PBL-Class Seminar-Series
Part 2 of 3:
Meso-scale Atmospheric Models

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Overview:

- Basic meso-met model Eqs., assumptions & approximations
- Coordinates, map projections, grids, numerics
- Parameterizations: turbulence, clouds, radiation
- IC/sBCs: larger-scale met-model linkage
- FDDA (obs & analysis nudgings)
- Applications

Starting Points

- Newton*: a = F/m (all are vector eqs)
- For atm: $\partial V^*/\partial t$ = -adv + F′/m + g' + F_L
- In rotating (x, y, z) Cartesian coordinates (2 new accelerations/forces):
  - $\partial V^*/\partial t$ = -adv + F′/m + g' + F_L + Co + Ce
  - Where Co has 4 non-zero components (2 horix & 2 vert)
- Assume:
  - g = g' + Ce
  - F_L is ignored
  - Tangent-plane coordinates (for now)→ earth-curvature ignored
- Result: $\partial V^*/\partial t$ = -adv + F′/m + g + Co
- *100 most influential: Mohamed, Newton, Jesus, John...

Reynolds (R.) Averaged Equations

- If: mesoscale energy-gap (diurnal-scale eddies) exists (?) b/t
  - Large eddies (synoptic-scale waves)
  - Small eddies (turbulence)
- Then: can R.-decompose all variables
  - $A^* = A + A'$ (instantaneous = mean + turbulent)
  - A is freq written $(\overline{\ })$
  - $(\overline{\ })$ is average over a Δt (& ΔVol in models)
- Thus: R.-average each Eq. (mV, heat,…) →
  - $\partial V/\partial t = -\text{adv} + F'/m + g + \text{Co} - V'V'$ [all terms have $(\overline{\ })$]
  - where $v'v'$ is effect of turbulence (from adv term) on V (a frictional drag); term must be "closed"

R.-averaged Navier-Stokes Eqs. in comp.-from (where D ( )/Dt = local + adv deriv; F is eddy-effects)

1) *Horizontal Momentum:*

$$\frac{Du}{Dt} = -\frac{1}{\rho}\frac{\partial p}{\partial x} + 2\Omega\, v \sin\phi - 2\Omega\, w \cos\phi + F_x$$

$$\frac{Dv}{Dt} = -\frac{1}{\rho}\frac{\partial p}{\partial y} - 2\Omega\, u \sin\phi + F_y$$

2) *Vertical Momentum:*

$$\frac{Dw}{Dt} = -\frac{1}{\rho}\frac{\partial p}{\partial z} - g + 2\Omega\, u \cos\phi + F_z$$

Eqs. (cont.)

3) *Temperature (error: DT/Dt→ ∂T/∂t):*

$$\frac{DT}{Dt} = -V \bullet \nabla T + \frac{1}{\rho c_p}\left(\frac{\partial p}{\partial t} + V \bullet \nabla p - \rho_0 g w\right) + \frac{\dot{Q}}{c_p} + \frac{T_0}{\theta_0} D_\theta$$

4) *Pressure:*

$$\frac{\partial p}{\partial t} - \rho_0 g w + \gamma p \nabla \bullet V = -V \bullet \nabla p + \frac{\gamma p}{T}\left(\frac{\dot{Q}}{c_p} + \frac{T_0}{\theta_0} D_\theta\right)$$

But model uses σ -transformed Eqs., where tranformed vertical-coordinate & horiz-derivatives are defined, respectively, by

$$\sigma = \frac{p_0 - p_t}{p_s - p_t} = \frac{p_0 - p_t}{p^*} \quad and \qquad \left(\frac{\partial}{\partial x}\right)_z \rightarrow \left(\frac{\partial}{\partial x}\right)_\sigma - \frac{\sigma}{p^*}\frac{\partial p^*}{\partial x}\frac{\partial}{\partial \sigma}$$

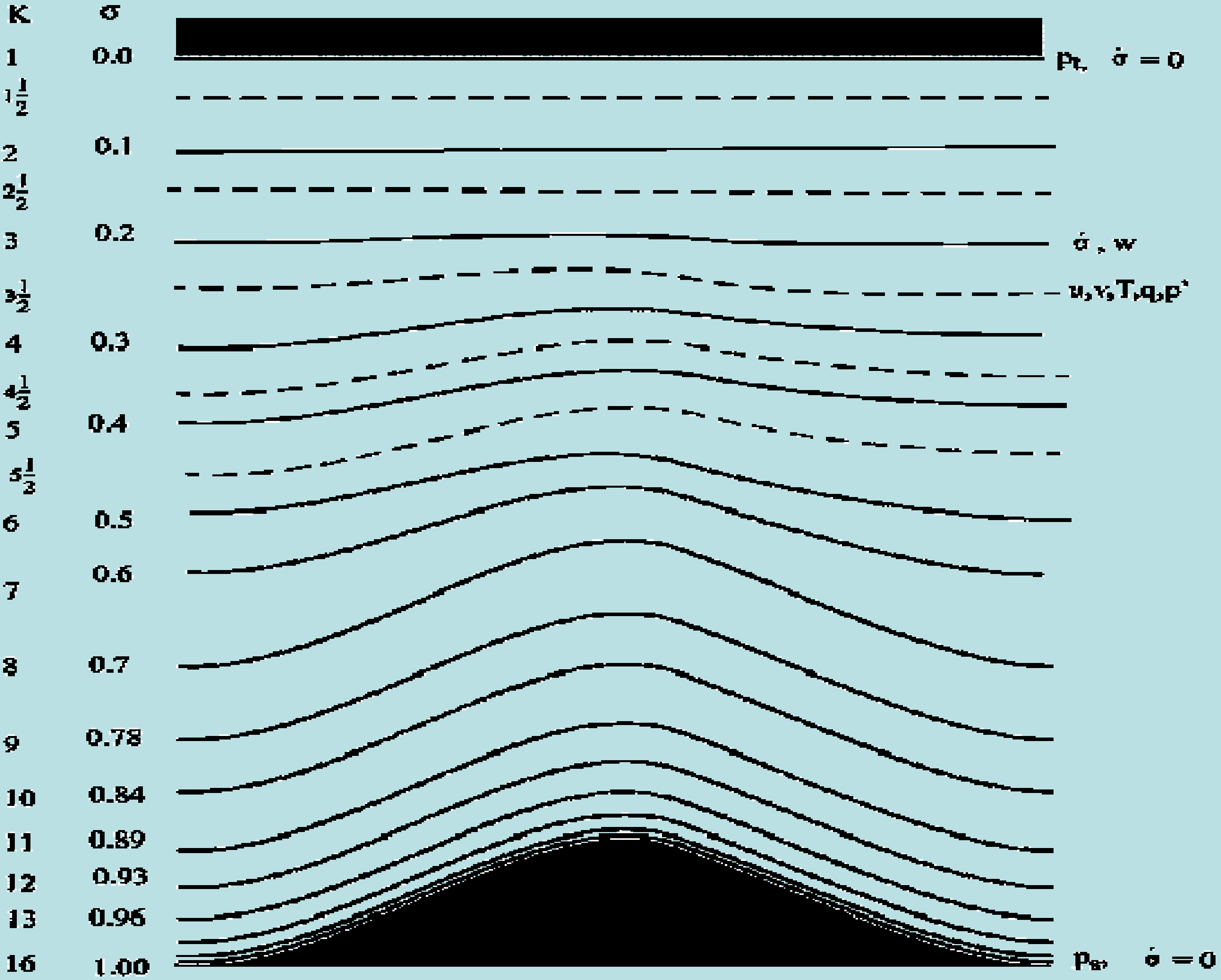
Coordinate transformations

Many varieties possible [Pielke (2002) text]

- Can be in terms of z, p (or σ), θ
- Some intercept terrain-features, some go over them
- Some follow terrain at all-levels, some become flat at model-top
- Some are normalized, e.g., by top-value → coordinate-heights are b/t 0 & 1
- Some are "scaled", e.g., by terrain height → coordinate-heights are fraction of "scale"
- MM5 coordinates: next slide

MM5 σ-coordinates (used at SJSU)

- A normalized (or relative) p-coordinate
- Not a scaled-coordinate
- Called terrain following, but
- Is terrain influenced, as
  - Surface σ-level follows terrain
  - But σ-level at model- top is flat
- Most models claim to be terrain-following, but they are really terrain-influenced (Theme 1)
- Real terrain-following models have only simple equations with no terrain-correction terms



Schematic representation of σ-coordinates in MM5

Hierarchy of topography-assumptions

- In German Ph.D. dissertation by Becker
- Hierarchy-concept from Mellor & Yamada ('74)
- Levels
  - Level 4: (best): all terrain-h terms included
  - Level 3: $(\partial^2 h/\partial x^2) = 0$
  - Level 2: $(\partial^2 h/\partial x^2) = (\partial h/\partial x)^2 = 0$
  - Level 1: $(\partial h/\partial x) = 0$ (worst, true terrain-following)
- MM5, RAMS, ARPS, WRF, etc. are Level 2 → problems in steep-terrain (Theme 2)

Map Projection: Required on Spherical-Earth

- Drop tangent-plane assumption
- Isometric vs Conformal (MM5's choice)
- Map scale factor defined

$$m = \frac{dis\tan ce\ on\ the\ projection}{dis\tan ce\ on\ the\ sphere}$$

- Polar stereographic vs Mercator Cylindrical vs Lambert Conical, with

$$r = r_0\left[\tan\left(\frac{\pi}{4} - \frac{\varphi}{2}\right)\right]^k \quad , \quad \theta = K(\lambda - \lambda_0)$$

- The constants r_0 and K make the projection "true" at $\varphi_1\ and\ \varphi_2$

  so that $r = (a/K)\ m(\varphi)\cos\varphi$

Map Projection (cont.)

where map scale factor m and constant K are given by

$$m(\varphi) = \left(\frac{\cos \varphi}{\cos \varphi_1} \right)^{(K-1)} \left(\frac{1 + \sin \varphi_1}{1 + \sin \varphi} \right)^{K}$$

$$K = \ell n \left(\frac{\cos \varphi}{\cos \varphi_1} \right) \div \ell n \left\{ \frac{\tan \left[(\pi/4) - (\varphi_1/2) \right]}{\tan \left[(\pi/4) - (\varphi_2/2) \right]} \right\}$$

Transformed-projected Eqs. (in J-papers):

1) *Horizontal momentum*

$$\frac{\partial p^* u}{\partial t} = -m^2 \left[\frac{\partial p^* uu/m}{\partial x} + \frac{\partial p^* vu/m}{\partial y} \right] - \frac{\partial p^* u \dot{\sigma}}{\partial \sigma}$$

$$+ uDIV - \frac{mp^*}{\rho} \left[\frac{\partial p'}{\partial x} - \frac{\sigma}{p^*} \frac{\partial p^*}{\partial x} \frac{\partial p'}{\partial \sigma} \right]$$

$$+ p^* fv - p^* ew \cos \theta + D_u$$

$$\frac{\partial p^* v}{\partial t} = -m^2 \left[\frac{\partial p^* uv/m}{\partial x} + \frac{\partial p^* vv/m}{\partial y} \right] - \frac{\partial p^* v \dot{\sigma}}{\partial \sigma}$$

$$+ vDIV - \frac{mp^*}{\rho} \left[\frac{\partial p'}{\partial y} - \frac{\sigma}{p^*} \frac{\partial p^*}{\partial y} \frac{\partial p'}{\partial \sigma} \right]$$

$$- p^* fu + p^* ew \sin \theta + D_v$$

Transformed-projected eqs. (p 2 of 3)

2) *Vertical momentum*

$$\frac{\partial p^{*} w}{\partial t} = -m^{2}\left[\frac{\partial p^{*} uw/m}{\partial x} + \frac{\partial p^{*} vw/m}{\partial y}\right] - \frac{\partial p^{*} w\dot{\sigma}}{\partial \sigma}$$

$$+\, wDIV \quad + p^{*} g\,\frac{\rho_{0}}{\rho}\left[\frac{1}{p^{*}}\frac{\partial p'}{\partial \sigma} + \frac{T_{v}'}{T} - \frac{T_{0}\,p'}{T p_{0}}\right]$$

$$-\, p^{*} g\left[\left(q_{c} - q_{r}\right)\right] + p^{*} e\left(u\cos\theta - v\sin\theta\right) + D_{w}$$

3) *Pressure*

$$\frac{\partial p^{*} p'}{\partial t} = -m^{2}\left[\frac{\partial p^{*} up'/m}{\partial x} + \frac{\partial p^{*} vp'/m}{\partial y}\right] - \frac{\partial p^{*} p'\dot{\sigma}}{\partial \sigma} + p'DIV$$

$$-\, m^{2} p^{*}\gamma p\left[\frac{\partial u/m}{\partial x} - \frac{\sigma}{mp^{*}}\frac{\partial p^{*}}{\partial x}\frac{\partial u}{\partial \sigma} + \frac{\partial v/m}{\partial y} - \frac{\sigma}{mp^{*}}\frac{\partial p^{*}}{\partial y}\frac{\partial v}{\partial \sigma}\right]$$

$$+\, \rho_{0} g\gamma p\,\frac{\partial w}{\partial \sigma} + p^{*}\rho_{0} g w$$

Transformed-projected Eqs.

4) *Temperature*

$$\frac{\partial p^* T}{\partial t} = -m^2 \left[\frac{\partial p^* u T / m}{\partial x} + \frac{\partial p^* v T / m}{\partial y} \right] - \frac{\partial p^* T \dot{\sigma}}{\partial \sigma} + T\, DIV$$

$$+ \frac{1}{\rho c_p} \left[p^* \frac{Dp'}{Dt} - p^* \rho_0 g w - D_{p'} \right] + p^* \frac{\dot{Q}}{c_p} + D_T$$

where,

$$DIV = m^2 \left[\frac{\partial p^* u / m}{\partial x} + \frac{\partial p^* v / m}{\partial y} \right] + \frac{\partial p^* \dot{\sigma}}{\partial \sigma}$$

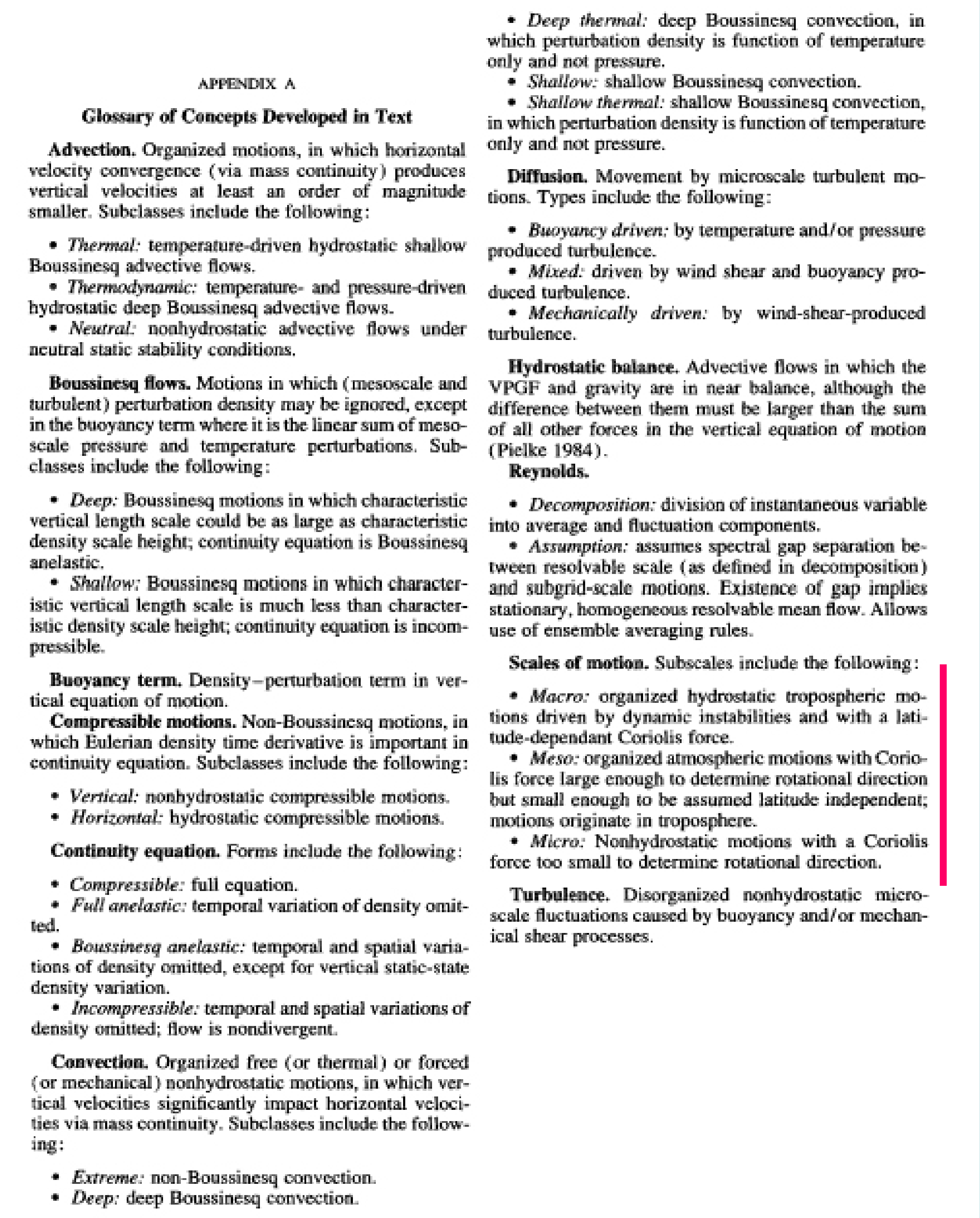
$$\dot{\sigma} = -\frac{\rho_0 g}{p^*} w - \frac{m\sigma}{p^*} \frac{\partial p^*}{\partial x} u - \frac{m\sigma}{p^*} \frac{\partial p^*}{\partial y} v$$

Hierarchy of meso-met models

- From Thunis & Bornstein (1996) for all [including non-Boussinesq (B.)] flows
- Hierarchy concept again from Mellor & Yamada (‘74)
- Follows scale-analyses of
  - Spiegel & Veronis (’60) for shallow B.-flow
  - Dutton & Fichtl (’69) for deep B.-flow
  - Mahrt (’86) for neutral-stability flow

Glossary (more in T & B)

- Need to speak same-language:
  within each discipline & b/t disciplines
- e.g., from air pollution
  - dispersion vs. diffusion
  - dispersion = transport by V + diffusion by V'
- e.g. from heat-flow re convection
  - engineers: if you heat it & it moves
  - meteorologists: w → V
- e.g., from meteor
  - advection: V → w
  - Mixing layer (daytime) vs. mixed layer (nocturnal residual layer)



APPENDIX A

Glossary of Concepts Developed in Text

Advection. Organized motions, in which horizontal velocity convergence (via mass continuity) produces vertical velocities at least an order of magnitude smaller. Subclasses include the following:

- *Thermal:* temperature-driven hydrostatic shallow Boussinesq advective flows.
- *Thermodynamic:* temperature- and pressure-driven hydrostatic deep Boussinesq advective flows.
- *Neutral:* nonhydrostatic advective flows under neutral static stability conditions.

Boussinesq flows. Motions in which (mesoscale and turbulent) perturbation density may be ignored, except in the buoyancy term where it is the linear sum of mesoscale pressure and temperature perturbations. Subclasses include the following:

- *Deep:* Boussinesq motions in which characteristic vertical length scale could be as large as characteristic density scale height; continuity equation is Boussinesq anelastic.
- *Shallow:* Boussinesq motions in which characteristic vertical length scale is much less than characteristic density scale height; continuity equation is incompressible.

Buoyancy term. Density–perturbation term in vertical equation of motion.

Compressible motions. Non-Boussinesq motions, in which Eulerian density time derivative is important in continuity equation. Subclasses include the following:

- *Vertical:* nonhydrostatic compressible motions.
- *Horizontal:* hydrostatic compressible motions.

Continuity equation. Forms include the following:

- *Compressible:* full equation.
- *Full anelastic:* temporal variation of density omitted.
- *Boussinesq anelastic:* temporal and spatial variations of density omitted, except for vertical static-state density variation.
- *Incompressible:* temporal and spatial variations of density omitted; flow is nondivergent.

Convection. Organized free (or thermal) or forced (or mechanical) nonhydrostatic motions, in which vertical velocities significantly impact horizontal velocities via mass continuity. Subclasses include the following:

- *Extreme:* non-Boussinesq convection.
- *Deep:* deep Boussinesq convection.
- *Deep thermal:* deep Boussinesq convection, in which perturbation density is function of temperature only and not pressure.
- *Shallow:* shallow Boussinesq convection.
- *Shallow thermal:* shallow Boussinesq convection, in which perturbation density is function of temperature only and not pressure.

Diffusion. Movement by microscale turbulent motions. Types include the following:

- *Buoyancy driven:* by temperature and/or pressure produced turbulence.
- *Mixed:* driven by wind shear and buoyancy produced turbulence.
- *Mechanically driven:* by wind-shear-produced turbulence.

Hydrostatic balance. Advective flows in which the VPGF and gravity are in near balance, although the difference between them must be larger than the sum of all other forces in the vertical equation of motion (Pielke 1984).

Reynolds.

- *Decomposition:* division of instantaneous variable into average and fluctuation components.
- *Assumption:* assumes spectral gap separation between resolvable scale (as defined in decomposition) and subgrid-scale motions. Existence of gap implies stationary, homogeneous resolvable mean flow. Allows use of ensemble averaging rules.

Scales of motion. Subscales include the following:

- *Macro:* organized hydrostatic tropospheric motions driven by dynamic instabilities and with a latitude-dependant Coriolis force.
- *Meso:* organized atmospheric motions with Coriolis force large enough to determine rotational direction but small enough to be assumed latitude independent; motions originate in troposphere.
- *Micro:* Nonhydrostatic motions with a Coriolis force too small to determine rotational direction.

Turbulence. Disorganized nonhydrostatic microscale fluctuations caused by buoyancy and/or mechanical shear processes.

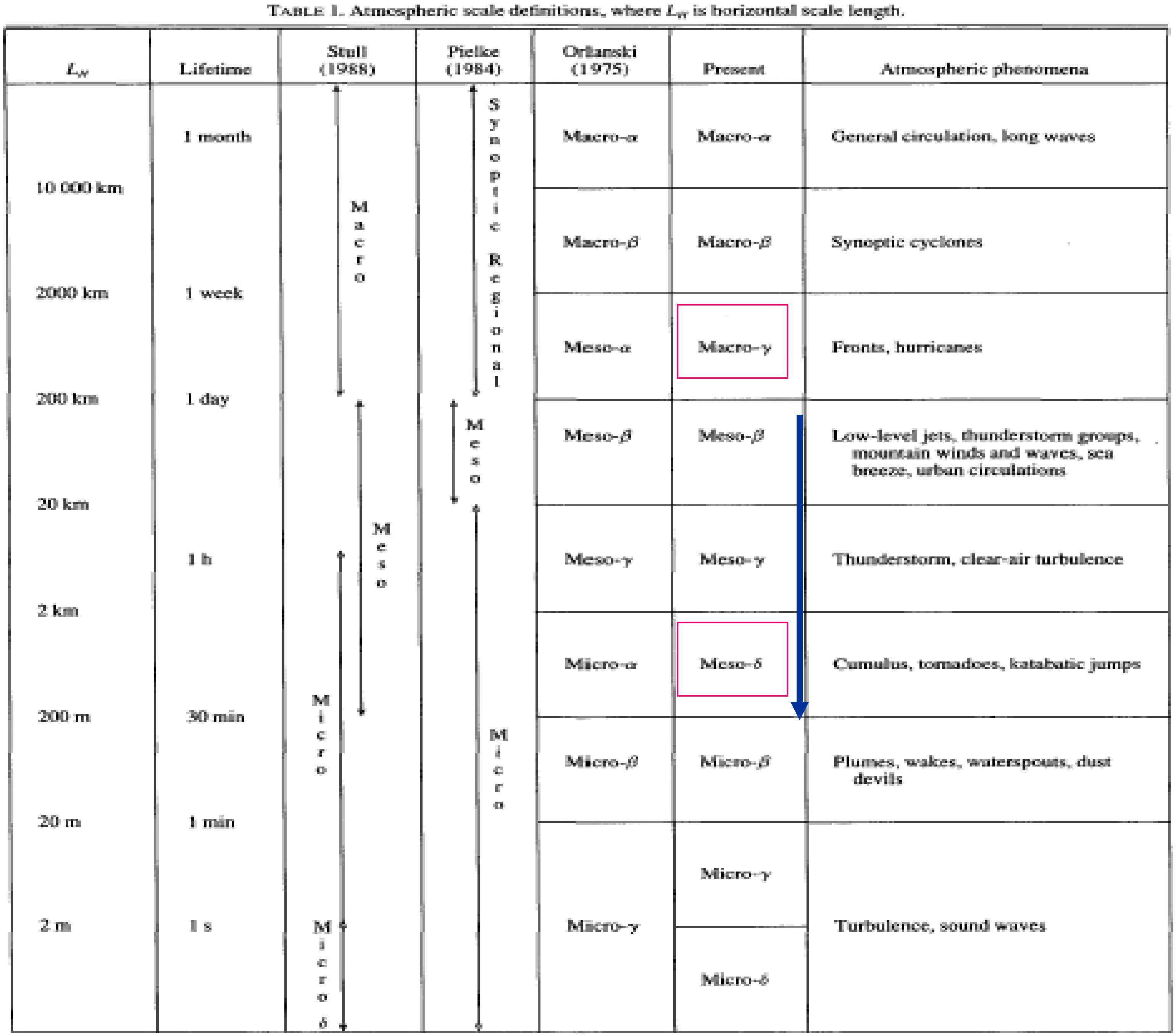


TABLE 1. Atmospheric scale definitions, where L_H is horizontal scale length.

L_H	Lifetime	Stull (1988)	Pielke (1984)	Orlanski (1975)	Present	Atmospheric phenomena
10 000 km	1 month	Macro	Synoptic Regional	Macro-α	Macro-α	General circulation, long waves
2000 km	1 week			Macro-β	Macro-β	Synoptic cyclones
200 km	1 day			Meso-α	Macro-γ	Fronts, hurricanes
20 km		Meso	Meso	Meso-β	Meso-β	Low-level jets, thunderstorm groups, mountain winds and waves, sea breeze, urban circulations
2 km	1 h	Micro	Micro	Meso-γ	Meso-γ	Thunderstorm, clear-air turbulence
200 m	30 min			Micro-α	Meso-δ	Cumulus, tornadoes, katabatic jumps
20 m	1 min			Micro-β	Micro-β	Plumes, wakes, waterspouts, dust devils
2 m	1 s			Micro-γ	Micro-γ	Turbulence, sound waves
		Micro δ			Micro-δ	

Hydrostatic

- Hydrostatic Eq.: VPGF = g
- Hydrostatic assumption
  - Does not say:
    - VPGF & g exactly-balance
    - all other w-eq forces are so small, they can be ignored
  - If VPGF & g did exactly-balance: other-forces (no matter how-small) would determine-w
  - It does say: VPGF minus g is small, but still larger than other forces, so they can be ignored

Boussinesq (B.) Flows

- All B.-flows
  - ρ' can be ignored in all terms, except in buoyancy term, where it is given by linearized Ideal Gas Law
  - $\rho'/\rho = -T'/T + p'/p$ (1)
- Types
  - – Deep: motions with z length-scale ~ to ρ scale-height (~ 8 km); Eq. (1) holds
  - – Shallow: motions with z length-scale << than ρ scale-height (~ 8 km); last term in Eq. (1) is dropped
- Summary (in Thunis & B.): next 5 slides

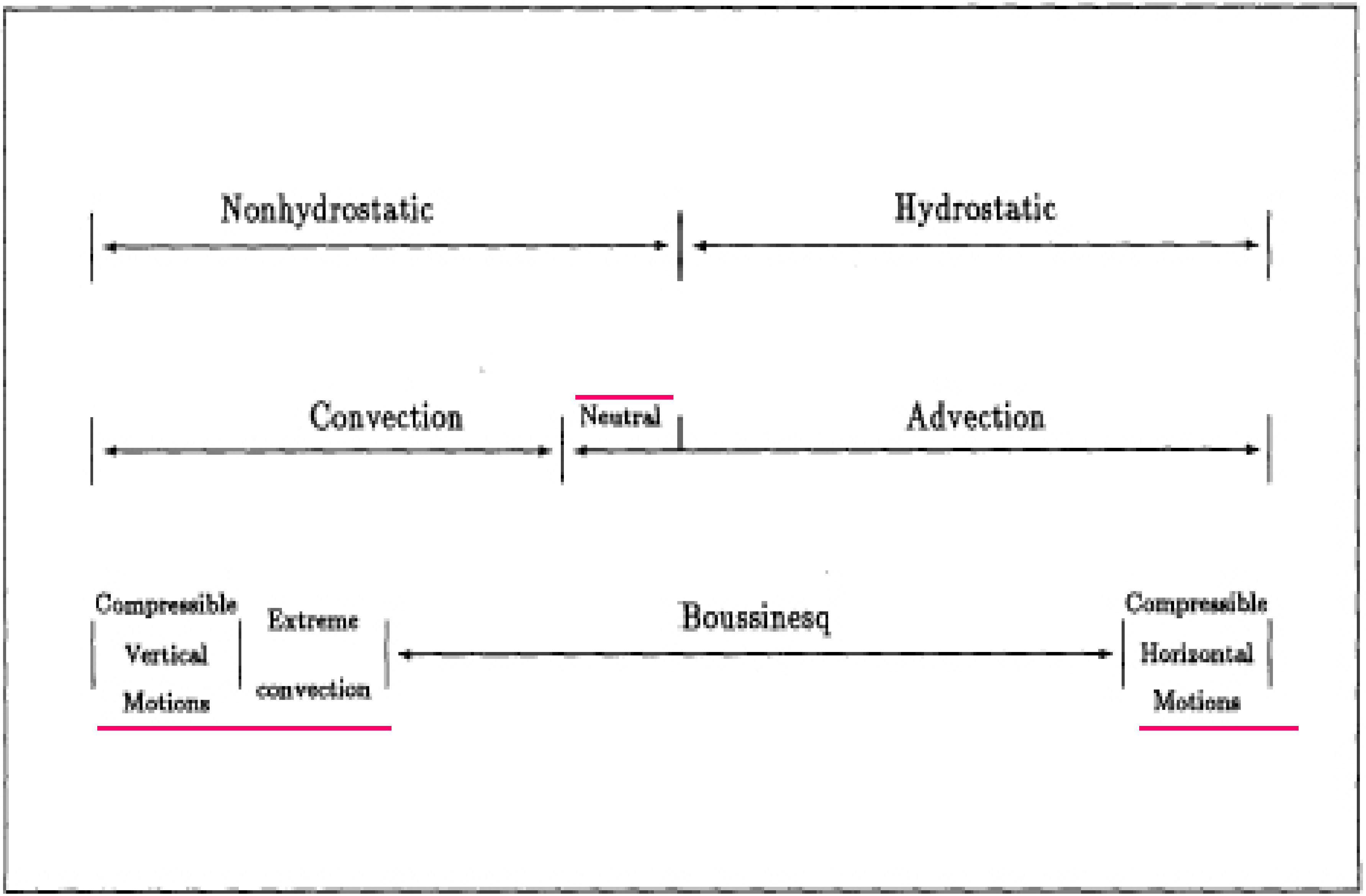
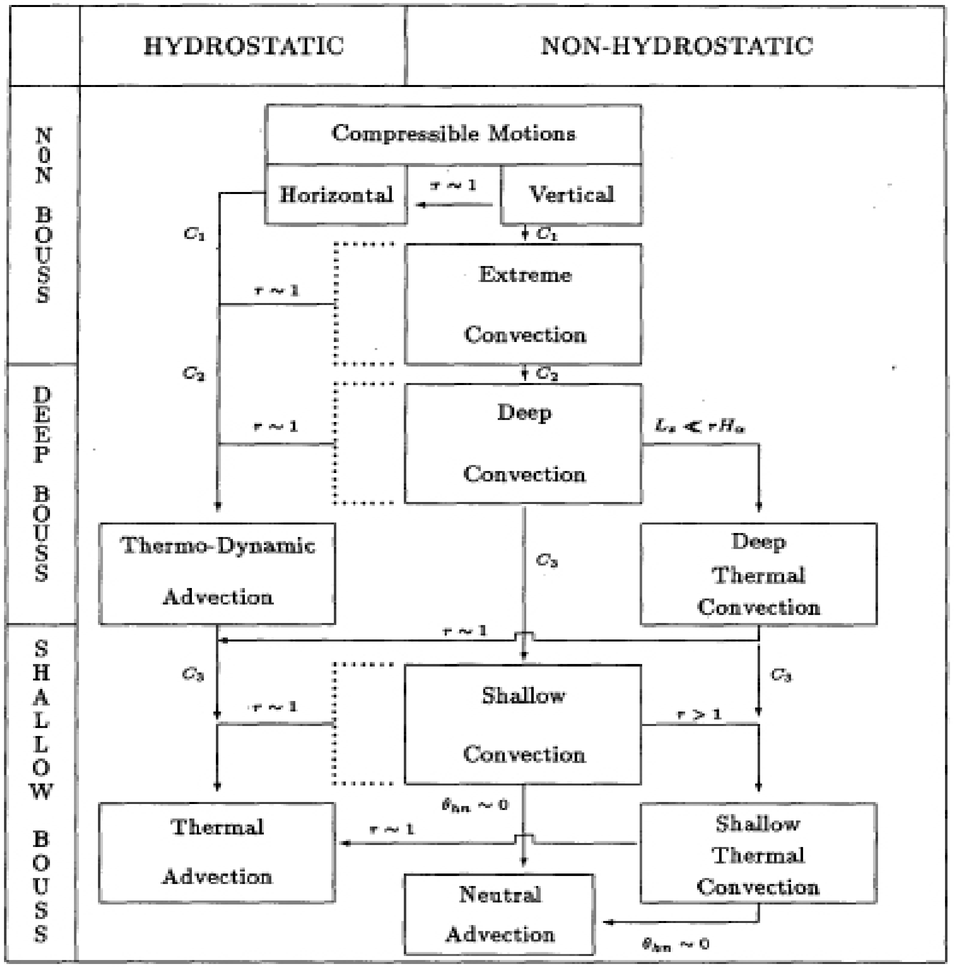


FIG. 1. Schematic of basic flow subclasses and assumptions.



			Text Eqs.
CRITERIA	C_1	$\tau \gg \frac{\alpha_M}{\alpha_s}\left[\frac{L_H}{V_H}, \frac{L_z}{W}, \frac{H_\alpha}{W}\right]_{min}$	(25)
	C_2	$\tau \gg \frac{\alpha_M}{\alpha_s}\left[\frac{L_H}{V_H}, \frac{L_z}{W}\right]_{min}$ $\left\|\frac{\alpha_M}{\alpha_s}\right\| \ll 1$, $\left\|\frac{\alpha'}{\alpha_s}\right\| \ll 1$ $\frac{L_z}{H_\alpha} \leq 1$, $\frac{V_H}{W} \leq \frac{L_H}{L_z}$	(21) (12), (26) (19), (17)
	C_3	$\frac{L_z}{H_\alpha} \ll 1$	(13)

FIG. 2. Flow subclass chart, whose organization is explained in text and whose symbols are defined in appendix B.

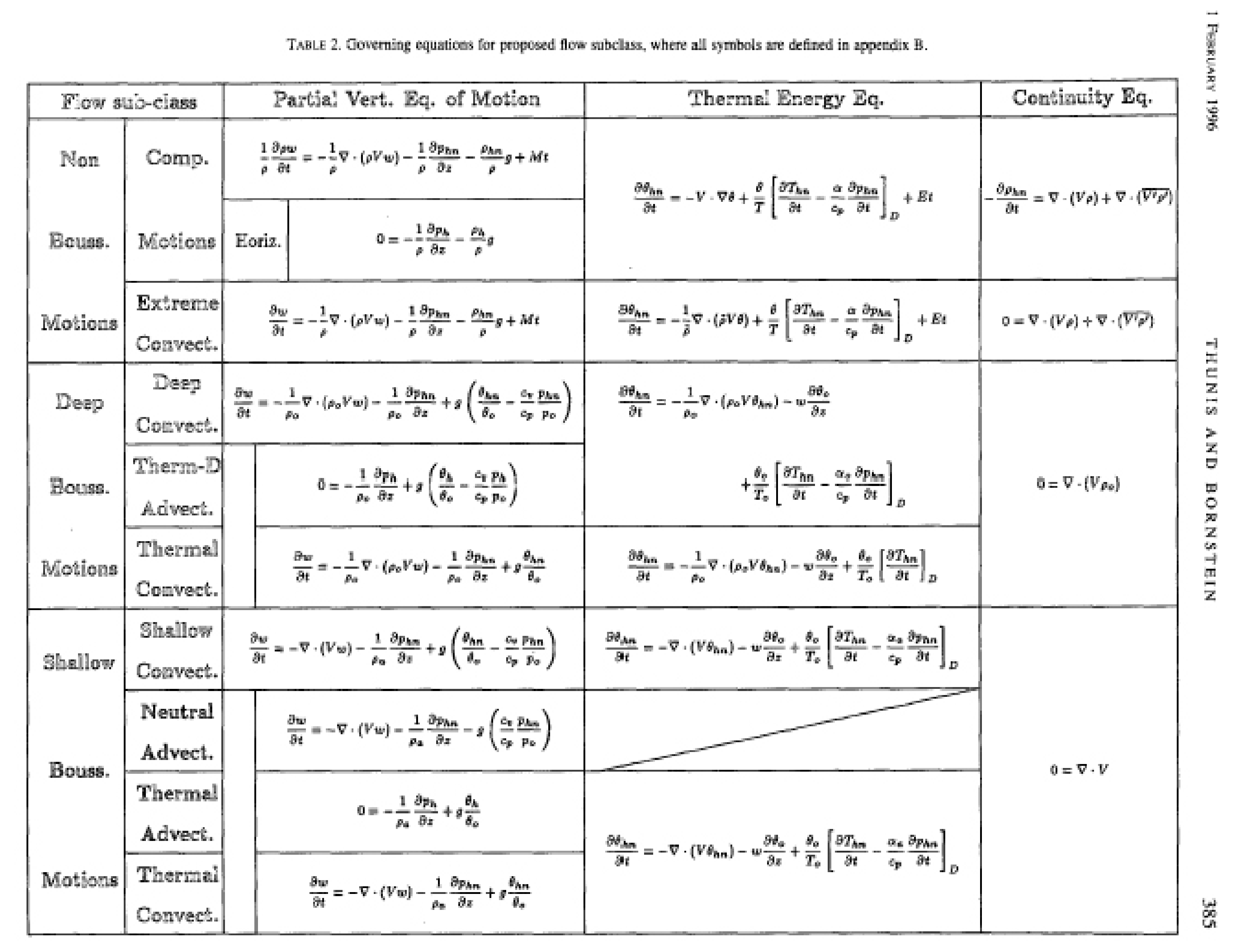


TABLE 2. Governing equations for proposed flow subclass, where all symbols are defined in appendix B.

Flow sub-class			Partial Vert. Eq. of Motion	Thermal Energy Eq.	Continuity Eq.
Non Bouss. Motions	Comp. Motions		$\frac{1}{\rho}\frac{\partial \rho w}{\partial t} = -\frac{1}{\rho}\nabla\cdot(\rho V w) - \frac{1}{\rho}\frac{\partial p_{hn}}{\partial z} - \frac{\rho_{hn}}{\rho}g + Mt$	$\frac{\partial\theta_{hn}}{\partial t} = -V\cdot\nabla\theta + \frac{\theta}{T}\left[\frac{\partial T_{hn}}{\partial t} - \frac{\alpha}{c_p}\frac{\partial p_{hn}}{\partial t}\right]_D + Et$	$-\frac{\partial\rho_{hn}}{\partial t} = \nabla\cdot(V\rho) + \nabla\cdot(\overline{V'\rho'})$
		Horiz.	$0 = -\frac{1}{\rho}\frac{\partial p_h}{\partial z} - \frac{\rho_h}{\rho}g$		
	Extreme Convect.		$\frac{\partial w}{\partial t} = -\frac{1}{\rho}\nabla\cdot(\rho V w) - \frac{1}{\rho}\frac{\partial p_{hn}}{\partial z} - \frac{\rho_{hn}}{\rho}g + Mt$	$\frac{\partial\theta_{hn}}{\partial t} = -\frac{1}{\bar\rho}\nabla\cdot(\bar\rho V\theta) + \frac{\theta}{T}\left[\frac{\partial T_{hn}}{\partial t} - \frac{\alpha}{c_p}\frac{\partial p_{hn}}{\partial t}\right]_D + Et$	$0 = \nabla\cdot(V\rho) + \nabla\cdot(\overline{V'\rho'})$
Deep Bouss. Motions	Deep Convect.		$\frac{\partial w}{\partial t} = -\frac{1}{\rho_o}\nabla\cdot(\rho_o V w) - \frac{1}{\rho_o}\frac{\partial p_{hn}}{\partial z} + g\left(\frac{\theta_{hn}}{\theta_o} - \frac{c_v}{c_p}\frac{p_{hn}}{p_o}\right)$	$\frac{\partial\theta_{hn}}{\partial t} = -\frac{1}{\rho_o}\nabla\cdot(\rho_o V\theta_{hn}) - w\frac{\partial\theta_o}{\partial z}$ $+\frac{\theta_o}{T_o}\left[\frac{\partial T_{hn}}{\partial t} - \frac{\alpha_o}{c_p}\frac{\partial p_{hn}}{\partial t}\right]_D$	$0 = \nabla\cdot(V\rho_o)$
	Therm-D Advect.		$0 = -\frac{1}{\rho_o}\frac{\partial p_h}{\partial z} + g\left(\frac{\theta_h}{\theta_o} - \frac{c_v}{c_p}\frac{p_h}{p_o}\right)$		
	Thermal Convect.		$\frac{\partial w}{\partial t} = -\frac{1}{\rho_o}\nabla\cdot(\rho_o V w) - \frac{1}{\rho_o}\frac{\partial p_{hn}}{\partial z} + g\frac{\theta_{hn}}{\theta_o}$	$\frac{\partial\theta_{hn}}{\partial t} = -\frac{1}{\rho_o}\nabla\cdot(\rho_o V\theta_{hn}) - w\frac{\partial\theta_o}{\partial z} + \frac{\theta_o}{T_o}\left[\frac{\partial T_{hn}}{\partial t}\right]_D$	
Shallow Bouss. Motions	Shallow Convect.		$\frac{\partial w}{\partial t} = -\nabla\cdot(V w) - \frac{1}{\rho_o}\frac{\partial p_{hn}}{\partial z} + g\left(\frac{\theta_{hn}}{\theta_o} - \frac{c_v}{c_p}\frac{p_{hn}}{p_o}\right)$	$\frac{\partial\theta_{hn}}{\partial t} = -\nabla\cdot(V\theta_{hn}) - w\frac{\partial\theta_o}{\partial z} + \frac{\theta_o}{T_o}\left[\frac{\partial T_{hn}}{\partial t} - \frac{\alpha_o}{c_p}\frac{\partial p_{hn}}{\partial t}\right]_D$	$0 = \nabla\cdot V$
	Neutral Advect.		$\frac{\partial w}{\partial t} = -\nabla\cdot(V w) - \frac{1}{\rho_o}\frac{\partial p_{hn}}{\partial z} - g\left(\frac{c_v}{c_p}\frac{p_{hn}}{p_o}\right)$		
	Thermal Advect.		$0 = -\frac{1}{\rho_o}\frac{\partial p_h}{\partial z} + g\frac{\theta_h}{\theta_o}$	$\frac{\partial\theta_{hn}}{\partial t} = -\nabla\cdot(V\theta_{hn}) - w\frac{\partial\theta_o}{\partial z} + \frac{\theta_o}{T_o}\left[\frac{\partial T_{hn}}{\partial t} - \frac{\alpha_o}{c_p}\frac{\partial p_{hn}}{\partial t}\right]_D$	
	Thermal Convect.		$\frac{\partial w}{\partial t} = -\nabla\cdot(V w) - \frac{1}{\rho_o}\frac{\partial p_{hn}}{\partial z} + g\frac{\theta_{hn}}{\theta_o}$		

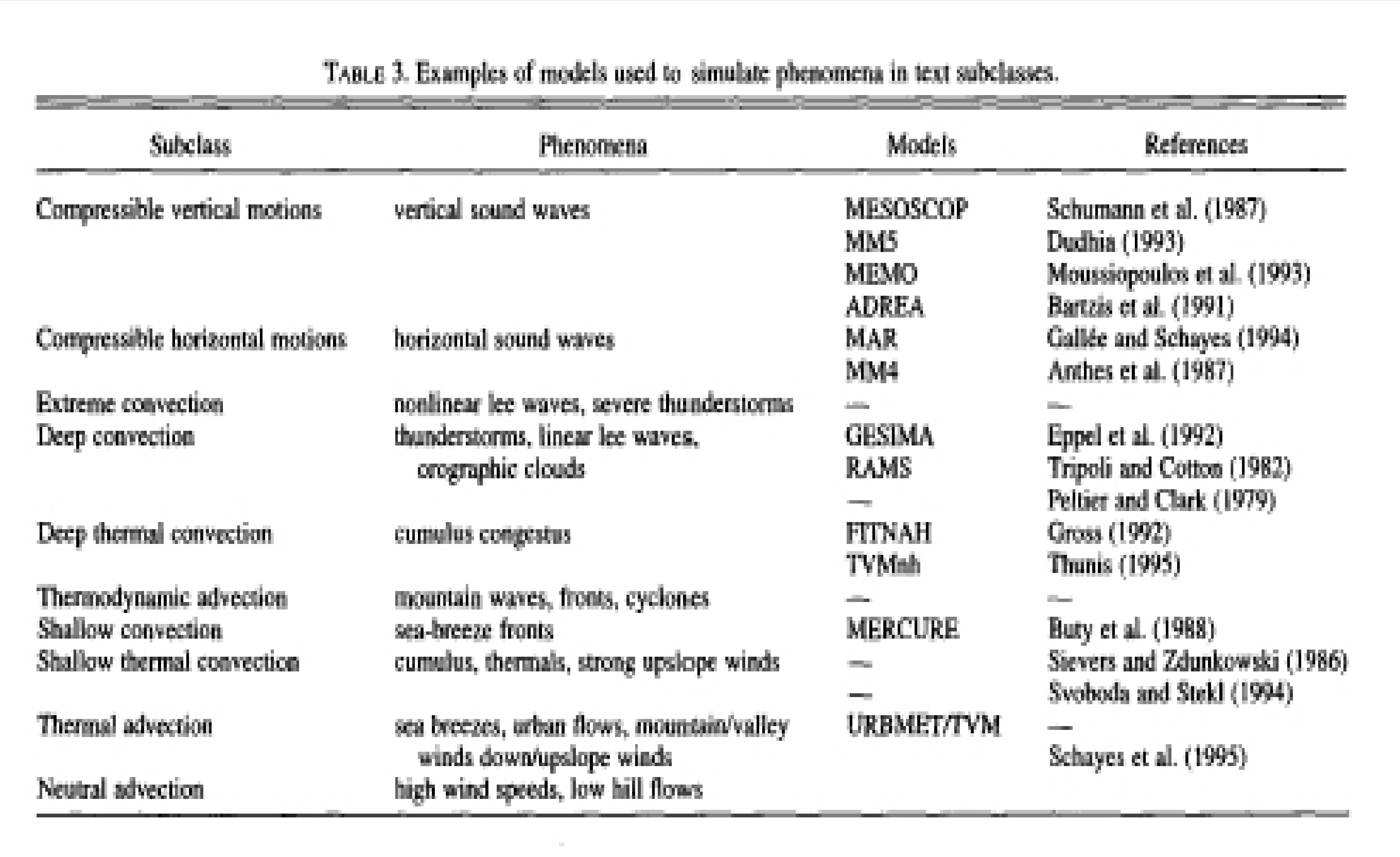


TABLE 3. Examples of models used to simulate phenomena in text subclasses.

Subclass	Phenomena	Models	References
Compressible vertical motions	vertical sound waves	MESOSCOP	Schumann et al. (1987)
		MM5	Dudhia (1993)
		MEMO	Moussiopoulos et al. (1993)
		ADREA	Bartzis et al. (1991)
Compressible horizontal motions	horizontal sound waves	MAR	Gallée and Schayes (1994)
		MM4	Anthes et al. (1987)
Extreme convection	nonlinear lee waves, severe thunderstorms	—	—
Deep convection	thunderstorms, linear lee waves, orographic clouds	GESIMA	Eppel et al. (1992)
		RAMS	Tripoli and Cotton (1982)
		—	Peltier and Clark (1979)
Deep thermal convection	cumulus congestus	FITNAH	Gross (1992)
		TVMnh	Thunis (1995)
Thermodynamic advection	mountain waves, fronts, cyclones	—	—
Shallow convection	sea-breeze fronts	MERCURE	Buty et al. (1988)
Shallow thermal convection	cumulus, thermals, strong upslope winds	—	Sievers and Zdunkowski (1986)
		—	Svoboda and Stekl (1994)
Thermal advection	sea breezes, urban flows, mountain/valley winds down/upslope winds	URBMET/TVM	—
			Schayes et al. (1995)
Neutral advection	high wind speeds, low hill flows		

Why use compressible-models?

- Compressible flow-models:

  from Engineering
- But, few atm-flows are compressible
- But, incompressible-flow models require solving (inverting a matrix) Laplacian of p
- Thus, numerics are easier in compressible-flow models

Required Parameterizations (covered by other speakers)

- Surface/subsurface energy & moisture balances → surface BCs
- Turbulence (SfcBL & PBL)
- Radiative flux-divergence
- Cumulus-scale convection (water in all forms)

MM5 Grids

- Vertical grid
  - On dimensionless σ-surfaces
  - Terrain influenced
  - Stretched (min-spacing near sfc)
  - Variables defined at
    - most variables: half σ-levels
    - *w* : full σ-levels
- Horizontal grid
  - Nested
  - Arakawa-B staggering
    - *u* & *v* : at grid-corners
    - scalars (θ, q, χ): at grid-centers

MM5 Numerics

- Spatial: finite-differencing
  - Second-order centered for all gradients, except
  - For precipitation-fall term, which is first-order upstream for positive-definiteness
- Temporal: finite-differencing
  - Second-order leapfrog (time n-1 to n+1)
  - Time-splitting
    - Fast terms (i.e., sound waves) need shorter Δt
    - Some radiation & cumulus options only recalculated every 30 min

MM5 BCs

- Upper
  - Rigid or moveable surface
  - Solid or permeable surface
- Lateral (from larger-scale Wx model)
  - Inflow & outflow
  - Zero-gradient vs. constant-flux
- Surface
  - Various complex forms of surface heat & moisture balance Eqs.: many new parameters
  - Surface types: from desert, forest, ice, to urban
  - Require: sub-surface layer & SfcBL values

FDDA

- Techniques: range from
  - 4DVAR (cutting edge) to
  - Newtonian nudging (in MM5) → a new (but smallest) term in each prog-Eq.
- Observational nudging
  - For some parameters: in some outer-domains
  - For some levels: within PBL
- Analysis nudging w/ larger-scale model-output
  - Vertical-profiles used as obs at given time-interval
  - For all-parameters in some outer-domains
  - For some levels: above PBL or (better even) above level of mesoscale-influences
  - Stronger larger-scale influences than from only BCs

Coffee break

Theme 3: GOOD MESO-MET MODELING

MUST CORRECTLY REPRODUCE:

- UPPER-LEVEL Syn/GC FORCING FIRST:
  pressure (the GC/Syn driver) → Syn/GC winds
- TOPOGRAPHY NEXT:
  min horiz grid-spacing → flow-channeling
- MESO SFC-CONDITIONS LAST:
  temp (the meso-driver) & roughness → meso-winds

e.g., SFBA Summer O_3-episode (Ghidey)

- Obs: daily max- O_3 sequentially moved from Livermore to Sacramento to SJV
- Large scale IC/BC:

  shifting meos-700 hPa high →

  shifting meos-sfc low →

  changing sfc-flow →

  max-O_3 changed location
- MM5 (next 2 slides):

SAC episode day: D-1 700 hPa Syn H moved to Utah with coastal “bulge” & L in S-Cal→ correct SW flow from SFBA to Sac

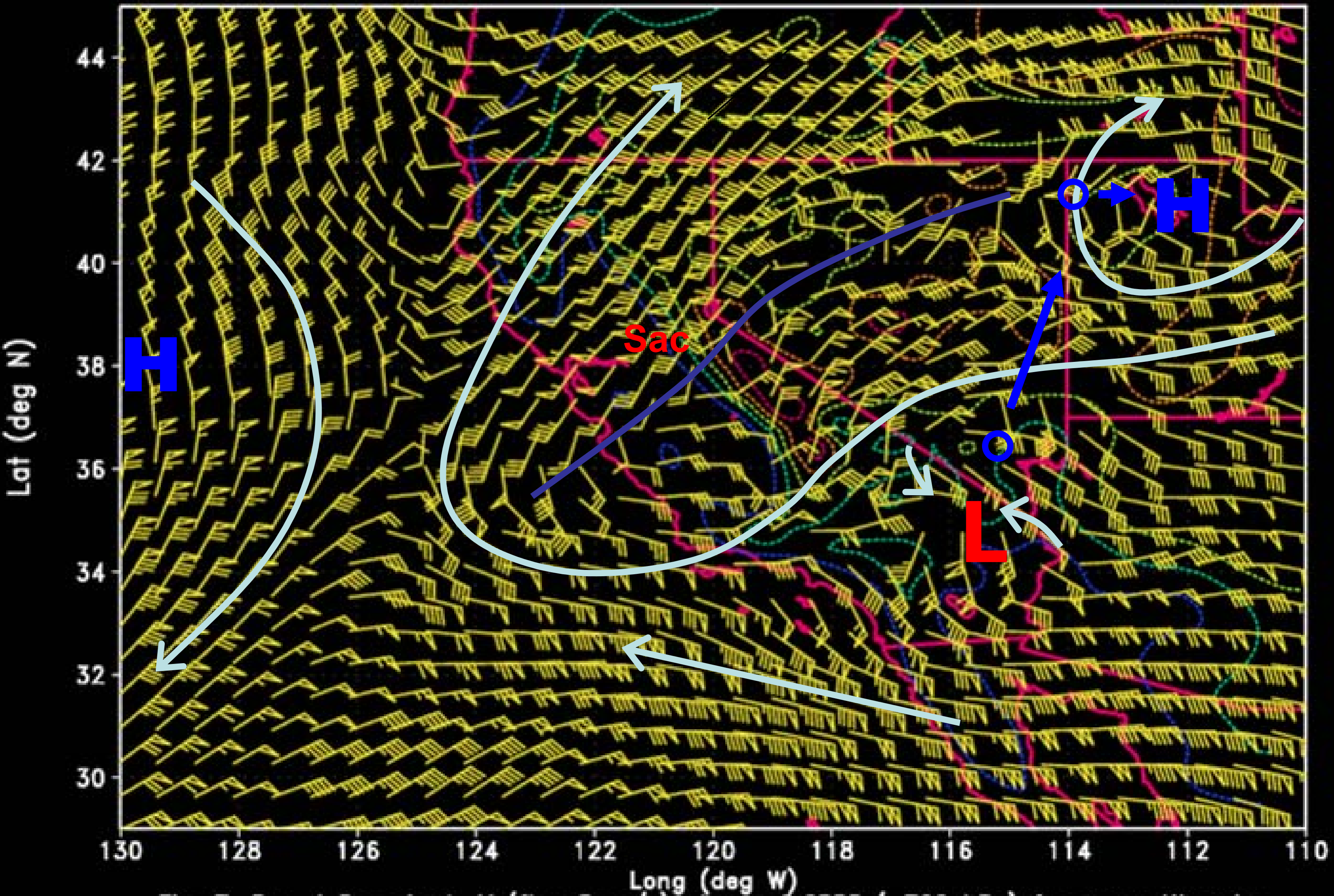


Fig. 7. Run 4 Domain 1, V (flag 5 m/s) at σ = 0.6555 (~700 hPa) for every 4th value at 1200 UTC 01 Aug, with topographic heights (dashed lines, at 500 m interval).

SJV episode day: D-3 700 hPa Fresno eddy moved N & H moves inland→ flow around eddy blocks SFBA flow to SAC, but forces it S into SJV

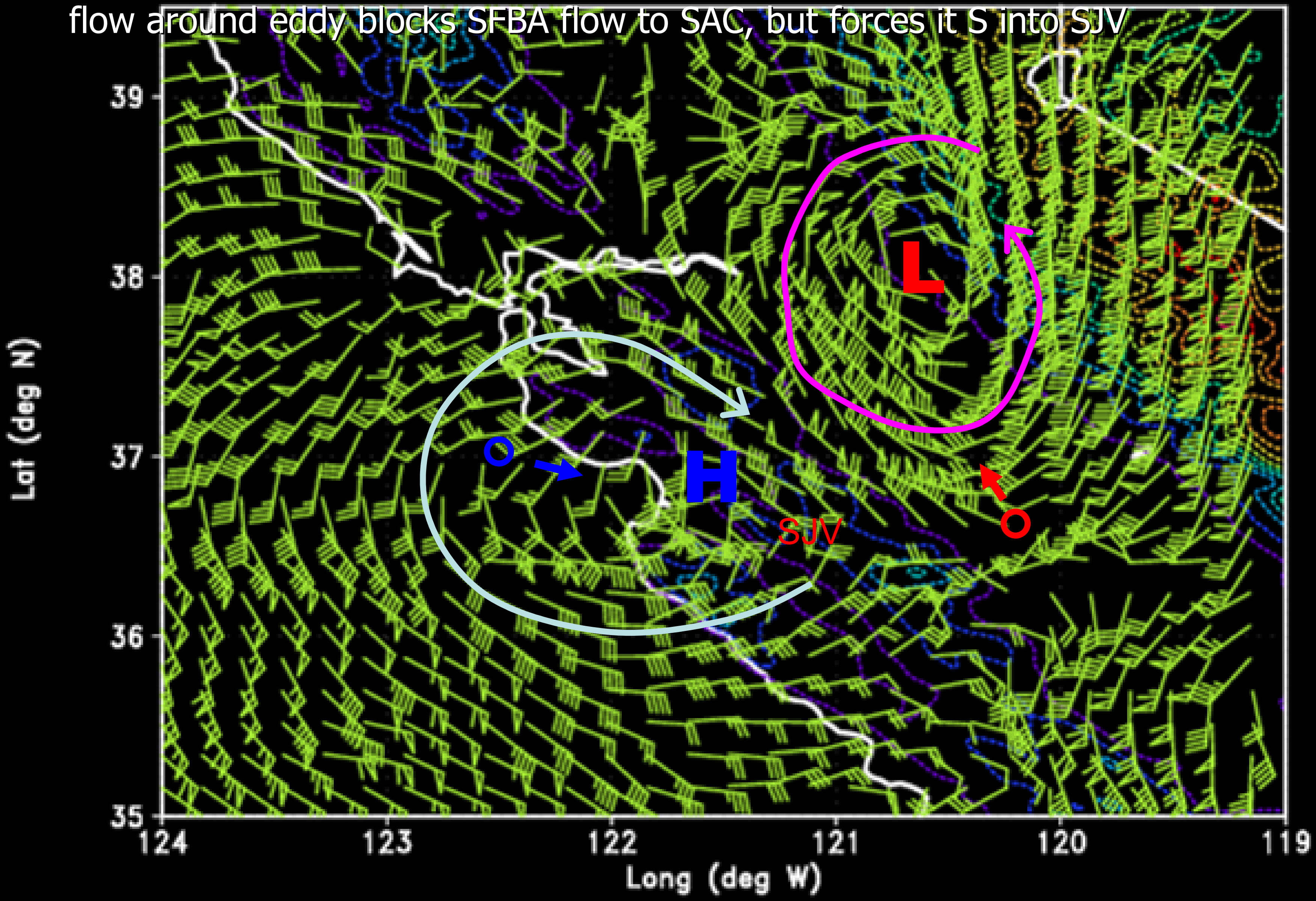


Fig. 17. Run 4 Domain 3, V (flag 5 m/s) at σ= 0.6555 (~700 hPa) for every 10th value at 2100 UTC on 02 Aug, with topographic heights (dashed lines, at 300 m interval).

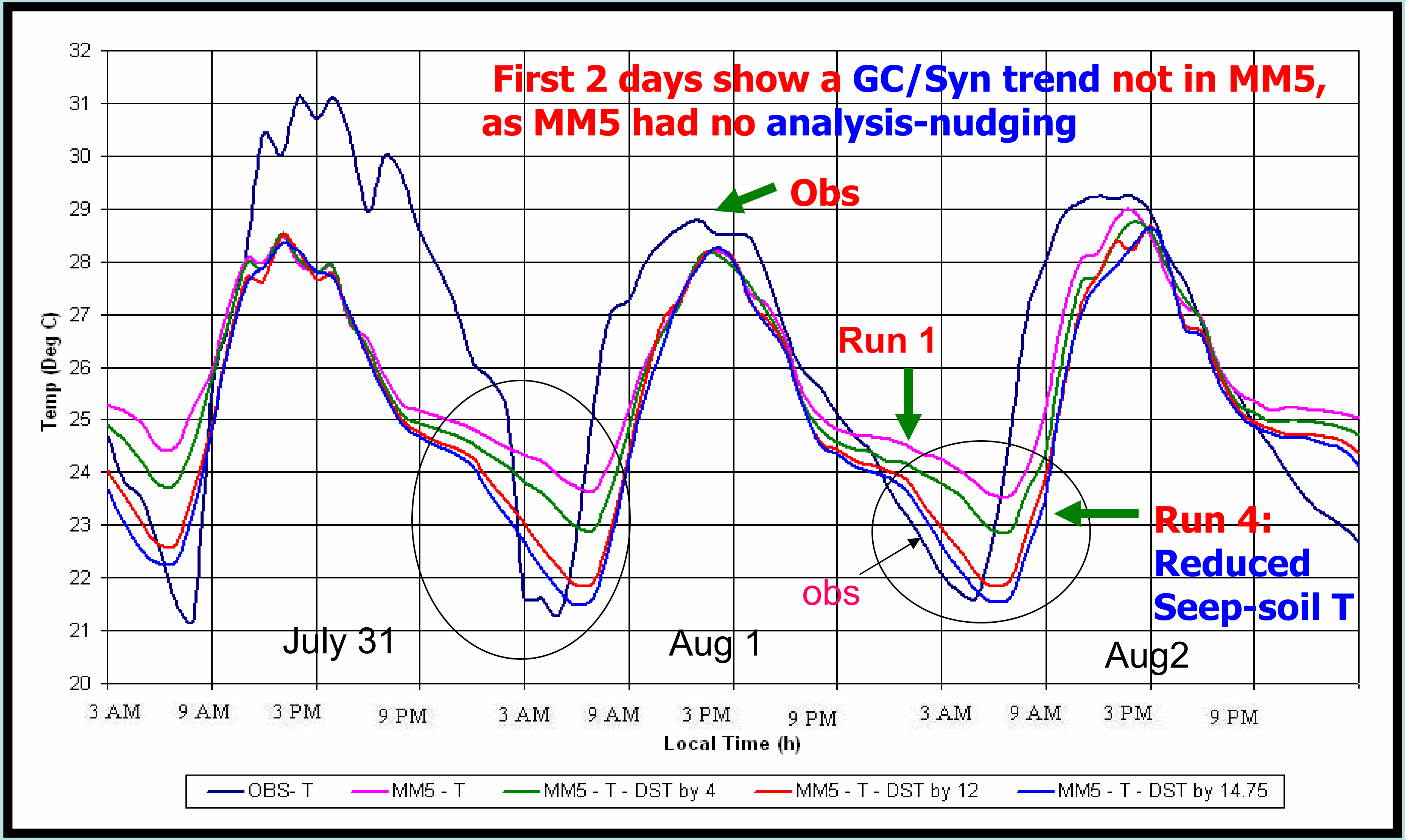
Theme 4:
MM5 Non-urban Sfc-IC/BC Issues

- Deep-soil temp: BC
  - Controls min-T
  - Values unknown & MM5-estimation is flawed
- Soil-moisture: IC
  - Controls max-T
  - Values unknown & MM5-table values too specific
- SST: IC/BC
  - Horiz coastal T-grad controls sea-breeze flow
  - Focus usually only on land-sfc temp
  - IC/BC SST values from large-scale model→ too coarse & not f(t)
- Details on following slides

MM5: deep soil temp

- Calculated as average large-scale model input surface-T during simulation-period
- This assumes zero time-lag b/t sfc lower-level (about 1 m) soil-temps
- But obs show
  - 2-3 month time-lag b/t these 2 temps
  - Larger-lag in low-conductivity dry-soils
- Thus MM5 min-temps are too-high in summer & too-low in winter
- Need to develop a tech (beyond current trial & error) to account for lag: next 2 slides

Mid-east Obs vs. MM5: 2-m T (Kasakech '06)



First 2 days show a GC/Syn trend not in MM5, as MM5 had no analysis-nudging

Run 4: Reduced Seep-soil T

6/3/2007

San Jose State University

Lower input deep-soil T → better 2-m T → better winds → better O_3

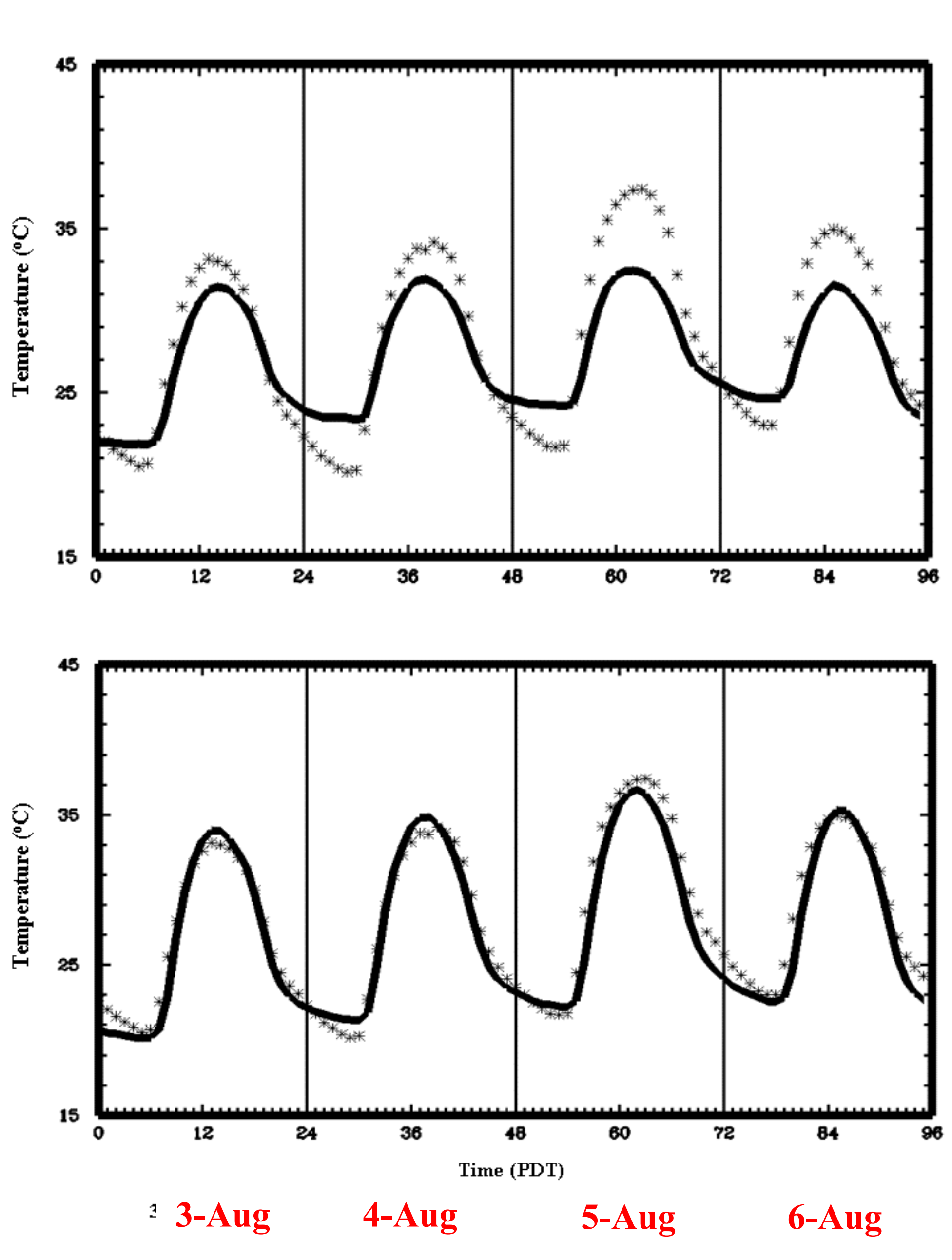
SCOS96 LA Temps (Boucouvula et al.)

RUN 1: has

- ➢No GC warming trend
- ➢Wrong max & min T

RUN 5: corrected, as it used

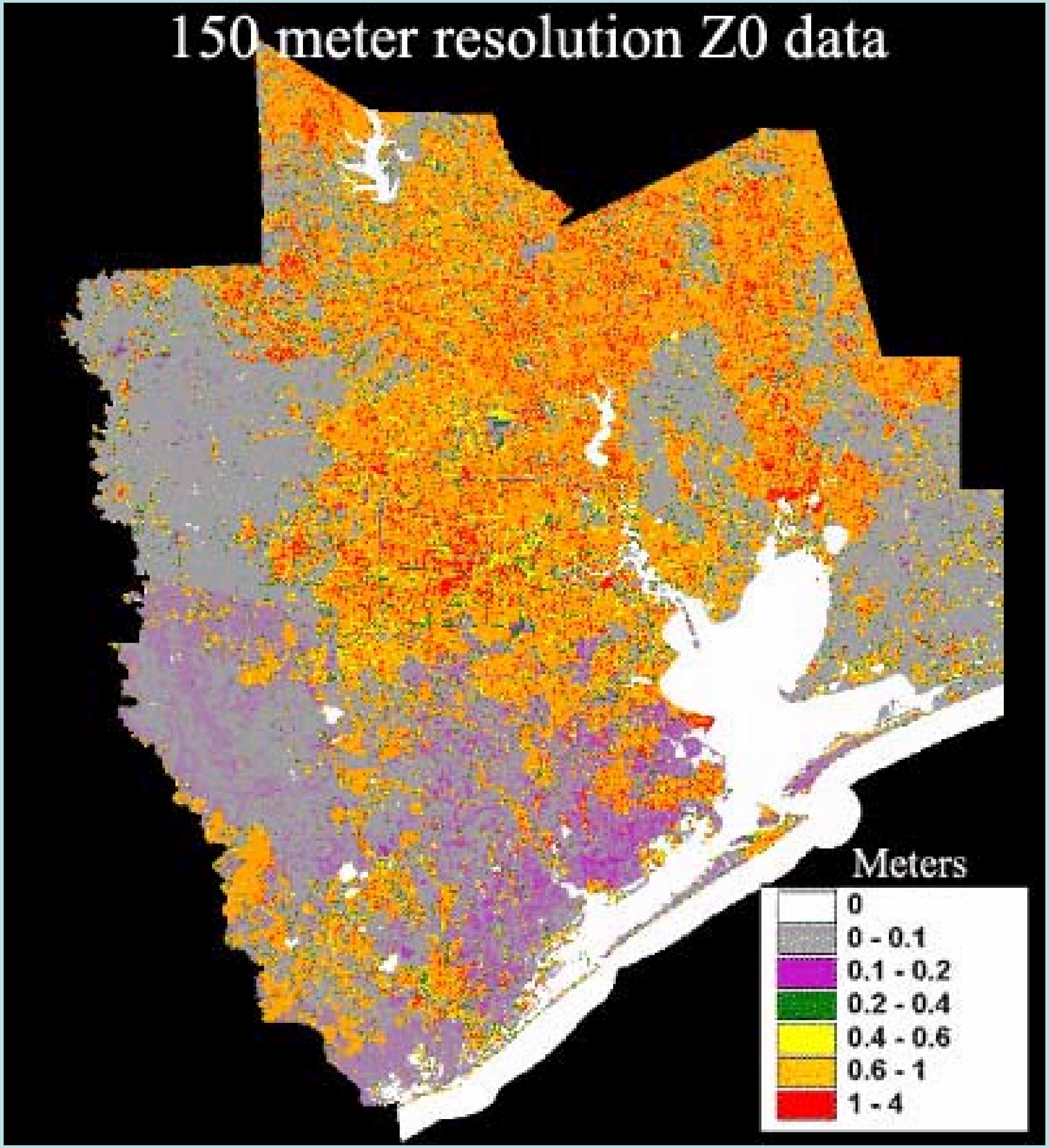
- > Analysis nudging
- > Reduced deep-soil T



MM5 input-table values: z_0 problems

- Water z_0 = 0.01 cm
  - Only IC → updated internally by Eq. = f(MM5 u_*)
  - But Eq. only valid for open-sea smooth-swell conditions
  - Observed values for rough-sea coastal-areas ~ 1 cm → MM5 coastal-winds are over-estimated
- Urban z_0 = 80 cm
  - too low for tall cities: obs up to 3-4 m → urban-speeds: too fast
  - Must adjust input-value or input GIS/RS f(x,y)
- See next slide

S. Stetson: Houston GIS/RS z_o input



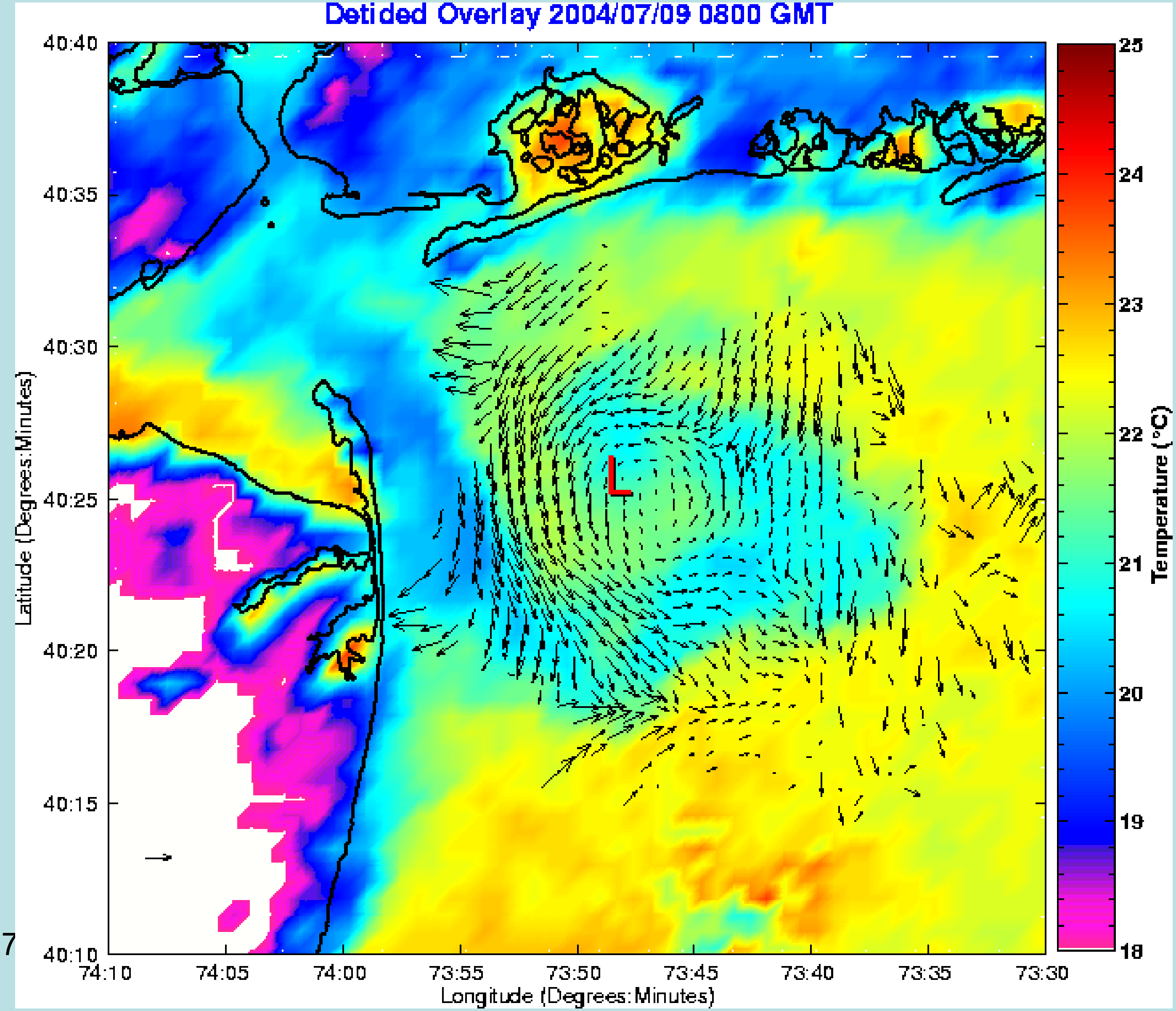
Values are too large, as they were $f(h)$ and not $f(\sigma_h)$

← Values up to 3 m

SSTs

- Large-scale BC-model SSTs do not have enough f(x,y,t)
- Satellite-SST have better detail
- NYC coastline + critical wind-dd →
  cold-core coastal ocean cyclonic-vortex →
  altered coastal wind-dd →
  altered dispersion pattern
- See next slide

NYC SST + currents: Pullen et al. (2007)



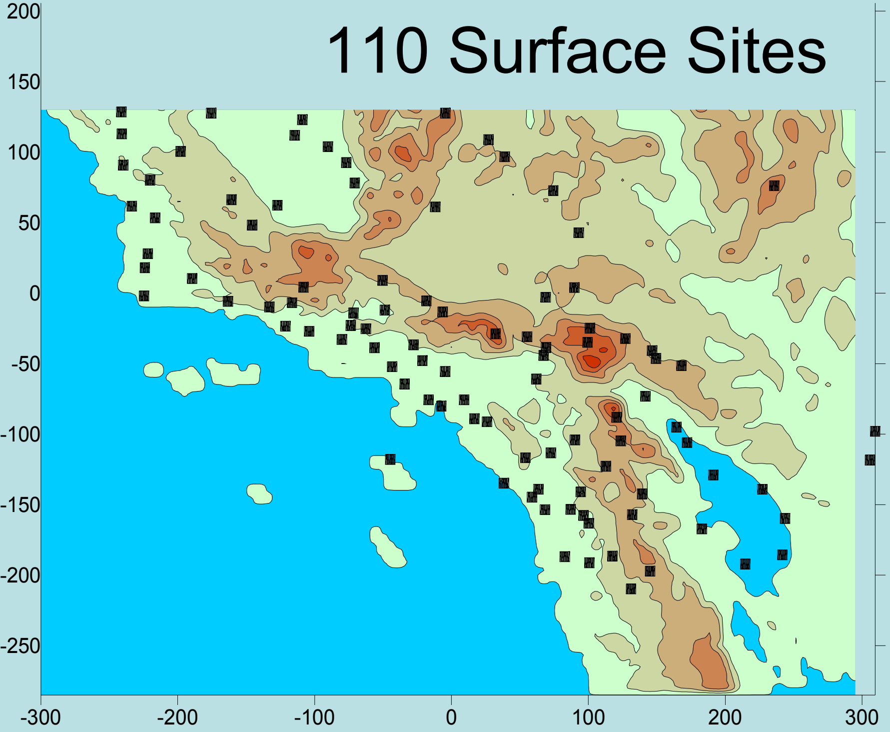
e.g., LA Basin O_3-Episode (Boucouvula et al., 2003)

Episode due to synoptic-change:

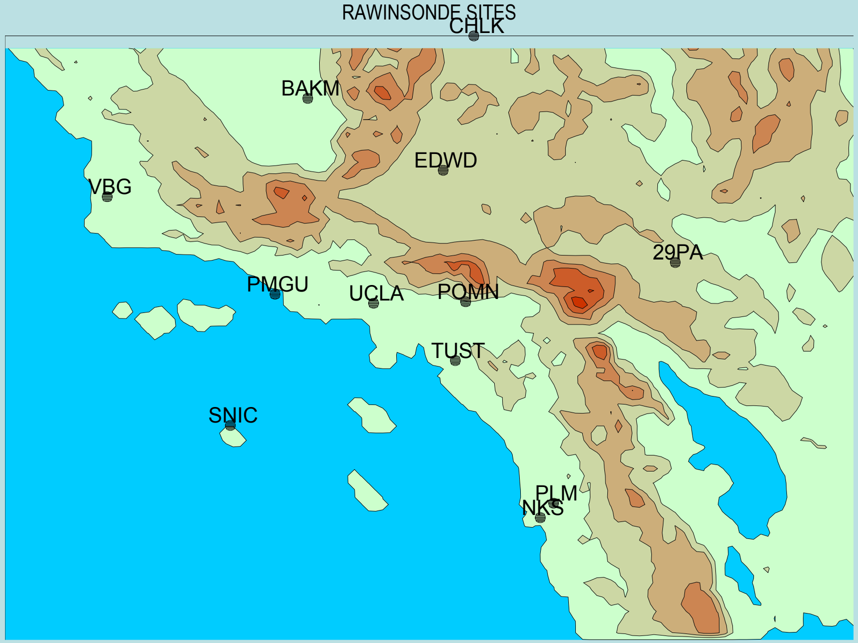
Onshore-movement of 700 mb coastal-H →

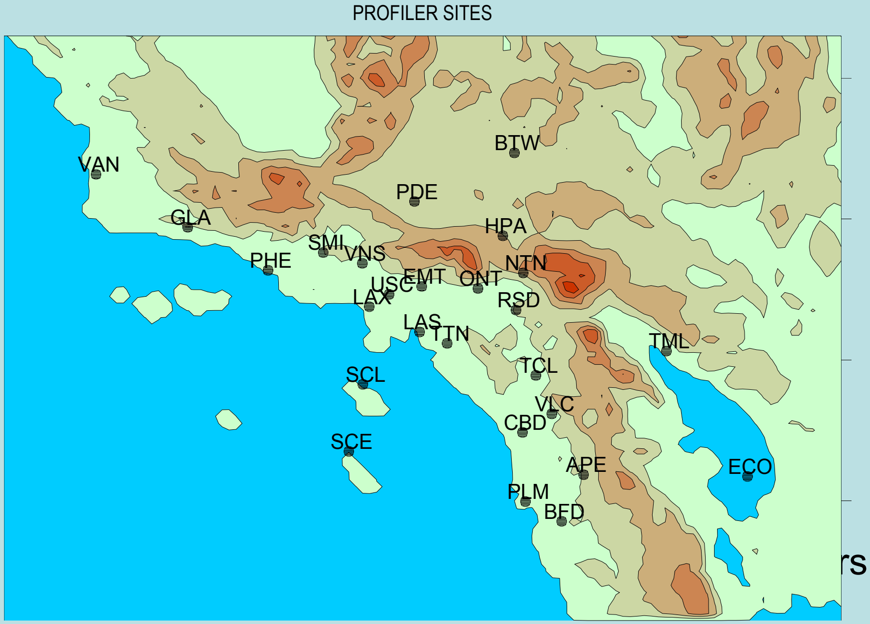
- Reduced Marine BL depth
- Subsidence warming → strengthened subsidence inversion-layer
- Upper-level easterly flow
- Easterly-flow at inland surface-sites
- Sea-breeze surface convergence-zone
- Max surface-ozone (180 ppb) at inland-sites in afternoon on 5 Aug within convergence-zone

110 Surface Sites

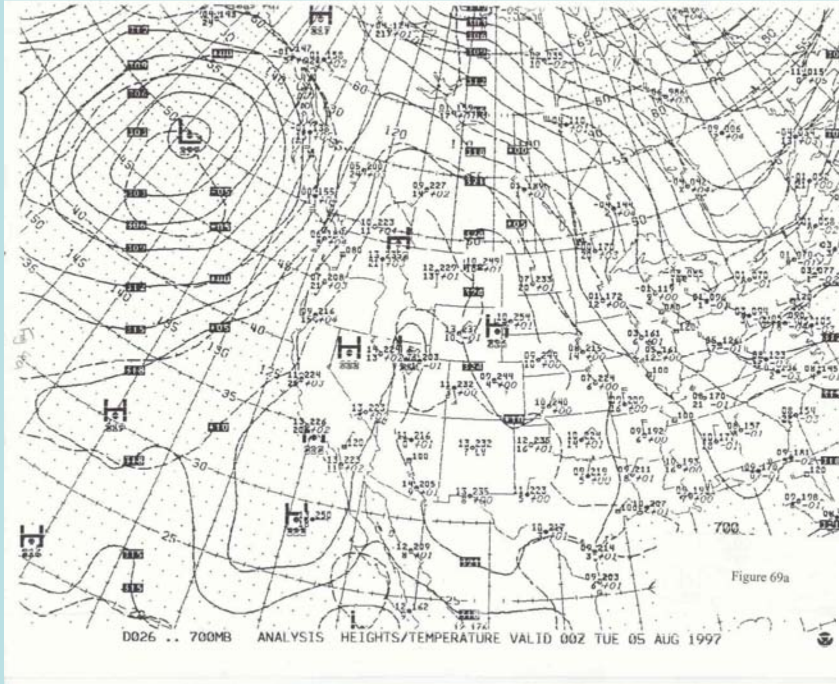


14 Rawinsonde sites

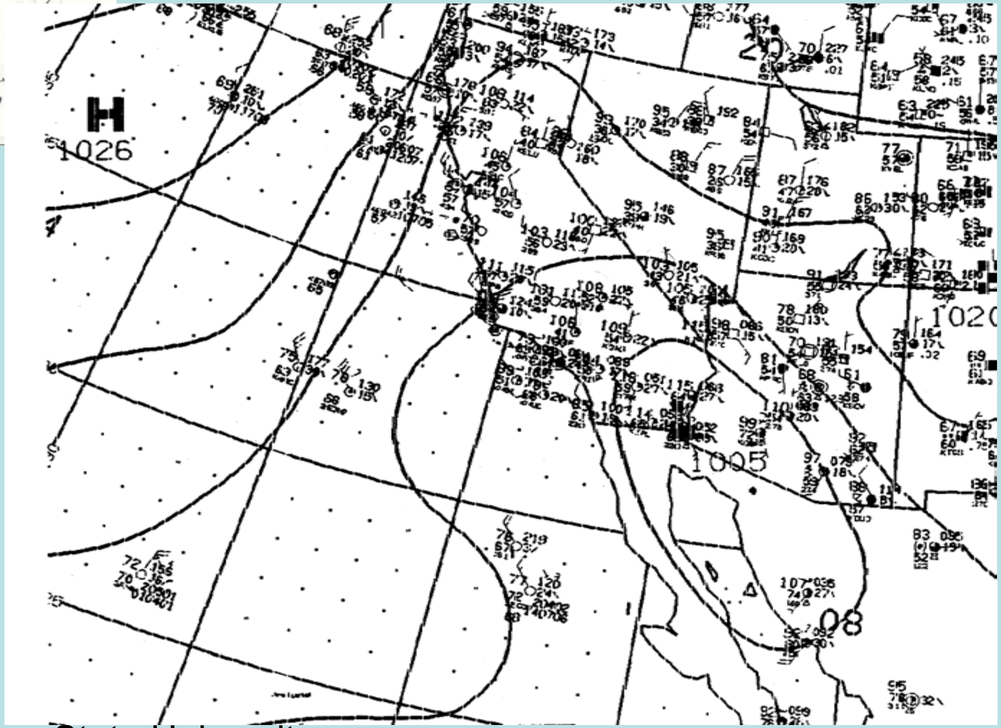




23 profiler sites (too many near Coastal zone)



NWS-charts show only
Typical summer-patters



But obs (next 4 slides)
show 700 hPa
meso-changes
at 12 hr intervals
(from profiler data)

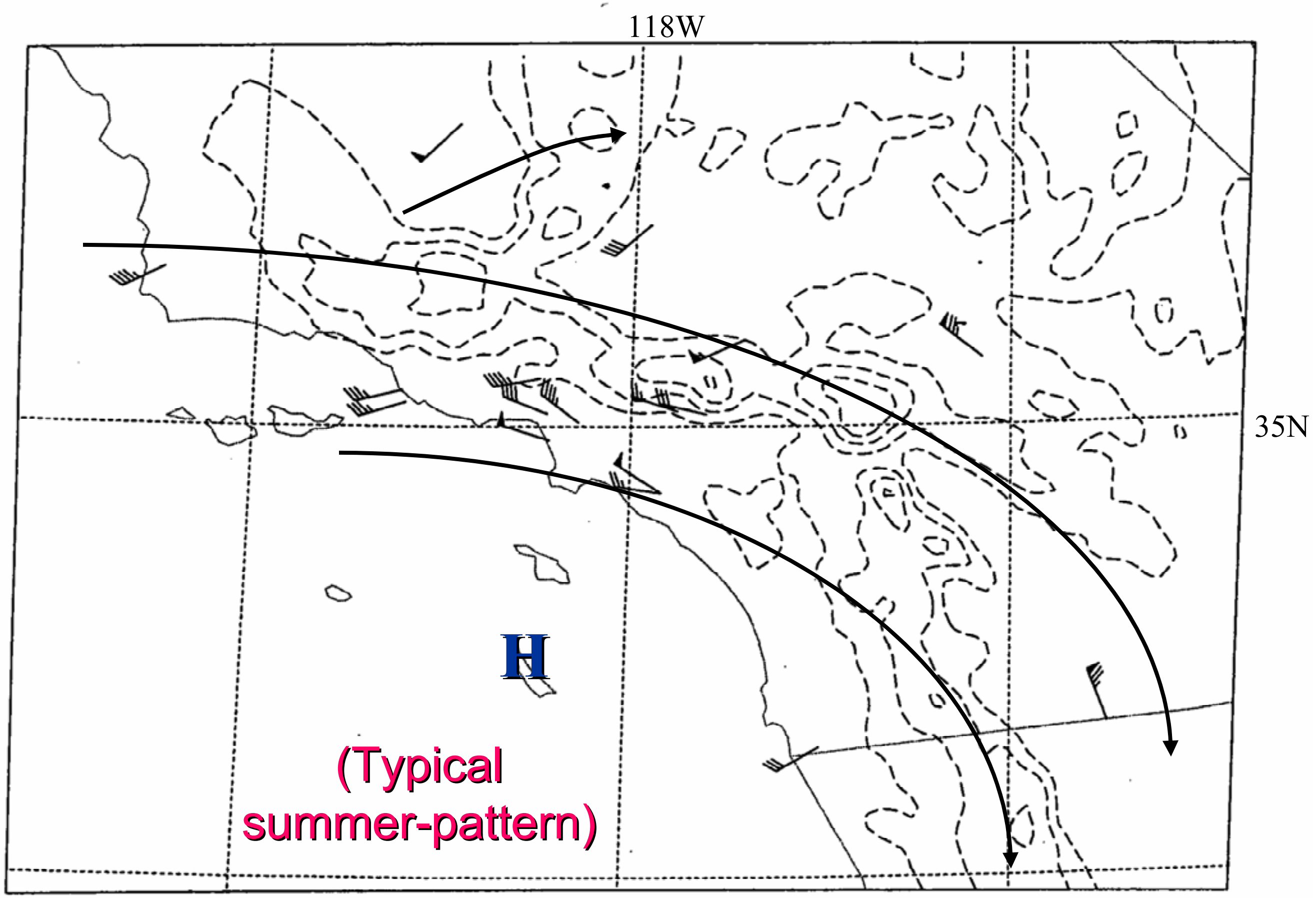


Fig. 8a

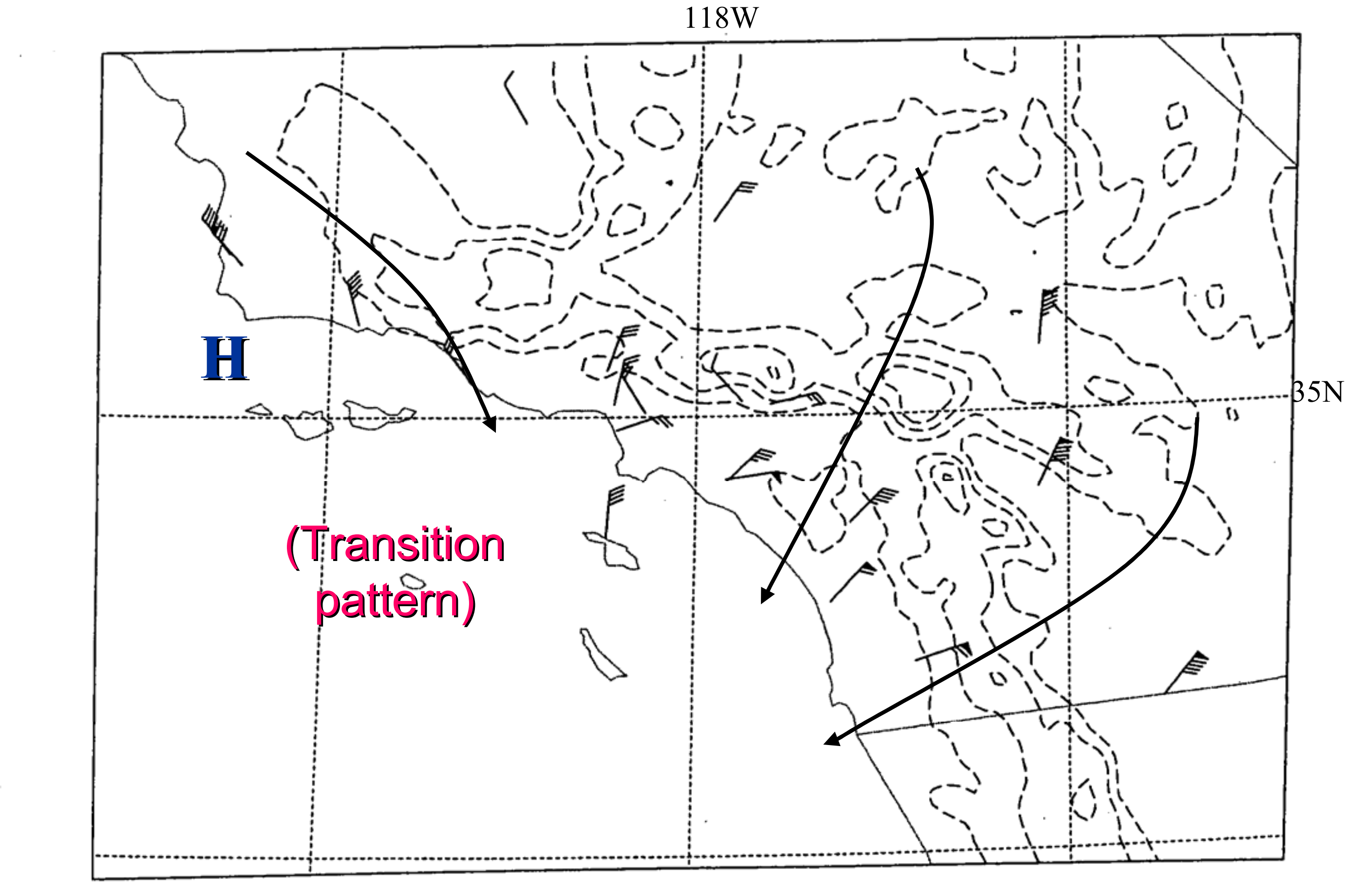


Fig. 8b

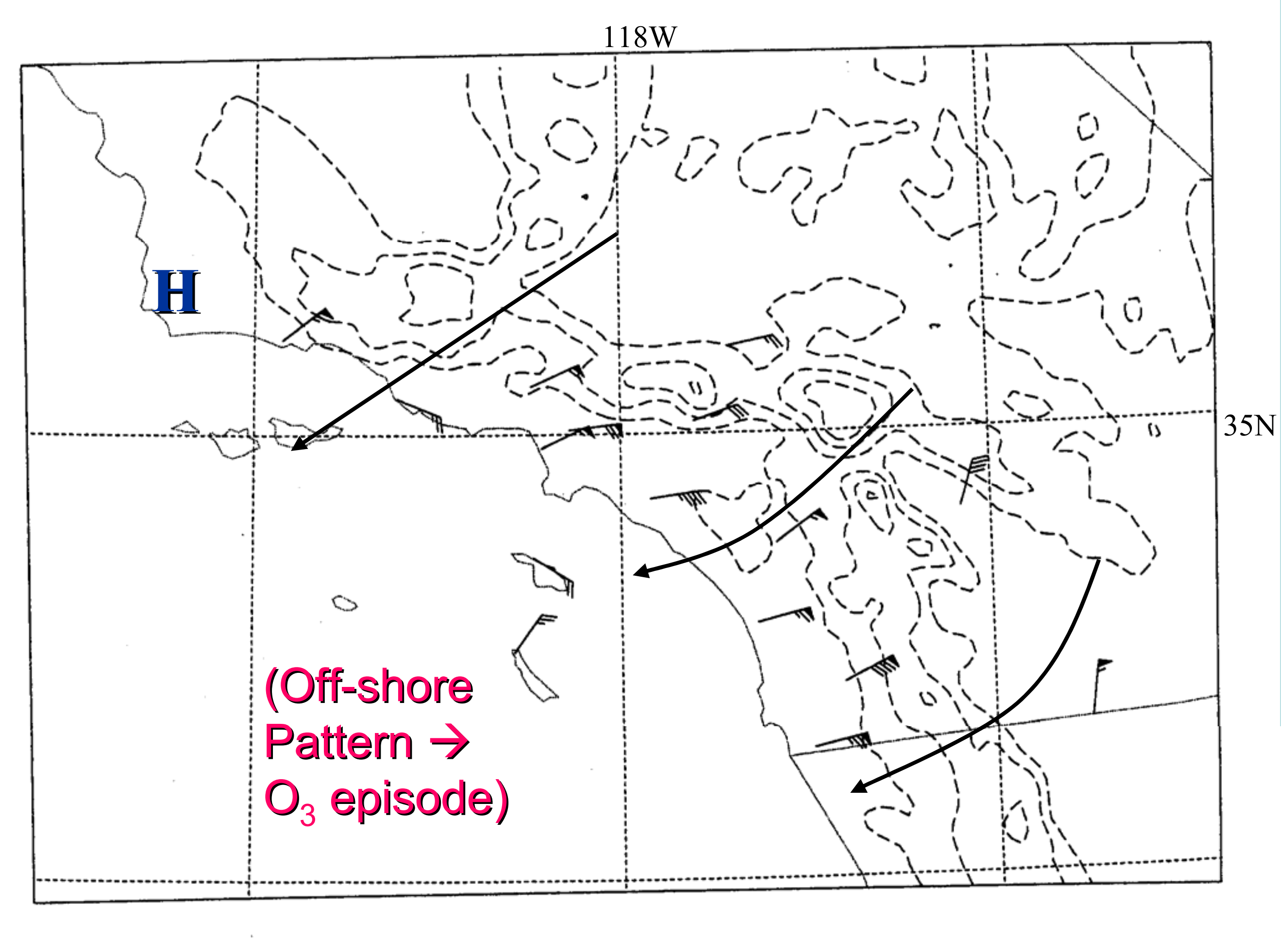
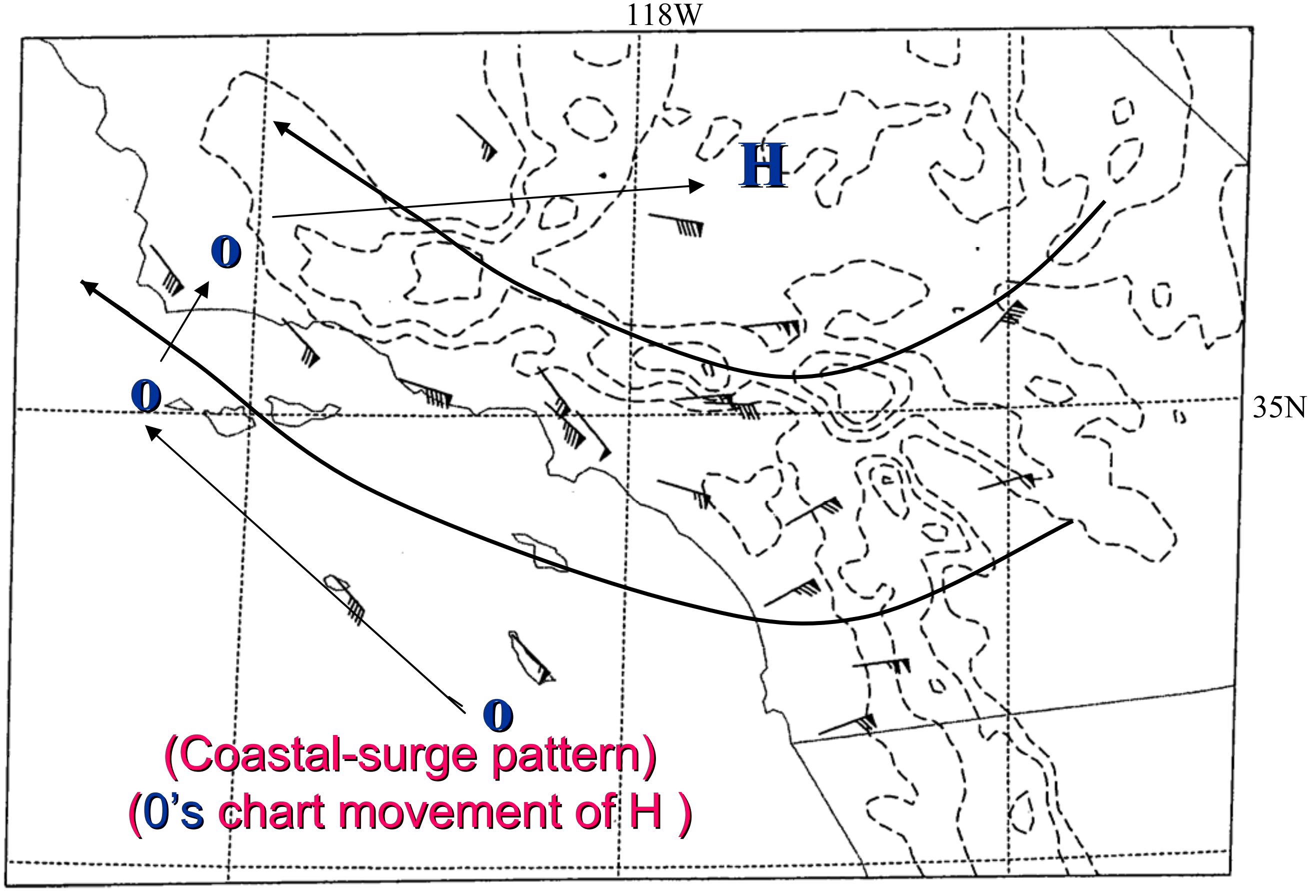


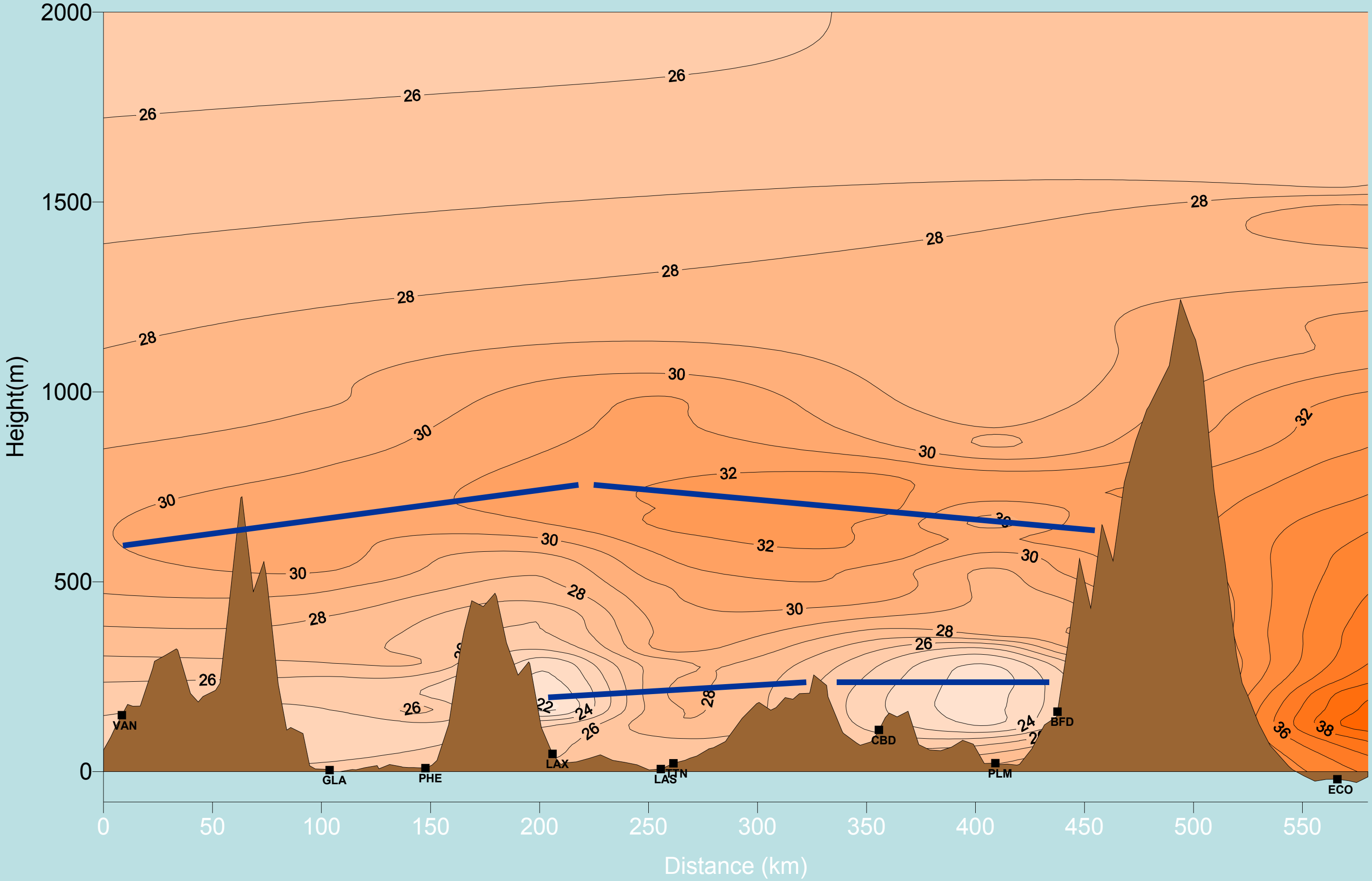
Fig. 8c



(Coastal-surge pattern)
(0's chart movement of H)

Fig. 8d

Along-coast T-section at 4 Aug, 1500 PDT (blue lines denote elev inversion)



T(z,t)-section (dot-lines denote elev-inversion)

Note: min-h_i (inversion at sfc) at O_3-episode time

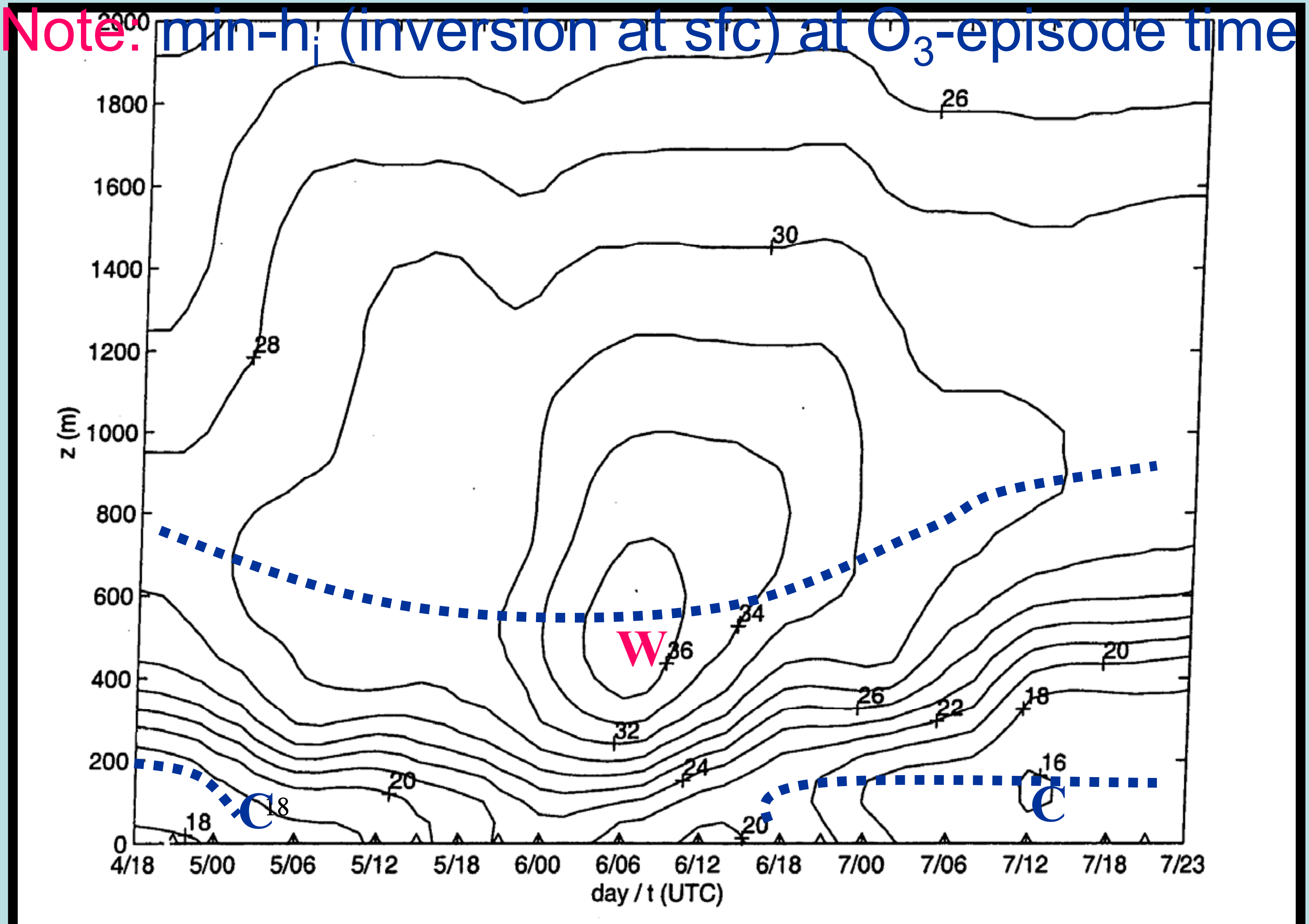


Fig. 12a

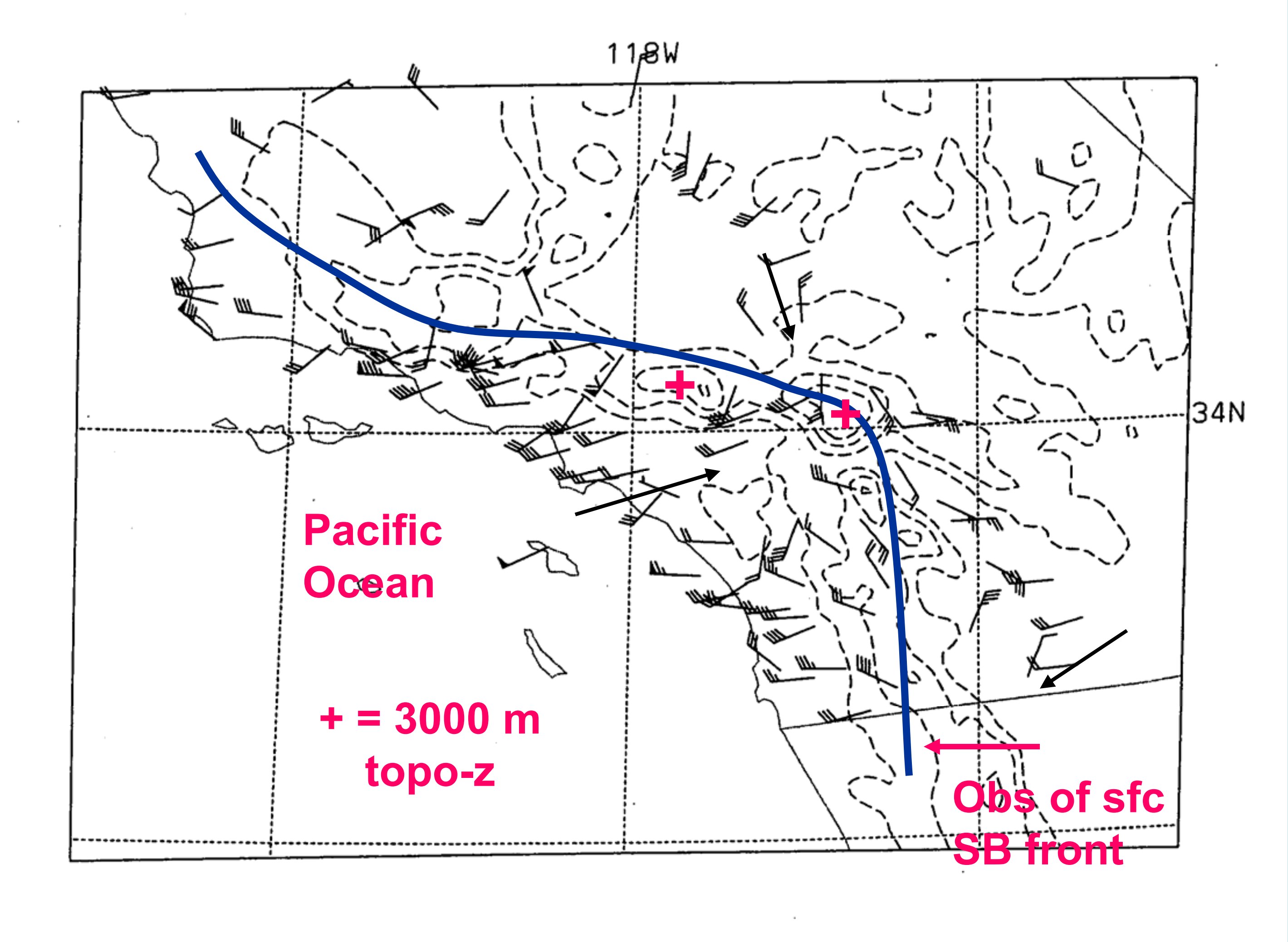


Fig. 9d

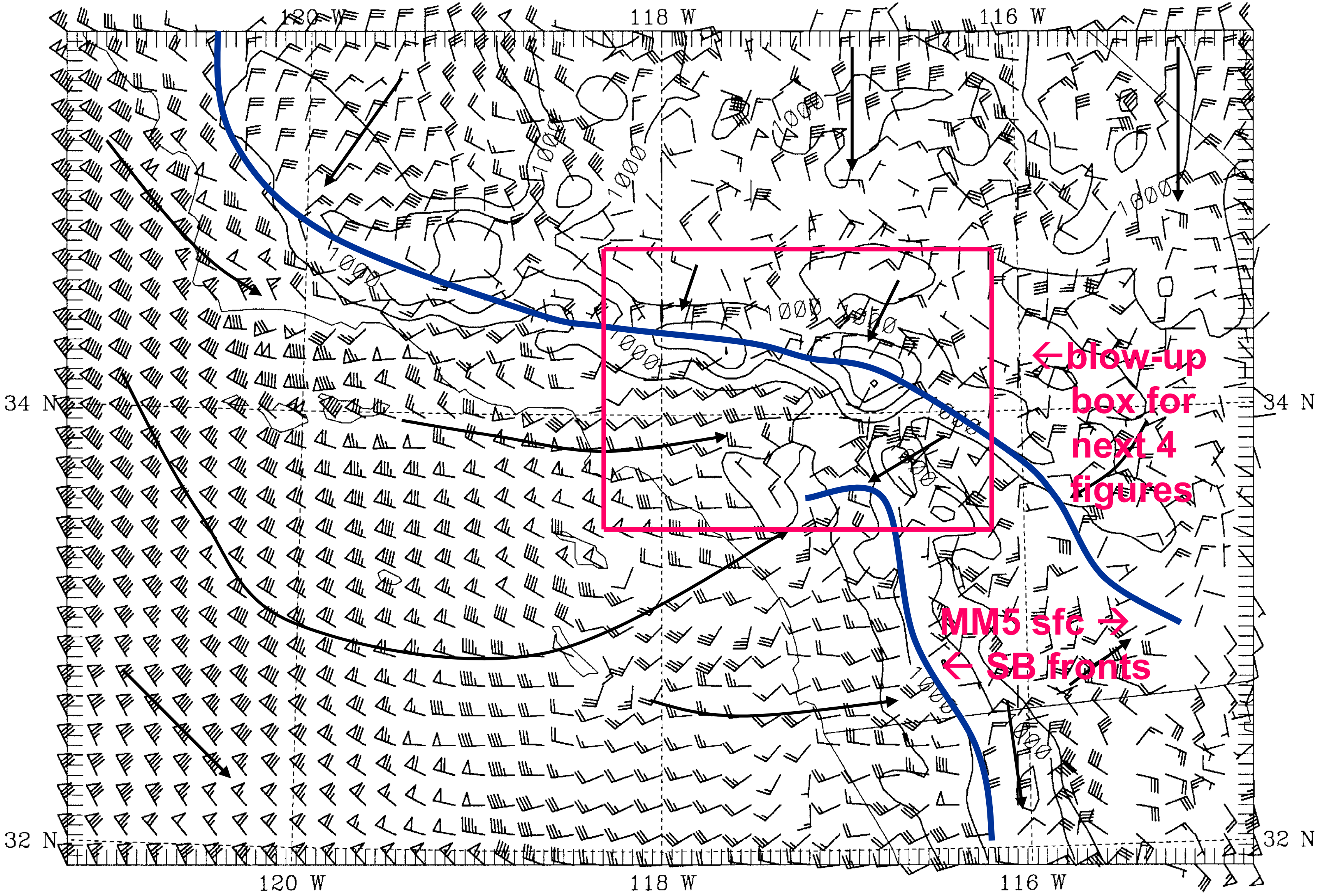

120 W
118 W
116 W
34 N
32 N
1000
←blow-up box for next 4 figures
MM5 sfc →
← SB fronts

Fig. 7d

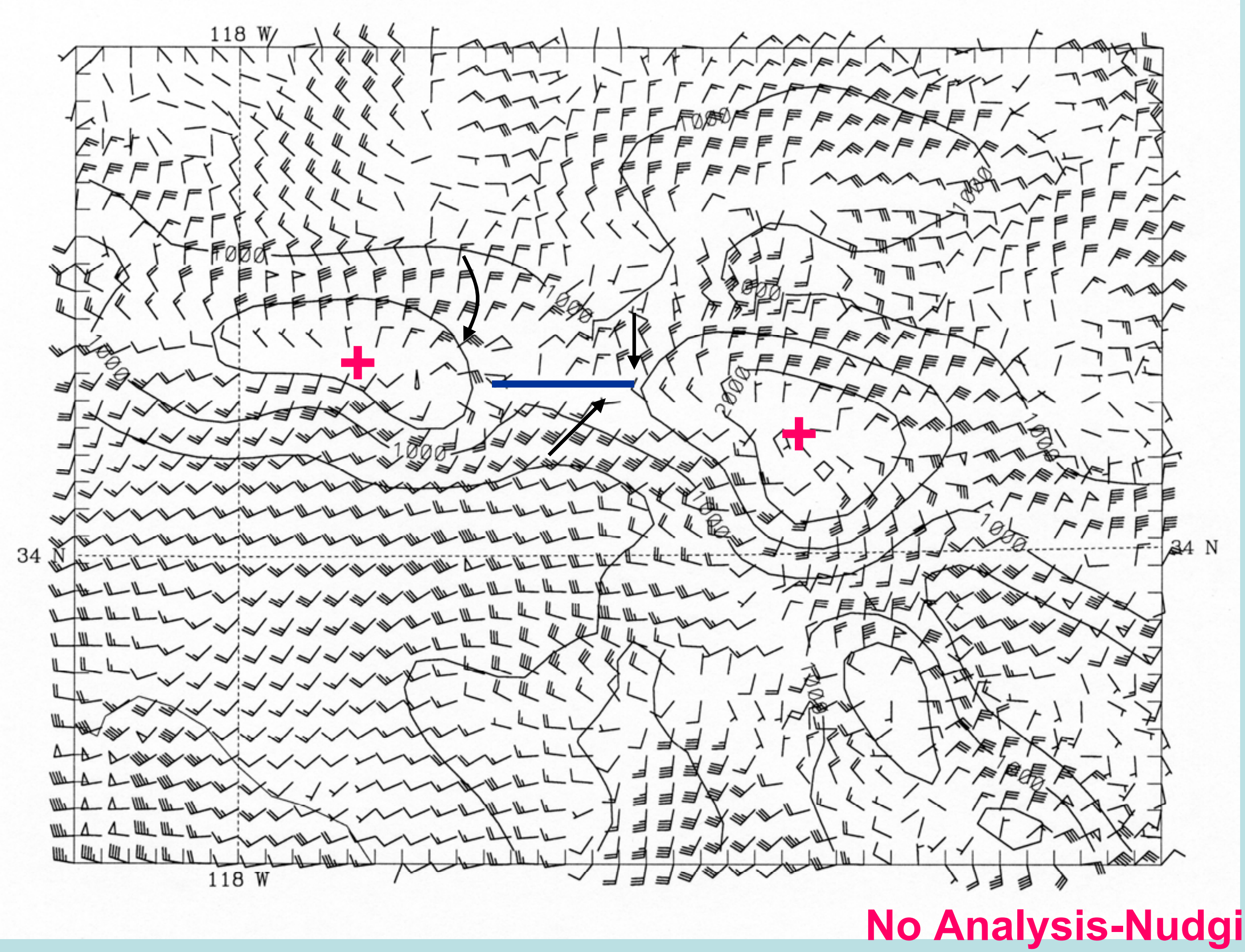


Fig. 8a

No Analysis-Nudging: MM5 sfc-V, 1-hour b/f O_3-max (weak oppos-ing sfc-flow)

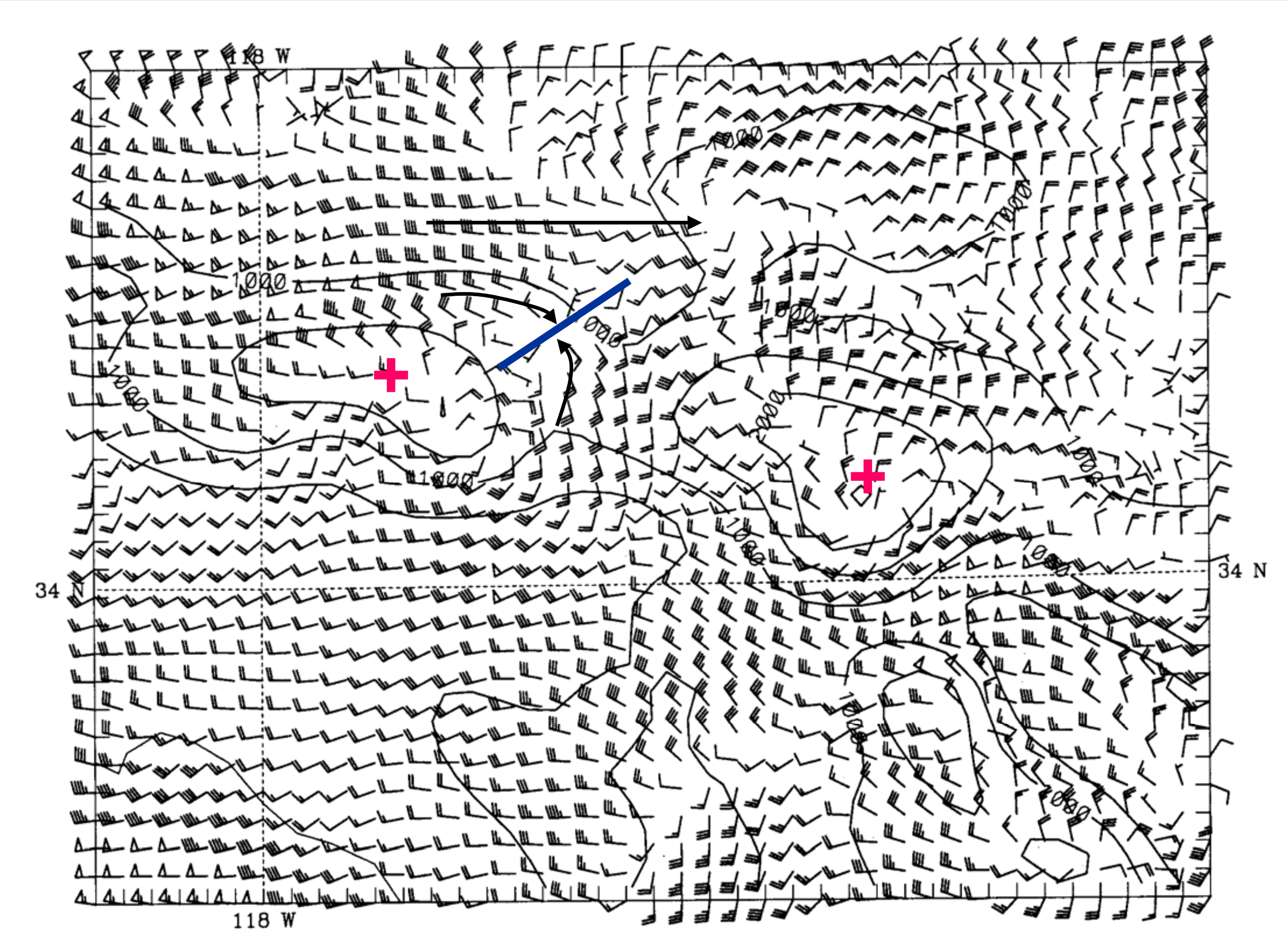


Fig. 8b

No Analysis-Nudging →
Weak opposing sfc-flow →
O_3 leaves valley → No episode

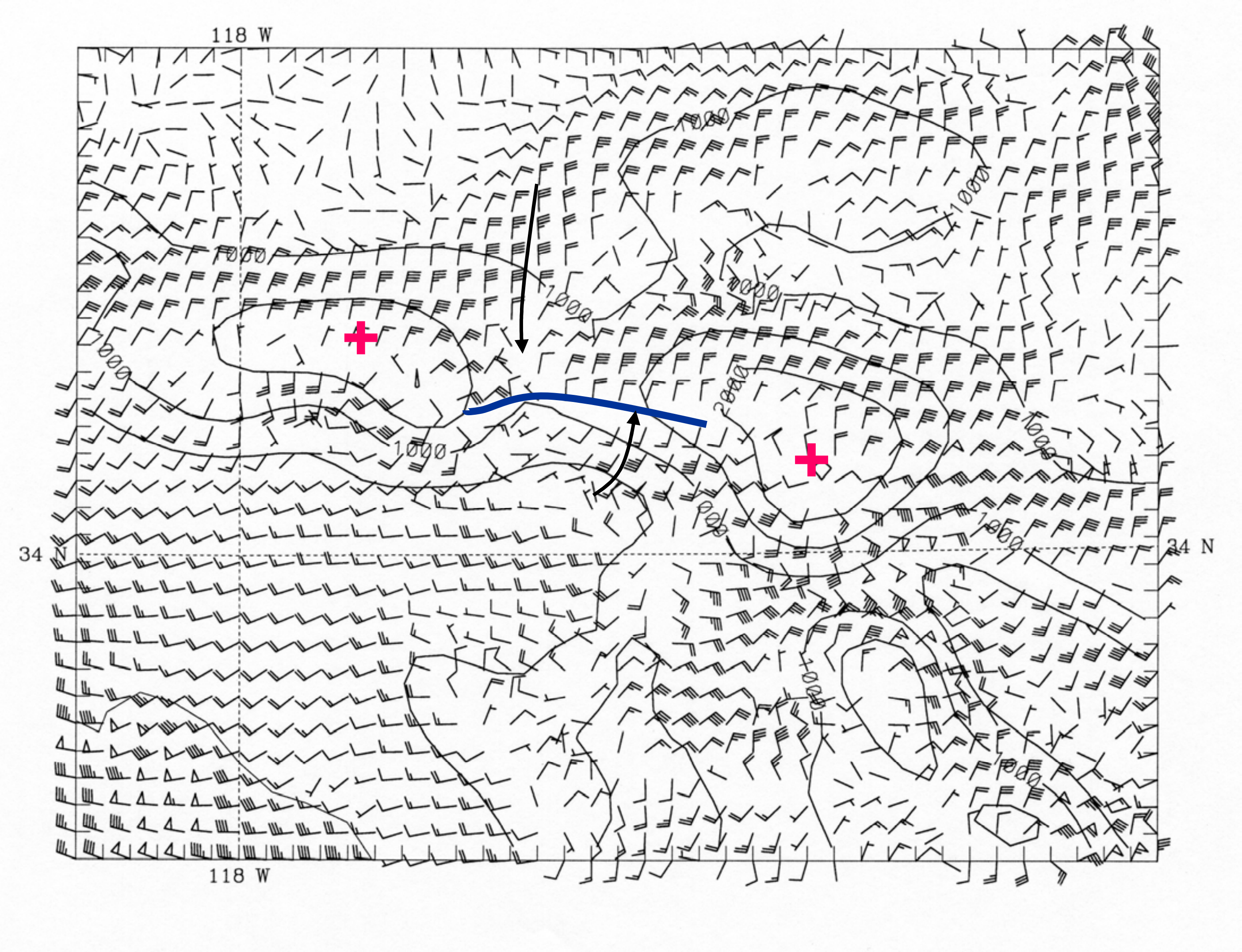


Fig. 8c **With Analysis-Nudging: MM5 sfc-V, 1-hour b/f O_3-max (stronger opposing sfc-flow)**

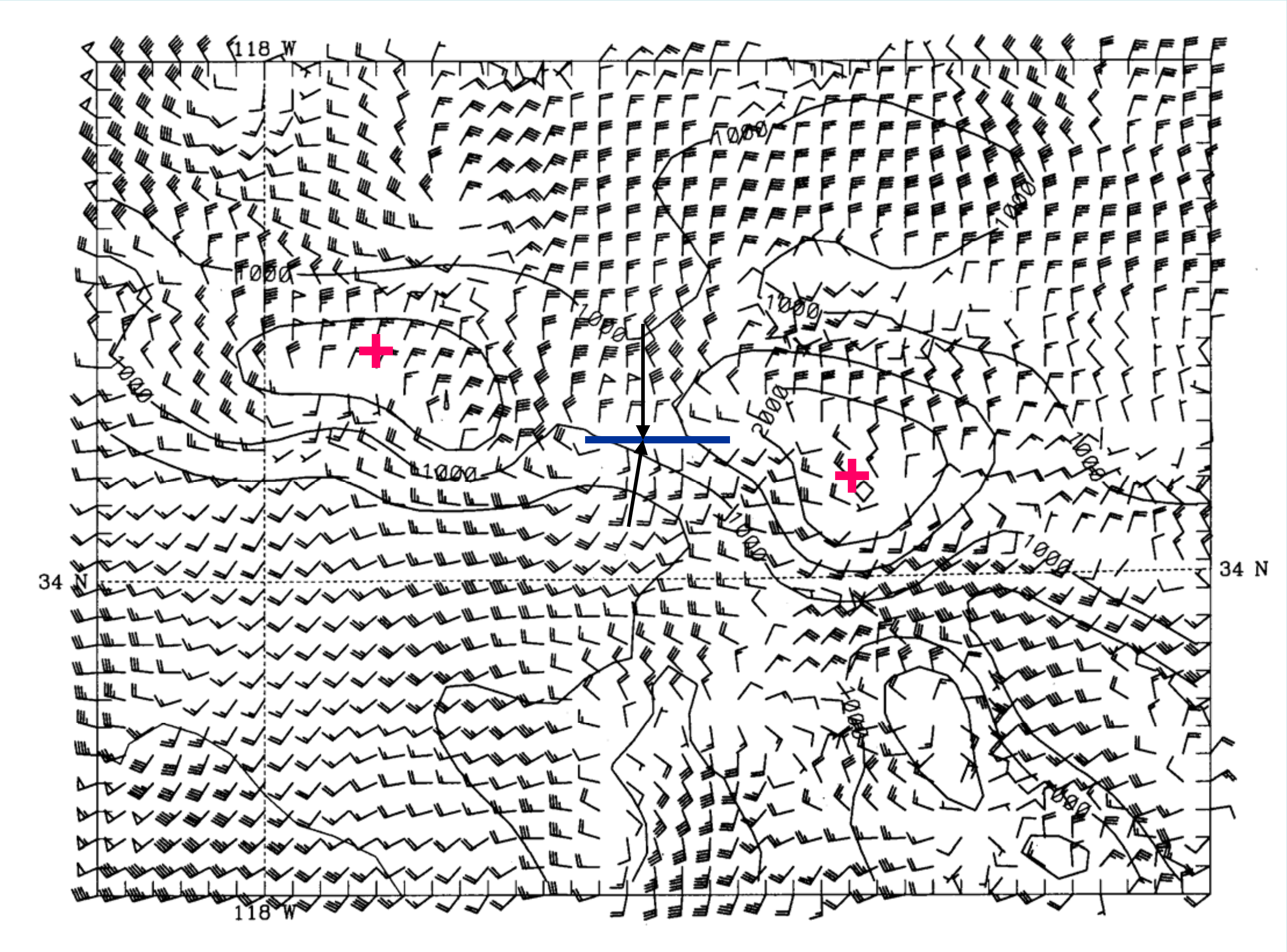


Fig. 8d

With Analysis-Nudging →
Strong opposing sfc-flow →
O_3 remains in valley→ episode

Conclusion: good meso-met model results require a good

- Meos-met model: eqs, parameterizations, grids, numerics, BCs, ICs
- Larger-scale NWP model-output
- Sfc & upper-air obs
- Experience/insight into error-sources

Final note: Well known results don't teach us anything, but the unexpected result might (or it might be wrong)

Key References

- Boucouvala, Bornstein, et al., 2003: MM5 simulations of a SCOS97 episode. *Atmos. Environ.*, **37(S2)**, 95-118.
- Mellor and Yamada, 1974: Hierarchy of turbulence closure models. *J. Atmospheric Sci.*, **31,** 1791-1806.
- Pielke, 2002: *Mesoscale Meteorological Modeling*. Academic Press, 676 pp.
- Thunis and Bornstein: 1996: J. *Atmospheric Sci.*, **53,** 380-397.

The end!

Any questions??