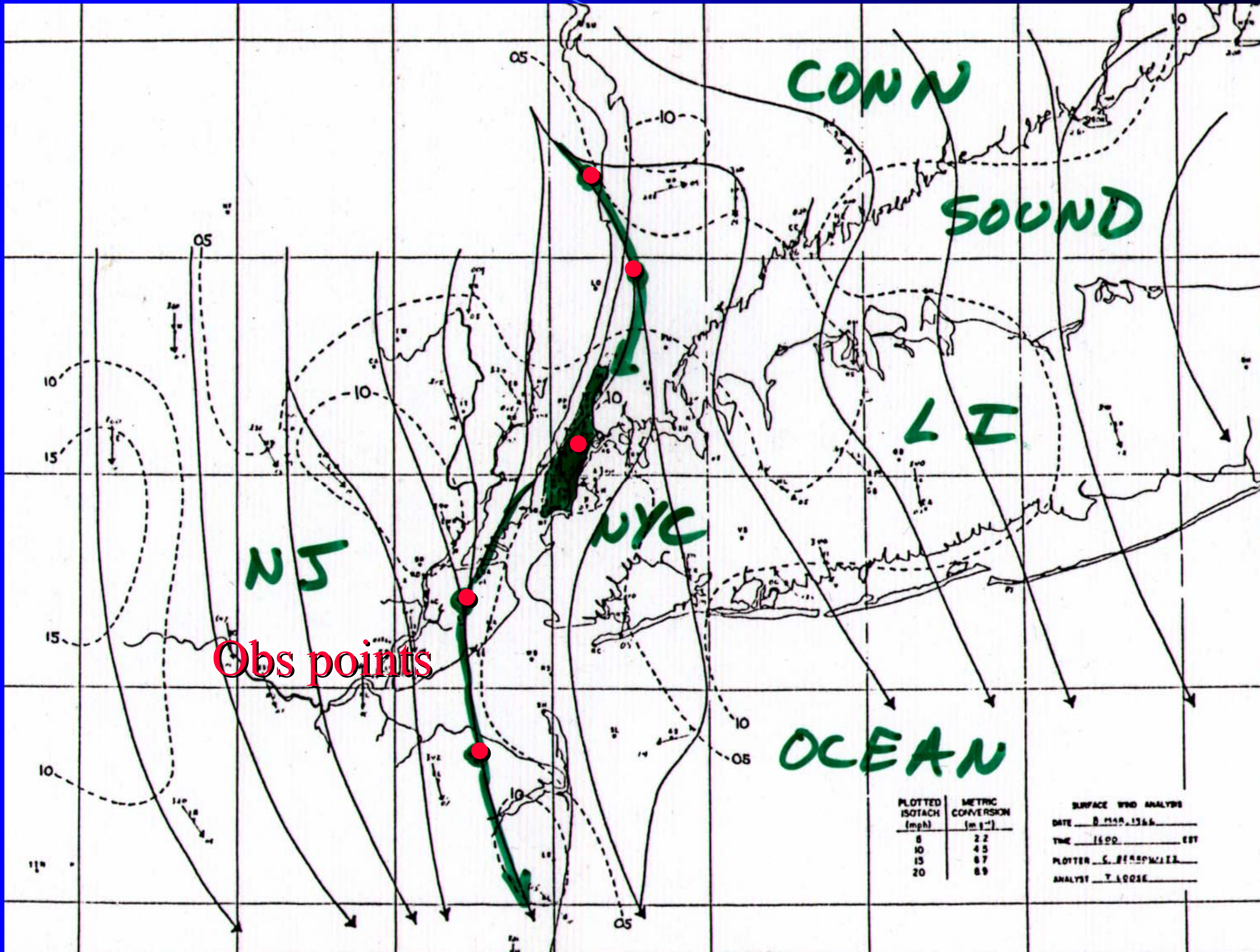


Urban effects on wind-speed (next 3 slides)

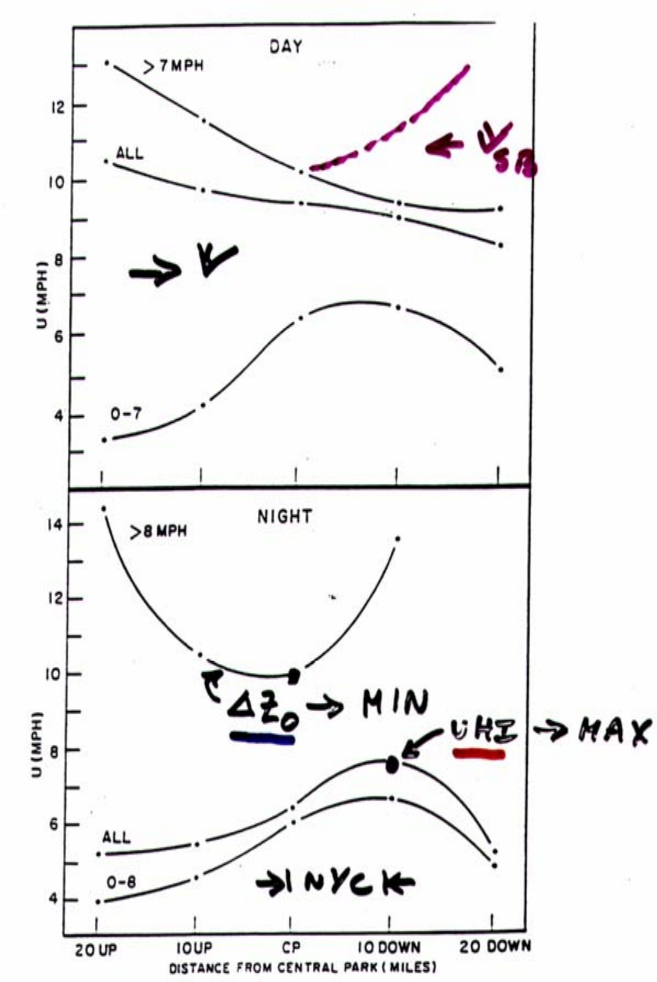
- FAST SYNOPTIC-SPEEDS → SMALL UHI → URBAN z_0-DECELERATES
- SLOW SYNOPTIC-SPEEDS LARGE UHI → ACCELERATION
- CRITICAL-V ~ 3-4 m/s (NY & London)
- MASS-BALANCE REQUIRES: REVERSE-EFFECT ALOFT

NYC STREAM LINE FIELD

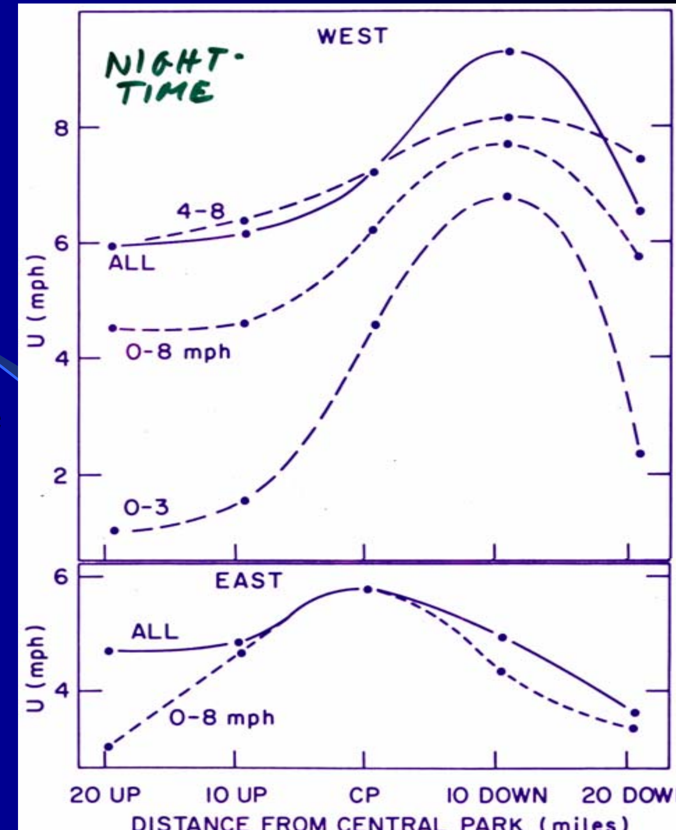
Note: 5 obs-points along stream- line thru Manhattan

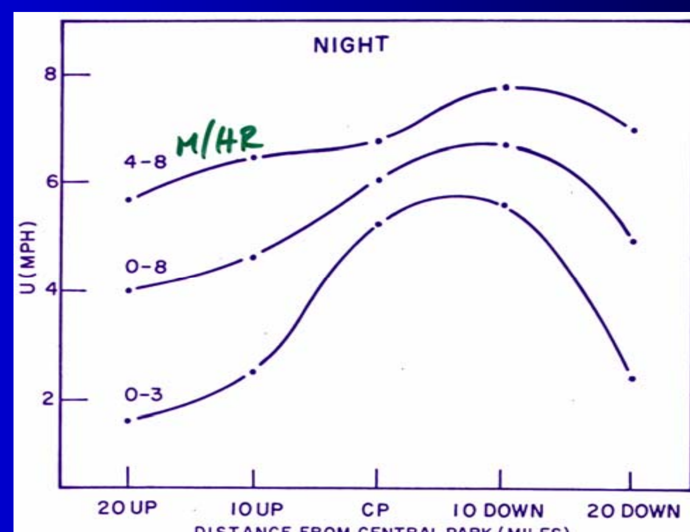


NYC Average 10-m V



Nighttime UHI-accelerated max-speed: always on downwind urban-edge →

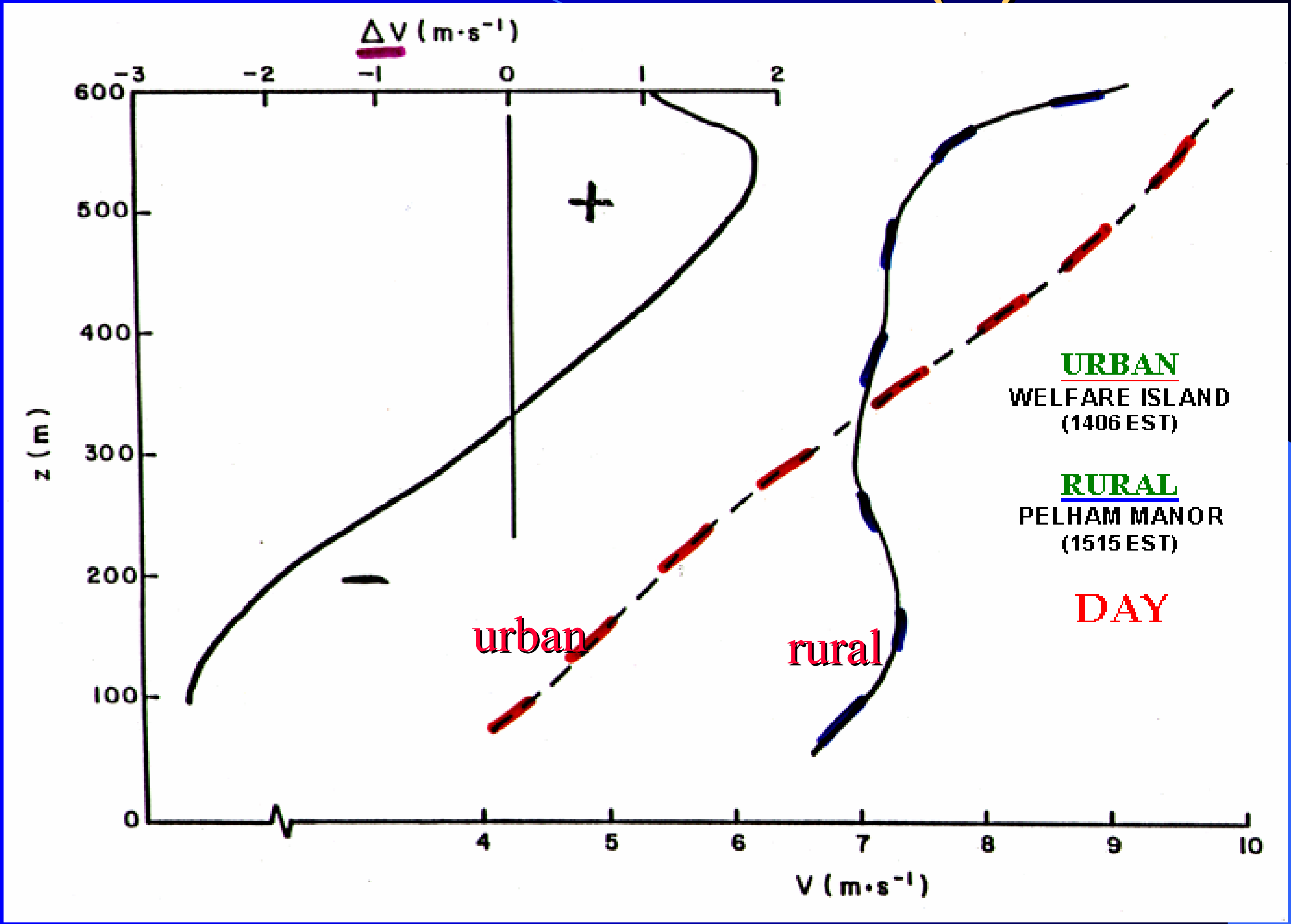




UHI accel is inversely prop to rural-speed

- See above figure
- Fast speed (D/N): urban decel
- Slow speed (D/N): urban accel
- No-return to upwind-speed during day b/c of opposing sea-breeze

NYC DAYTIME ΔV (z)

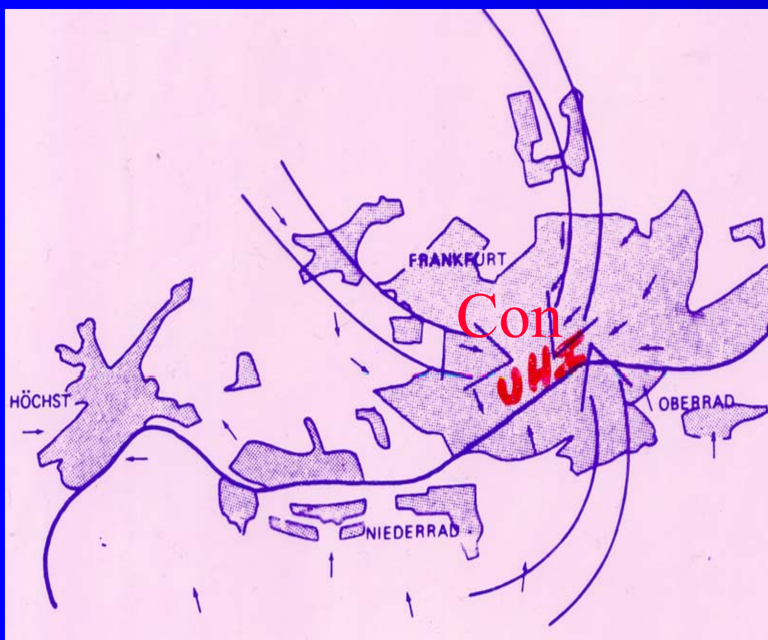


URBAN-EFFECTS ON WIND-DIR

- FAST SYNOPTIC-V → WEAK UHI → URBAN BUILDING-BARRIER EFFECT → FLOW DIVERGES AROUND CITY
- SLOW SYNOPTIC-V → LARGE UHI → LOW PRESSURE → CONVERGENCE INTO CITY
- MODERATE SYNOPTIC-V → CONVERGENCE ZONE ADVECTED TO DOWNWIND URBAN-EDGE
- LARGE URBAN Z_0 → LOWER V → SMALLER CORIOLIS → FLOW TURNS TO RIGHT (secondary effect)

NOCTURNAL-UHI INDUCED SFC-CONFLUENCE WITH:

a. otherwise-calm (conf-center over urban center): Frankfurt (left)
b. low-speed regional-flow from N (con-center advected to downwind urban-edge): NYC (right)



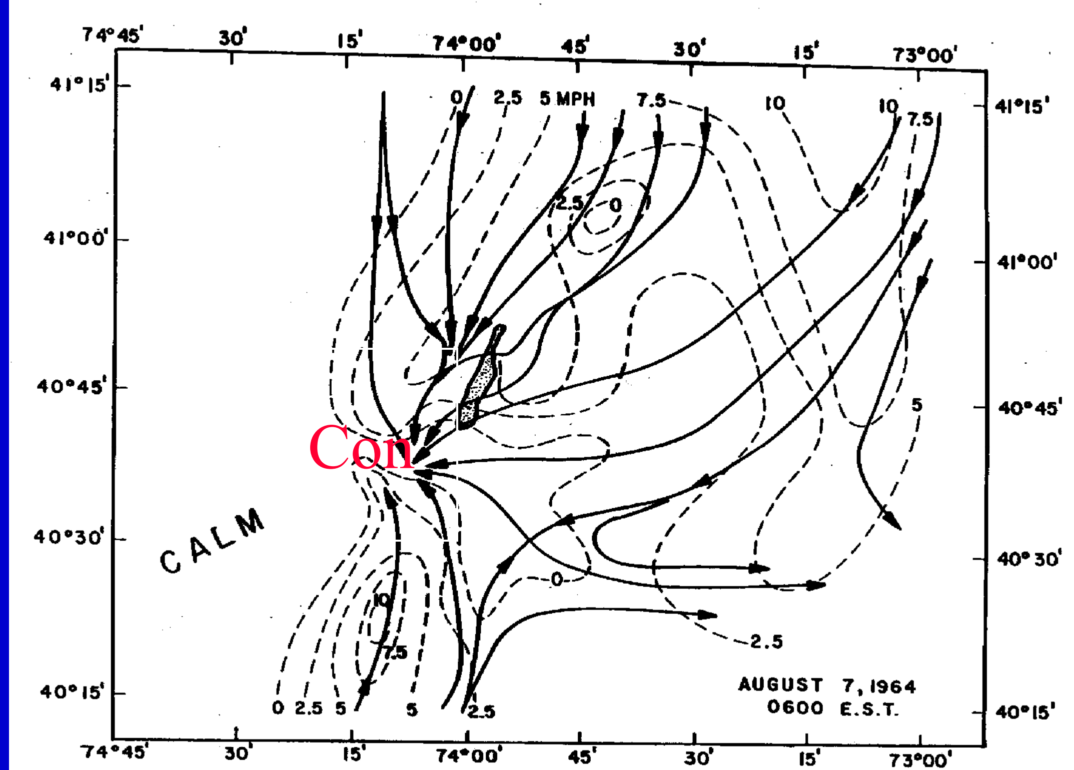
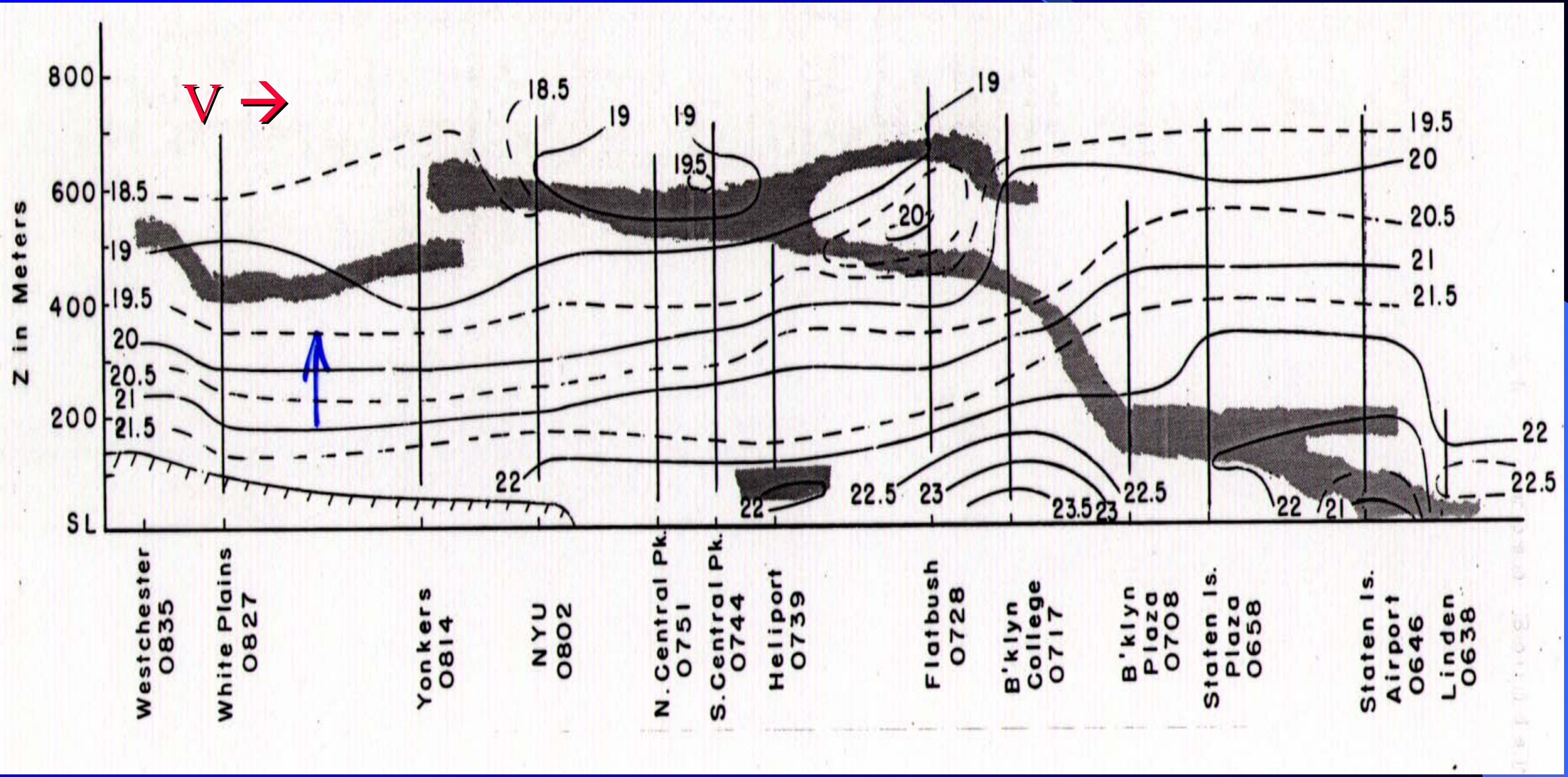


Fig. 20 Streamline (solid lines) and isotach (dashed lines) analyses (mph) showing nocturnal urban-induced confluence region downwind of urban center (Manhattan Island, shown) (from Davidson, 1967).

NYC inversion pattern several hrs after previous x-section:

Note: flow hit urban upwind edge → roughness-deceleration → up-motion → inversion raised

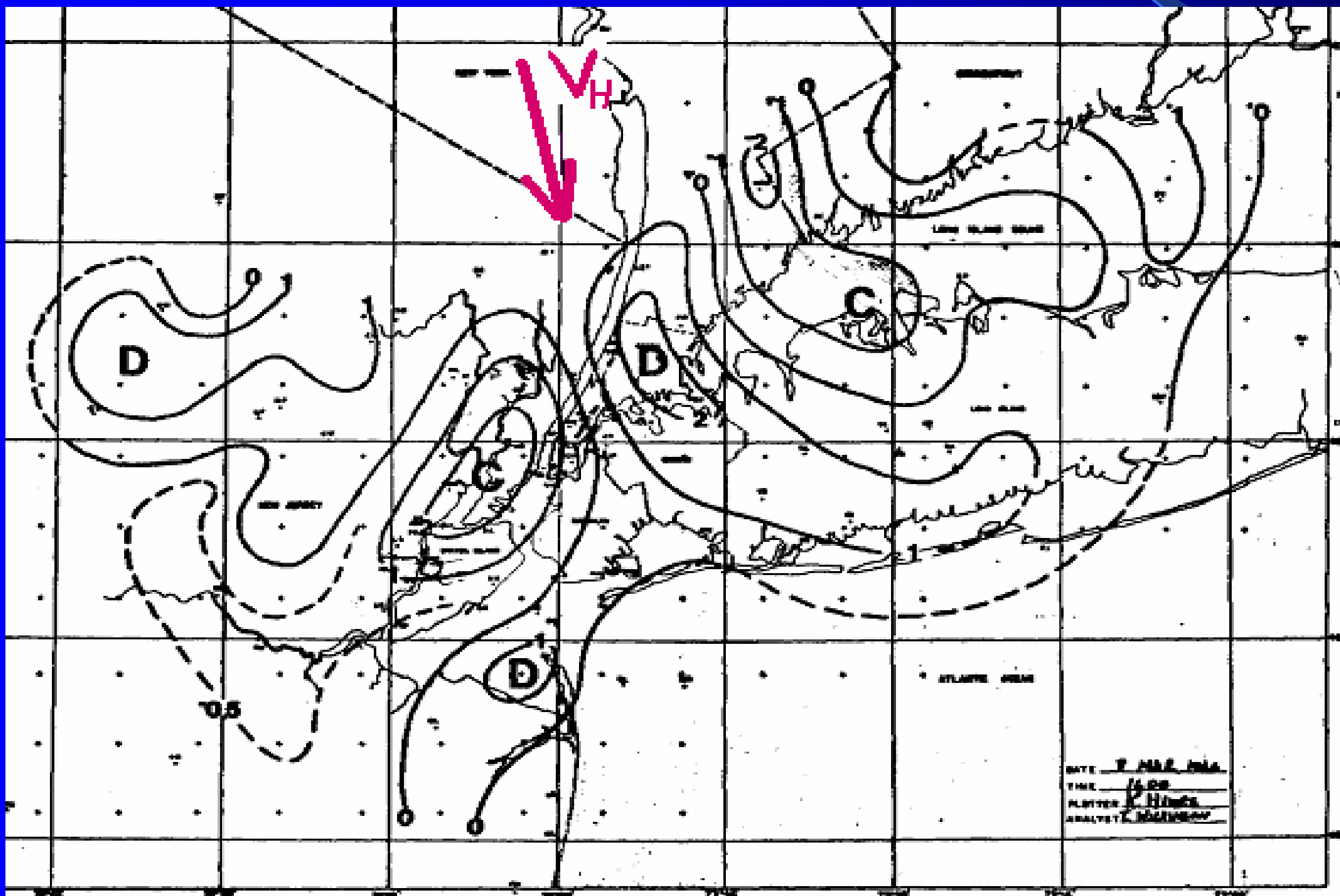


NYC daytime sfc div-field: like flow around rock

Note: (a) divergence-area over city-core → $w < 0$

(b) conv-areas on lateral urban-edges: where diverted flow merges with undisturbed flow → $w > 0$

(c) lack of downwind obs (over ocean)



D ($10^{-4} s^{-1}$)

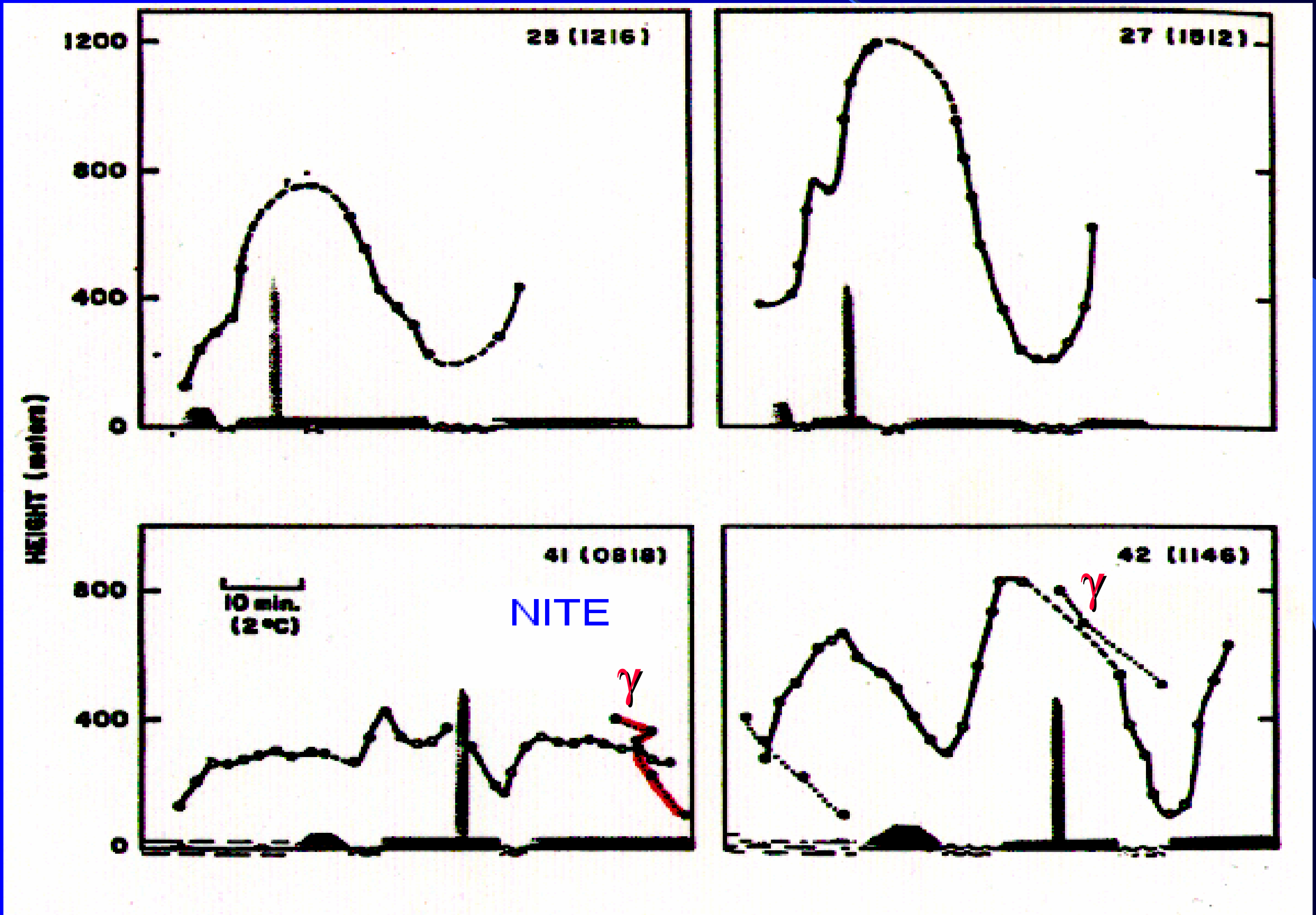
$D = \partial u/\partial x + \partial v/\partial y$

NYC TETROON-DERIVED w-VELOCITIES:

Note (a) larger during unstable daytime-hours

(b) Smaller during more stable nighttime-hours

(c) thin, weak nocturnal urban elev-inversion layer-base stops w



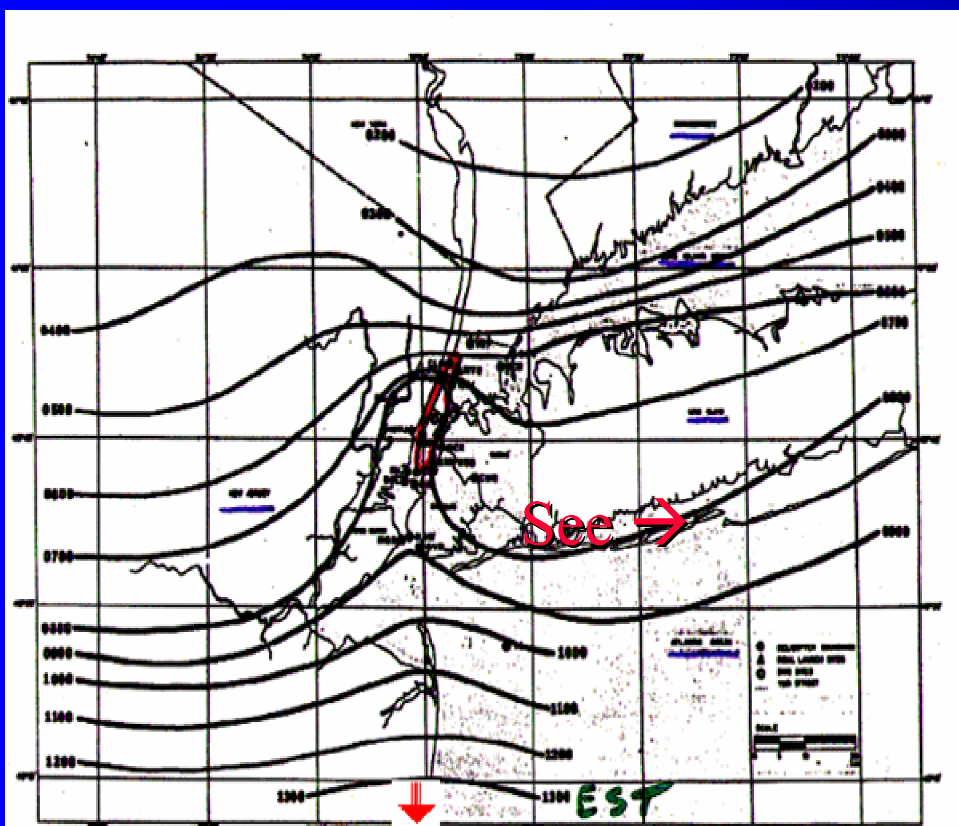
NYC Urban effects on moving Wx fronts

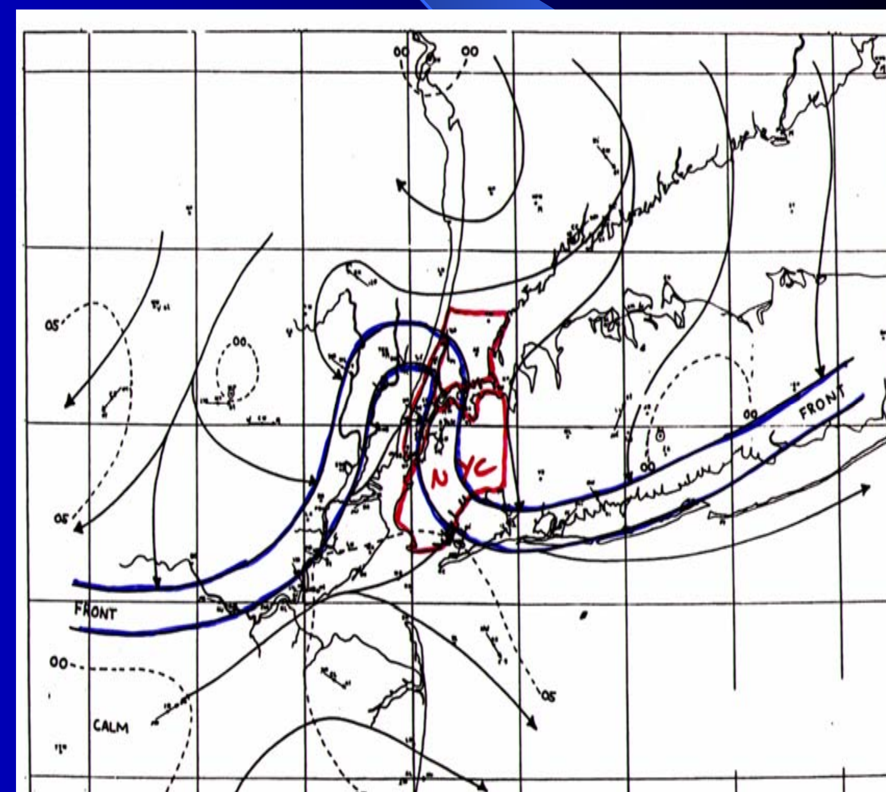
- For (synoptic & sea breeze) fronts
- Urban effects
  - building-barrier effect (& not just z_0) retards frontal movement
  - UHI accelerates frontal-movement
- See next 3 slides

Weak cold-frontal (N to S) passage over NYC

a. Hourly positions (left)

b. At 0800 EST (right): T, q, & SO_2 z-profile-changes showed lowest 250 m of atm not-replaced, as front "jumped" over city (Theme 3)

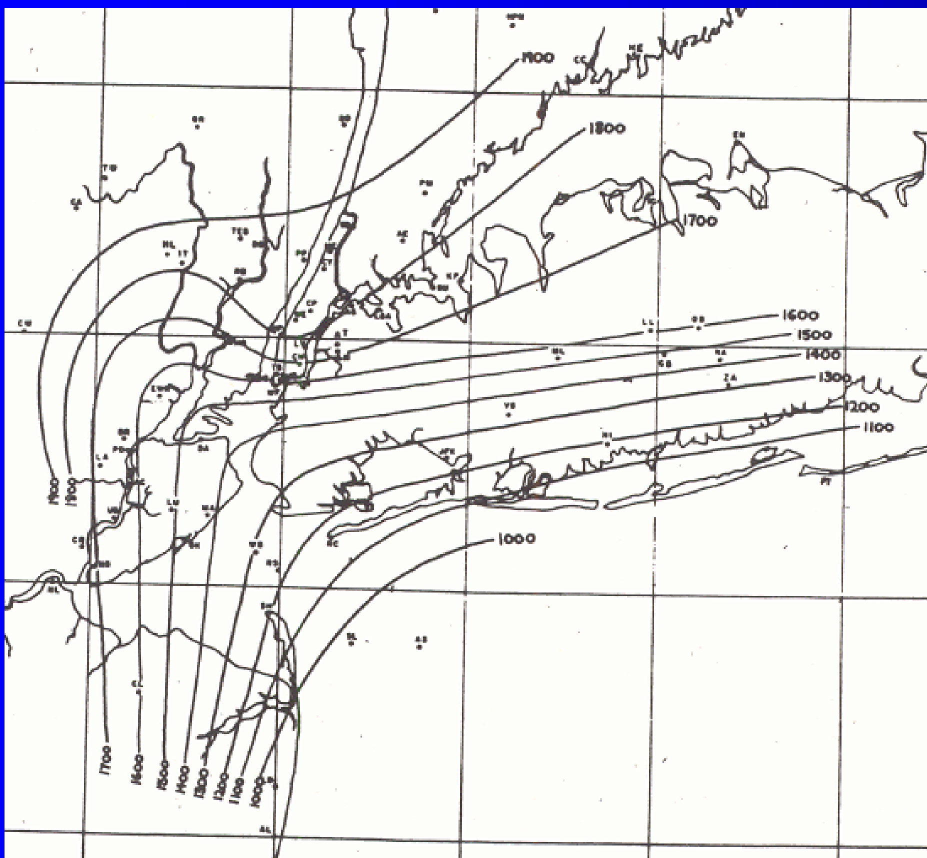


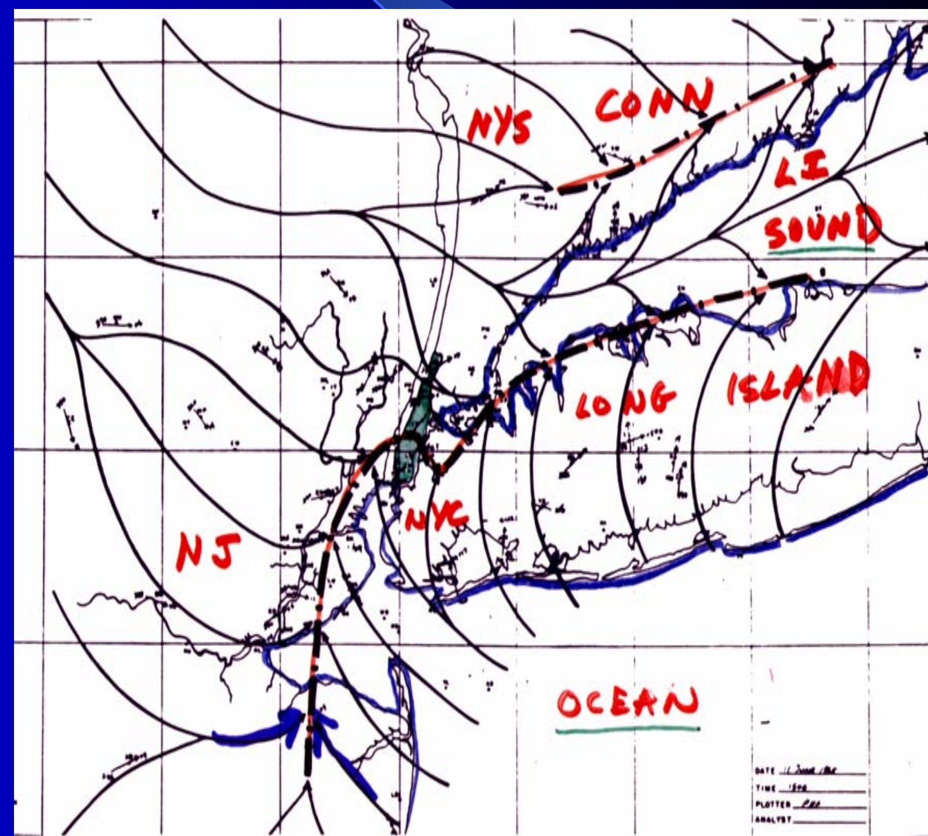


Sea-breeze frontal (S to N) passage over NYC: 9 March 1966

a. hourly positions (left)

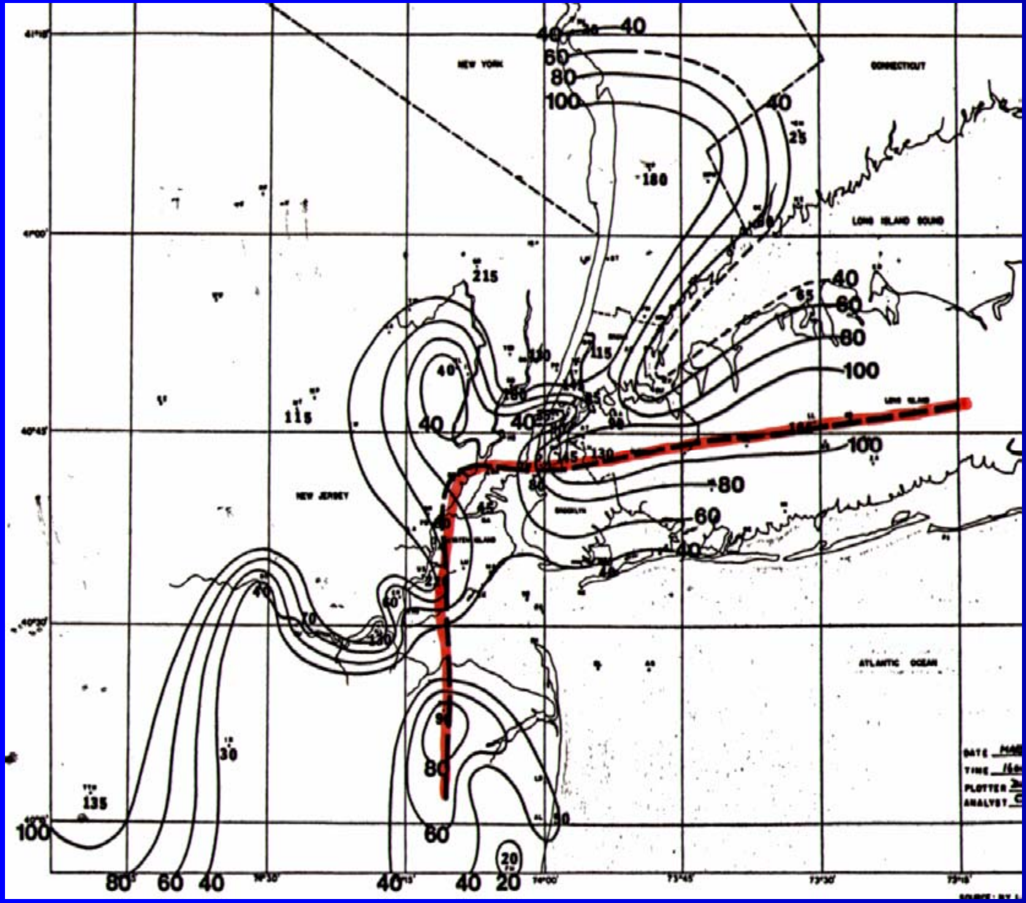
b. 1800 EST (right): note urban-induced retardation area

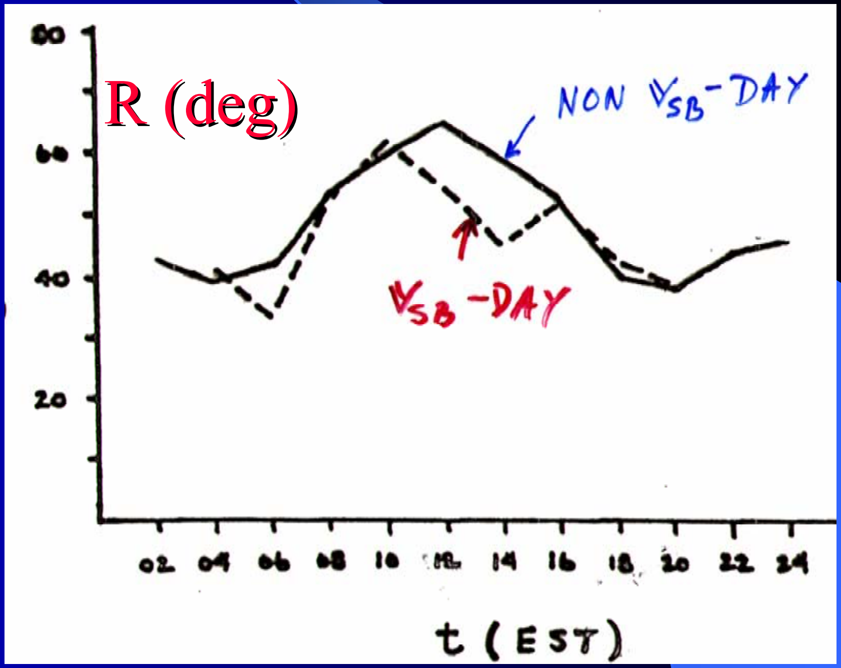




URBAN TURBULENCE DURING A NYC SEA-BREEZE FRONTAL-PASSAGE:

- VALUES HIGH ALONG-FRONT (LEFT)
- AIR STABLE BEHIND-FRONT (RIGHT)





URBAN-EFFECTS ON MOISTURE

- URBAN VAPOR-PRESSURE, e
  - ↓ DUE TO ↓ DAYTIME EVAPORATION
  - ↑ DUE TO ANTHRO-MOSITURE FROM
    - COMBUSTION (WINTER & NIGHTTIME)
    - ↓ NOCTURNAL DEW-FORMATION
- URBAN RH ↓ (AS UHI → ↑e_s)
- URBAN FOG ↑ (EVEN WITH ↑ e_s) DUE TO ↑ HYGROSCOPIC-NUCLEI

URBAN-EFFECTS ON PRECIP

- OTHERWISE-CALM CONDITIONS →
  STRONG UHI → <u>CONVERGENCE</u> →
  PRECIP-MAX OVER URBAN-CENTER
- MOVING REGIONAL STORMS →
  - UPWIND DIVERGENCE →
    PRECIP MIN OVER CITY <u>AND</u>
  - LATERAL/DOWNWIND <u>CONVERGENCE</u> →
    LATERAL AND DOWNWIND PRECIP-MAX
- WEAK REGIONAL WINDS →
  UHI, CONVERGENCE, AND MAX-PRECIP ADVECTED TO DOWNWIND URBAN-EDGE

NYC URBAN EFFECTS ON ρ_v (g/cm^3):

Night (max-sfc urban): UHI, q-island, & RH-deficit

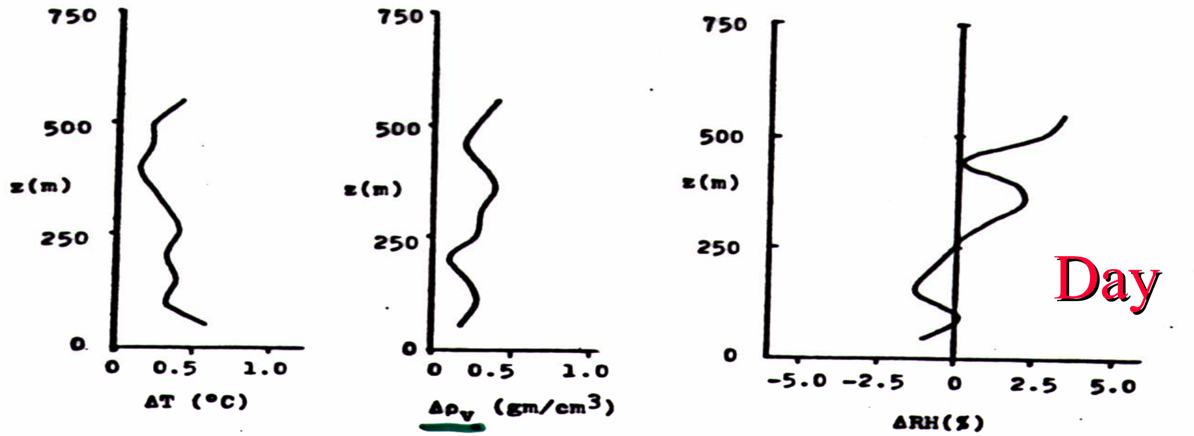


FIG. 5. Composite values of urban minus rural values of temperature, absolute humidity and relative humidity for the midday tests.

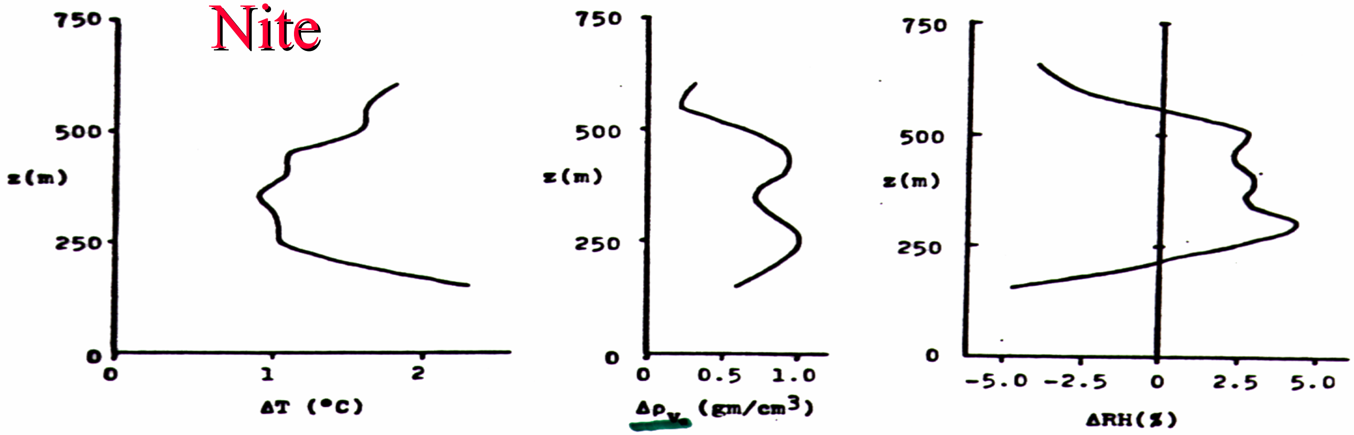


FIG. 6. Same as Figure 5, but for early morning tests.

URBAN IMPACTS ON PRECIP

- AEROSOL MICROPHYSICS
  - SLOW → SECONDARY DOWNWIND-ROLE?
  - METROMEX & D. ROSENFELD
- THERMODYNAMICS
  - LIFTING FROM
    - UHI CONVERGENCE
    - THERMAL & MECHANICAL CONVECTION
  - DIVERGENCE FROM
    - BUILDING-BARRIER EFFECT

Theme 4: SYNTHESIS

- OTHERWISE-CALM CONDITIONS →

  STRONG UHI → CONVERGENCE →

  PRECIP-MAX OVER URBAN-CENTER
- MOVING REGIONAL-STORMS →
  - UPWIND DIVERGENCE →

    PRECIP-MIN OVER CITY AND
  - LATERAL/DOWNWIND CONVERGENCE →

    LATERAL AND DOWNWIND PRECIP-MAX
- WEAK REGIONAL-WINDS →

  UHI, CONVERGENCE, & MAX-PRECIP:
  ALL ADVECTED TO DOWNWIND URBAN-EDGE

Annual-average Shanghai urban-impacts

- On: e, RH, & precip
- Problem: averages are small-Δ b/t 2 large conflicting-impacts
- See next slide

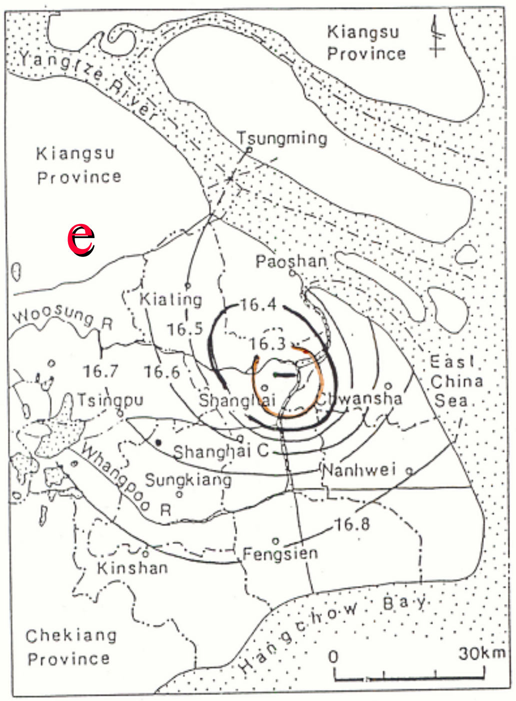


Figure 15. The mean annual humidity (vapour pressure) in Shanghai districts in the period 1961-1980.

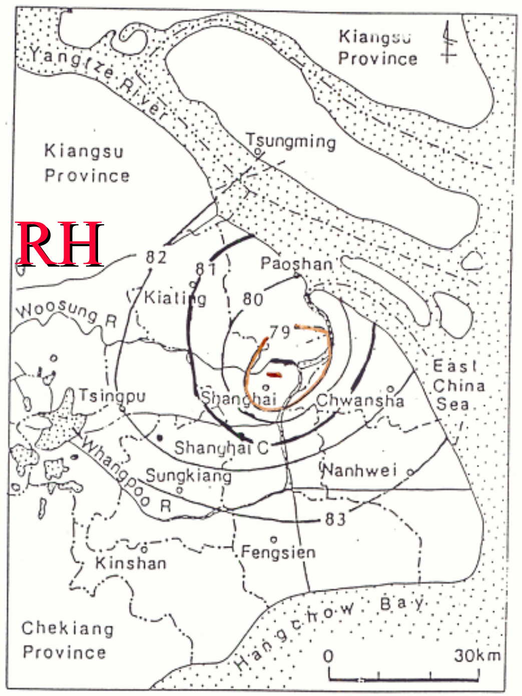


Figure 16. The mean annual relative humidity in Shanghai districts in the period 1961-1980.

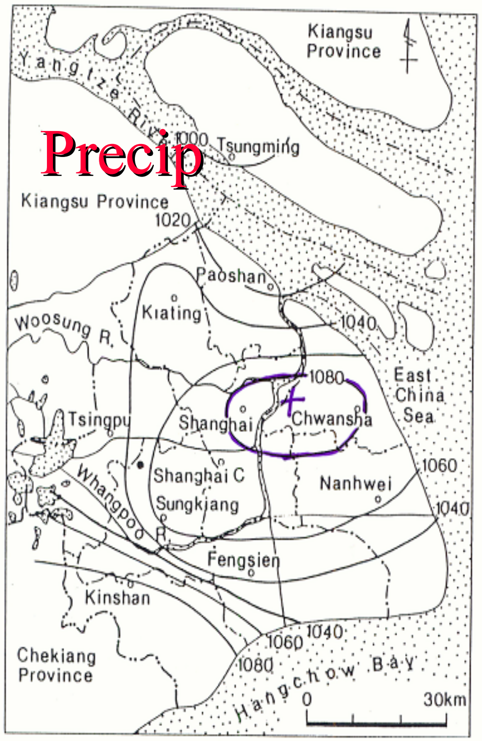
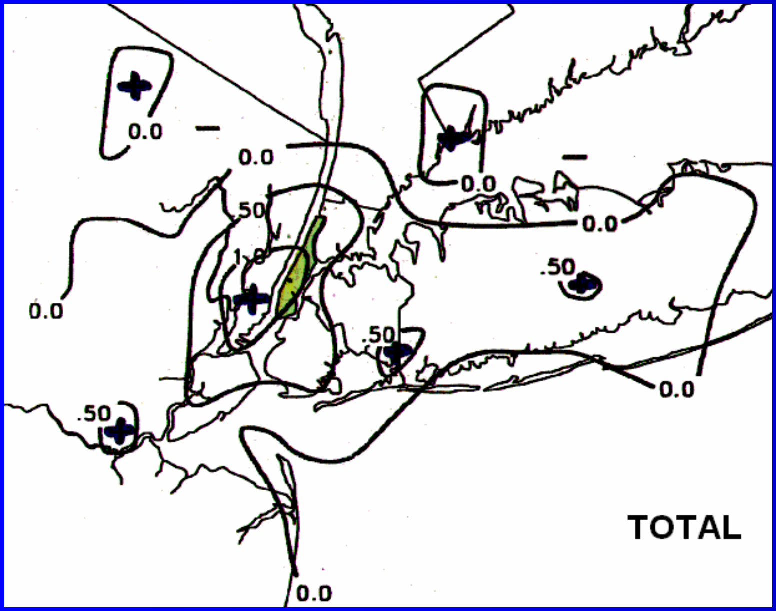
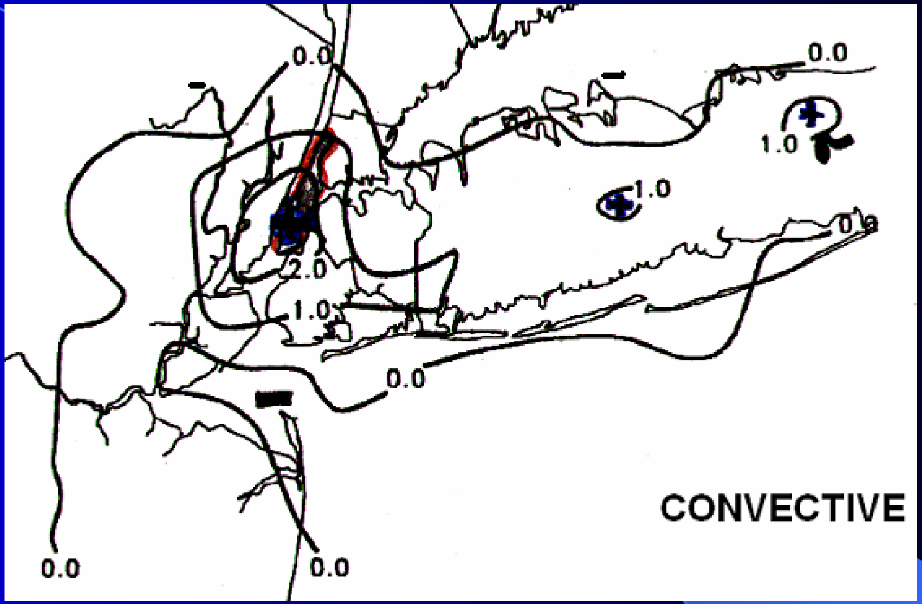
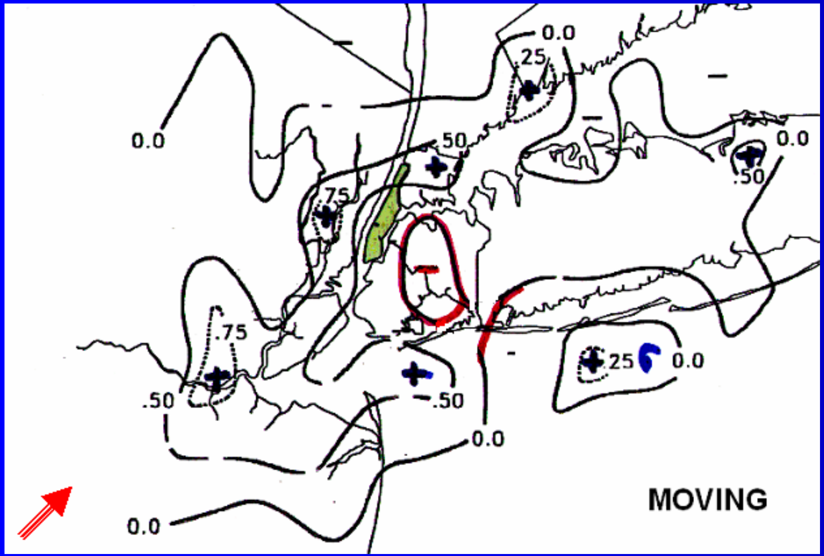


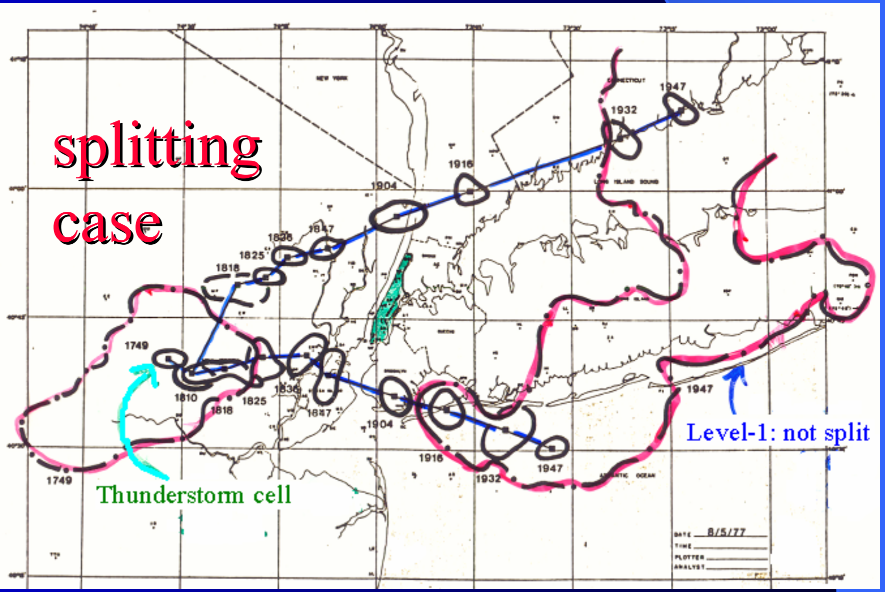
Figure 18. Mean annual precipitation over Shanghai districts (1959-1978).

2-summer daytime-average thunderstorm-precip radar-echos (σ's from uniform-distribution) for all, convective, & moving cases









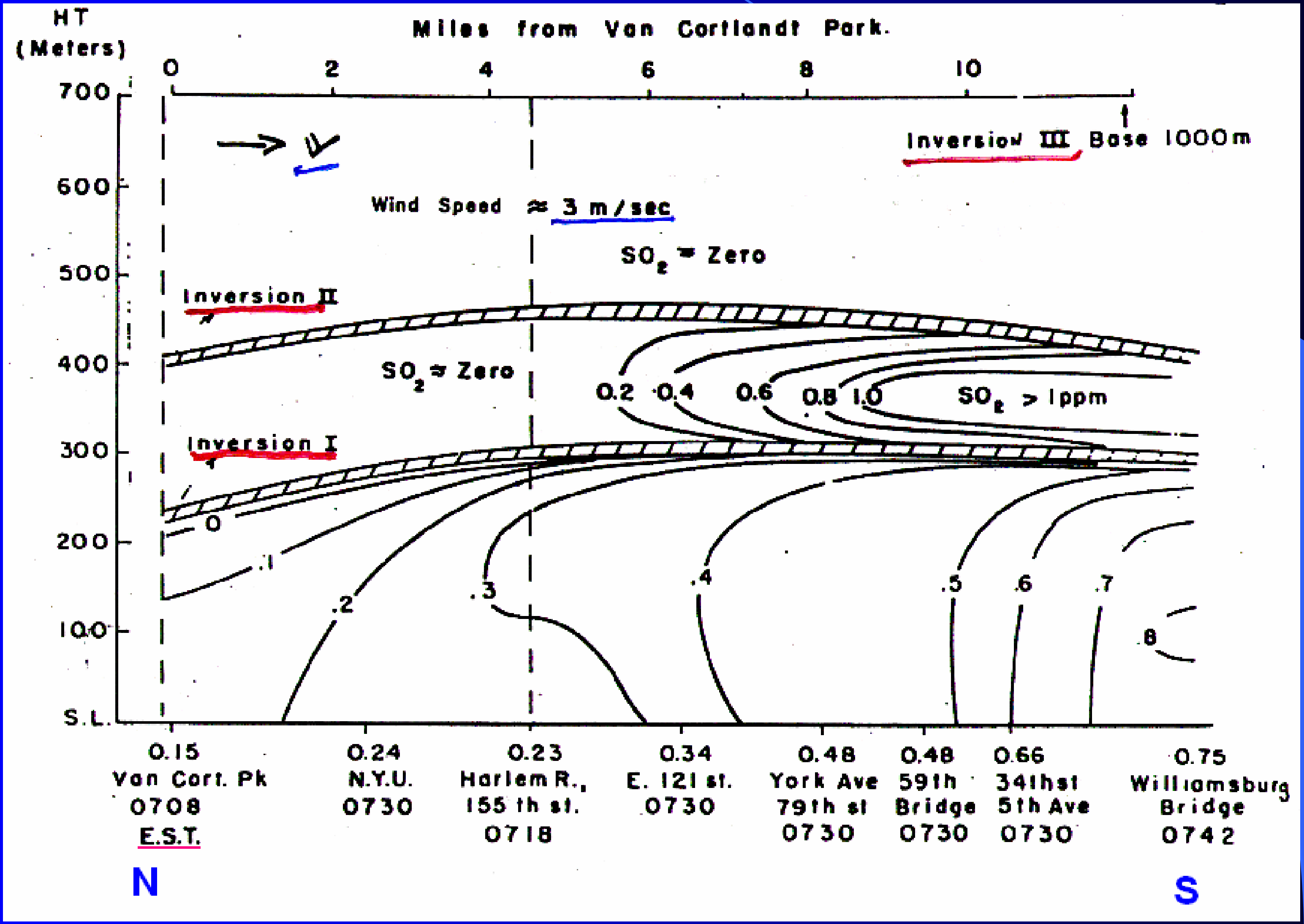
Dispersion effects

- Vertical diffusion: limited by urban-induced elevated-inversions (next slide)
- Urban-park low-concentrations (1 slide)
- Transport: 3-D effects of urban-induced flow-modifications (one slide)
- Convergence-zone high-concentrations: due to
  - Urban area (1 slide)
  - Sea breeze flows (1 slide)

> Urban-induced nocturnal elevated inversion-I traps all area-source Q

> Power-plant plume is trapped b/t urban-induced inversions-I & -II

> Inversion-III is regional-inversion



Source-free Central-Park prevents higher-χ build-up

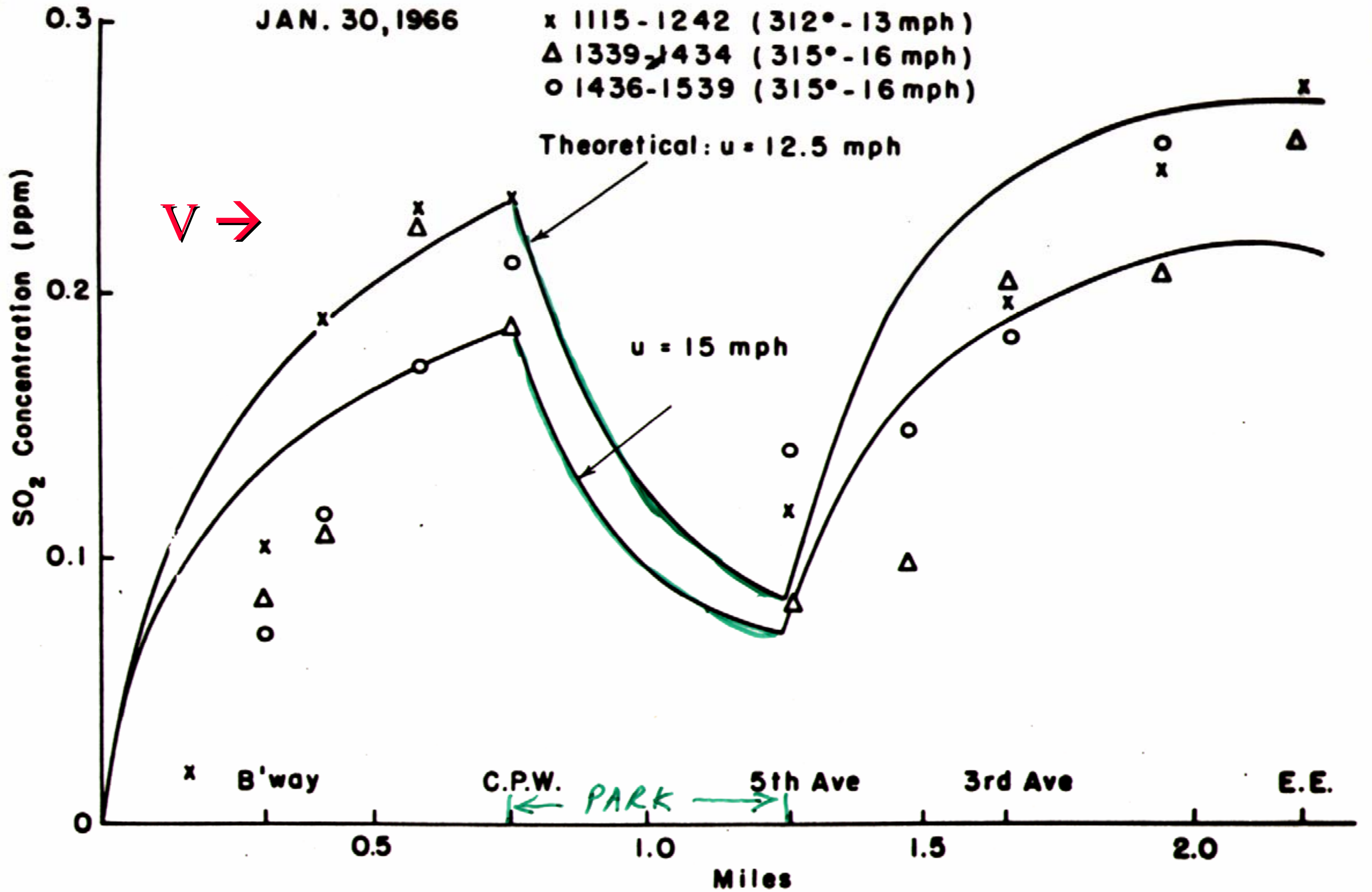
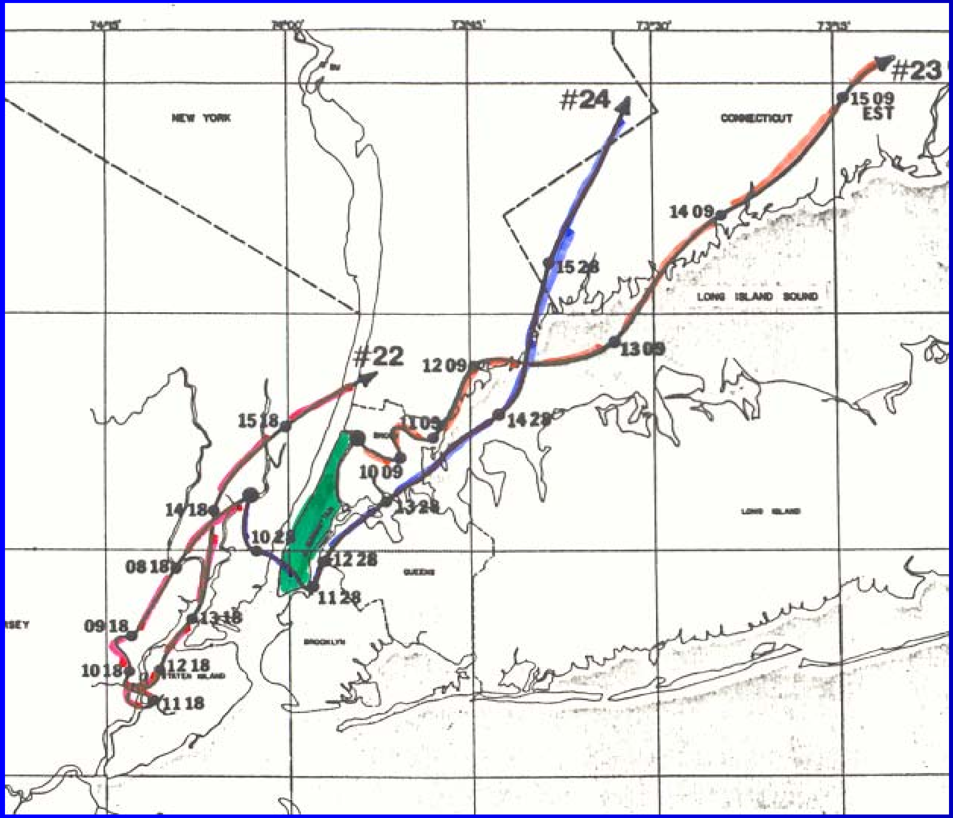


Figure Theoretical computed concentration curves versus observed data along a 79th Street crosstown traverse, in the direction of the mean flow.

Tetroons in sea-breeze flows produce interesting (x, y) and (x, z) trajectories that returns balloon (left) and raises it (right)



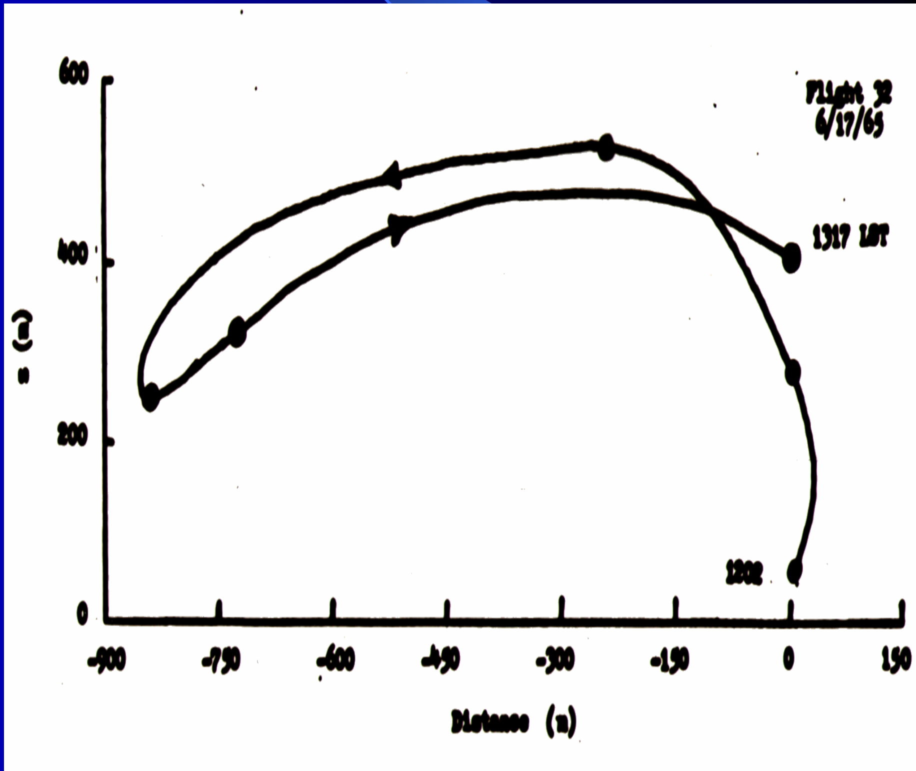
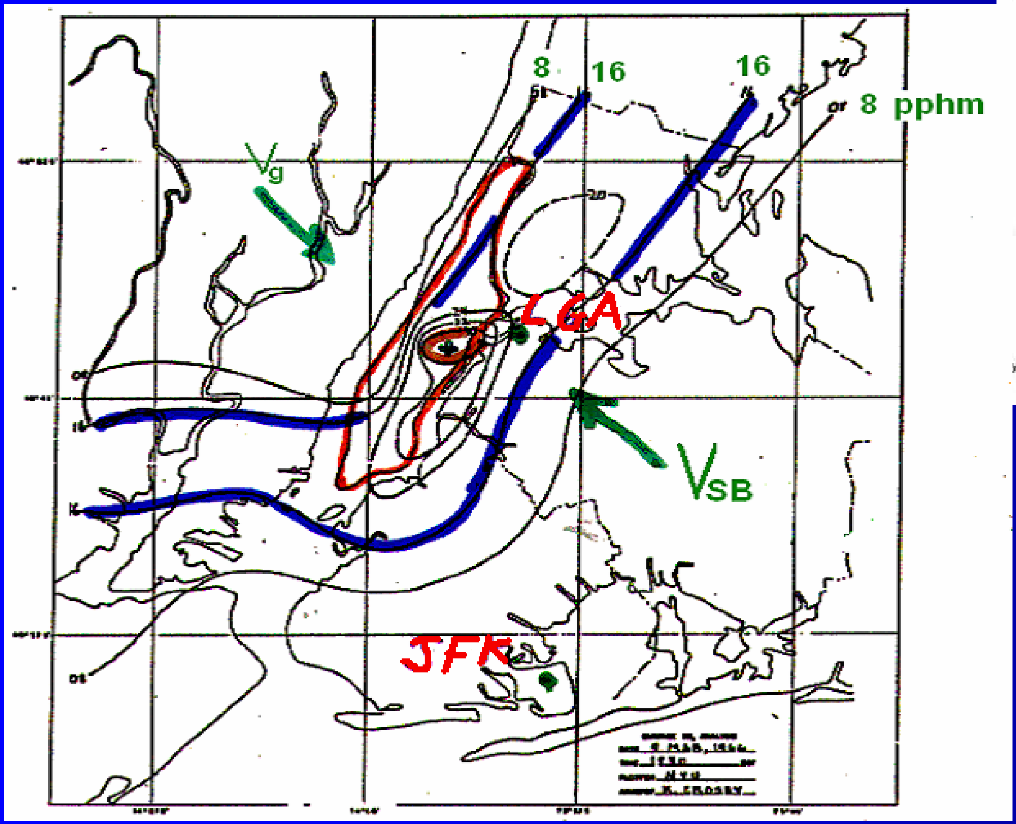
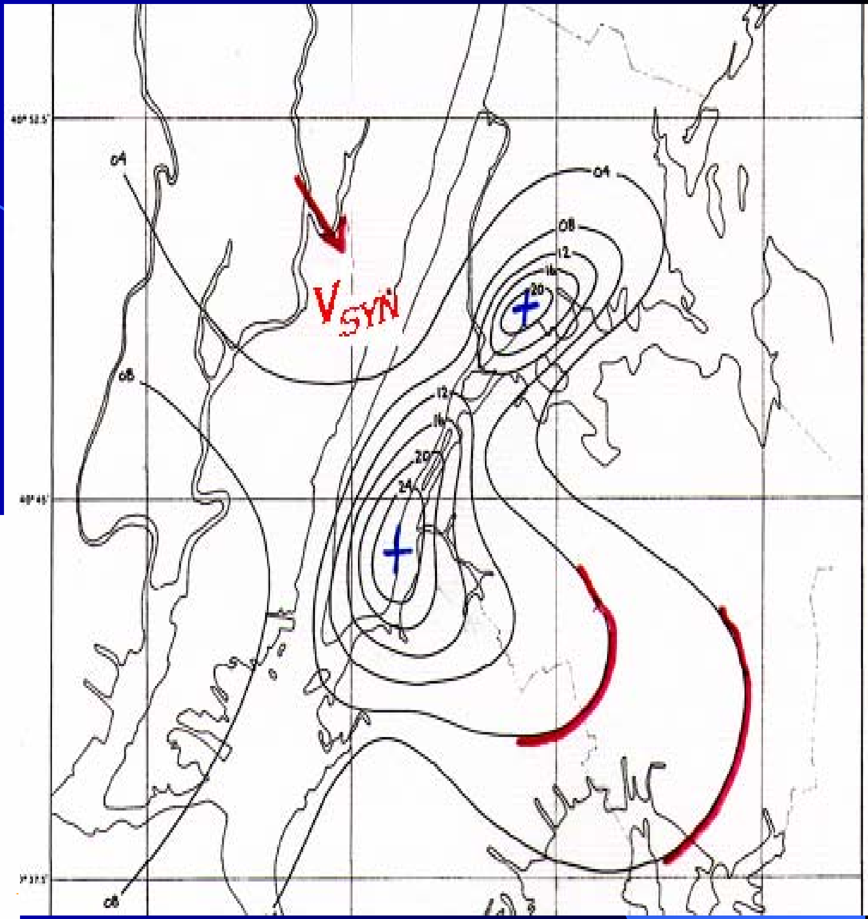


Figure 16. Latitudinal Height Variation.

SEA-BREEZE (SB) EFFECTS ON χ

- AM: synoptic flow pushes it offshore →
- PM> sea breeze flow pushes it onshore & concentrates it w/in narrow conv-zone

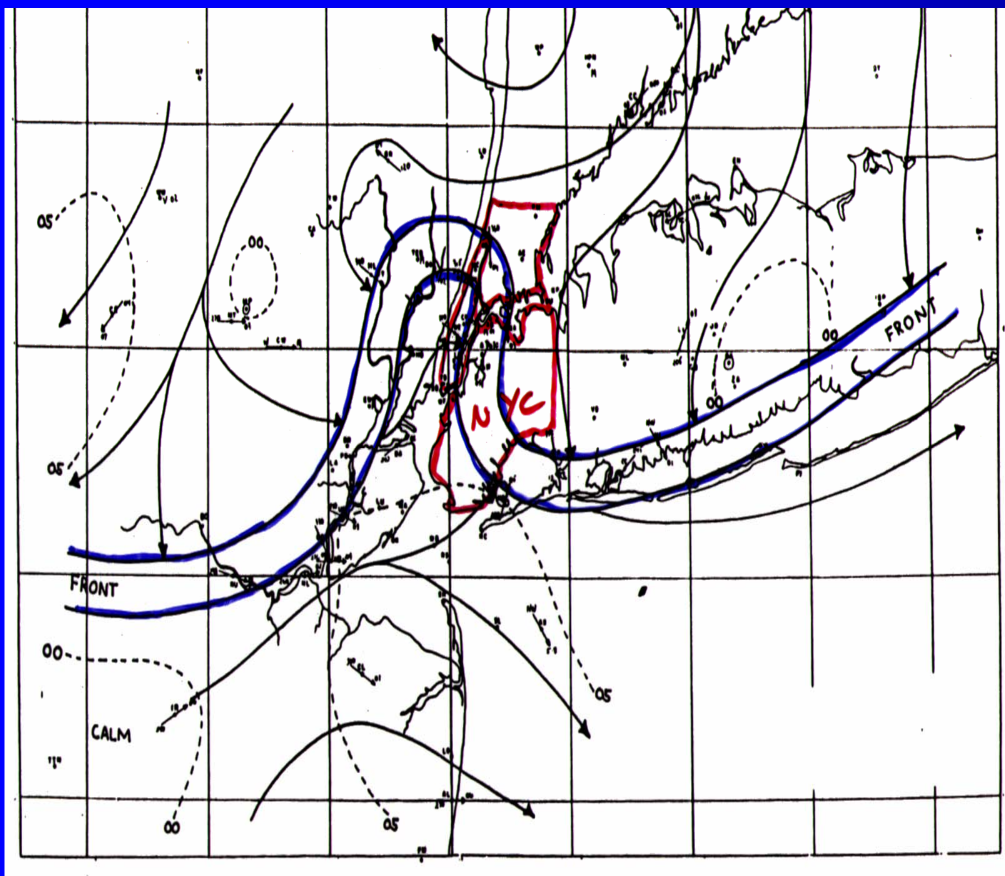


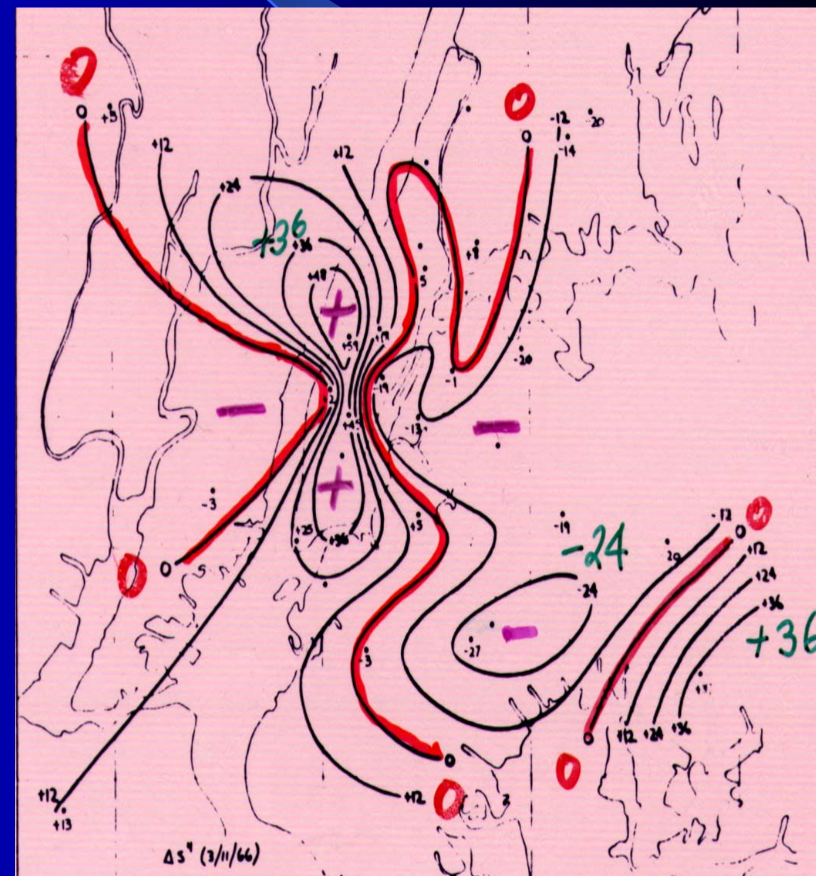


Urban-distorted syn-front (left) results in Δ SO_2 (pphm, right) :

(a)↓outside of city, when front passes

(b)↑over-city, as air not-replaced (front never passes)





Required Research

- Urban field studies: METROMEX, NYU/NYC, URBAN 2000, JOINT URBAN, BUBBLE, UAO04
- Wind-tunnel, fluid, LES, CFD, & DNS models→

  improved urban-canyon parameterizations
- Non-M-O analytical SBL-parameterizations
- GIS urban-inputs
- Links b/t CFD/LES & meso-models

NYC-OBS REFERENCES

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- Born. & Johnson, 1977: *At. Env.*, 11, 597-04
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Any questions?