Stratocumulus, Towering Cumulus during Undisturbed Weather and Heavy Orographic Rains with possible Geo-Engineering Applications

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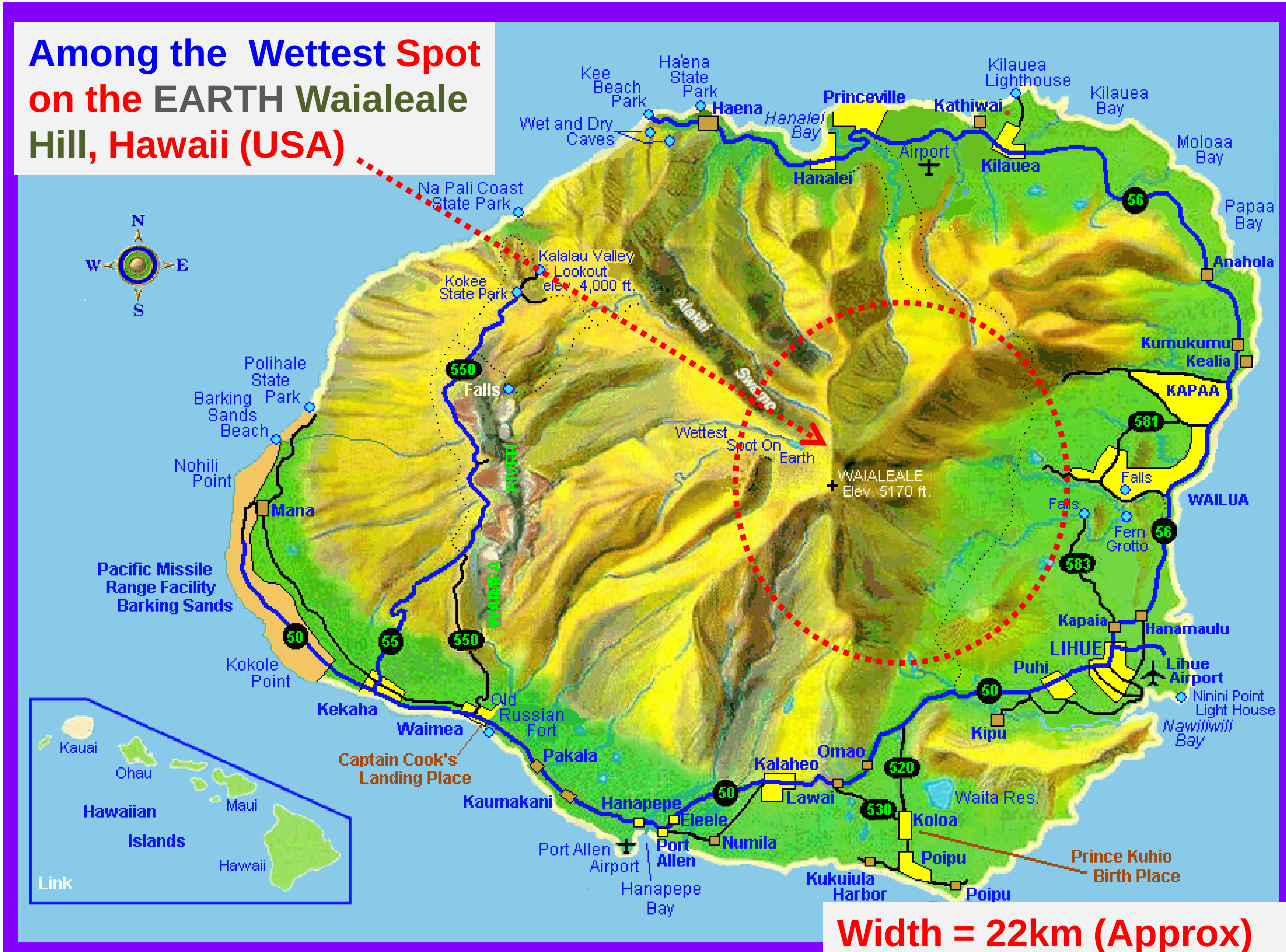
21-26 January 2013, at CAOS, IISc, Bangalore, India.

Hawaii Islands (USA)

Among the Wettest Spot on the EARTH Waialeale Hill, Hawaii (USA)



Width = 22km (Approx)

Height = 1.5 Km (Approx)

Mount Waialeale, Hawaiian Wai‘ale‘ale, peak, central Kauai island, Hawaii, U.S. Waialeale (Hawaiian: “Rippling Water”), with an elevation of 5,148 feet (1,569 metres), is a dissected (eroded) dome. It is part of a central mountain mass that includes Kawaikini (5,243 feet [1,598 metres]), the island’s highest peak, immediately south. Waialeale is located at the southeastern edge of an extinct caldera that is now a plateau called Alakai Swamp. Shrouded in clouds, Waialeale is one of the world’s wettest spots, averaging some 450 inches (11,430 mm) of rainfall annually. In 1982, 666 inches (16,916 mm) of rain were recorded on the peak, establishing an official record. Only a few miles away, however, the amount of rain drops dramatically to only 10 inches (250 mm) a year.

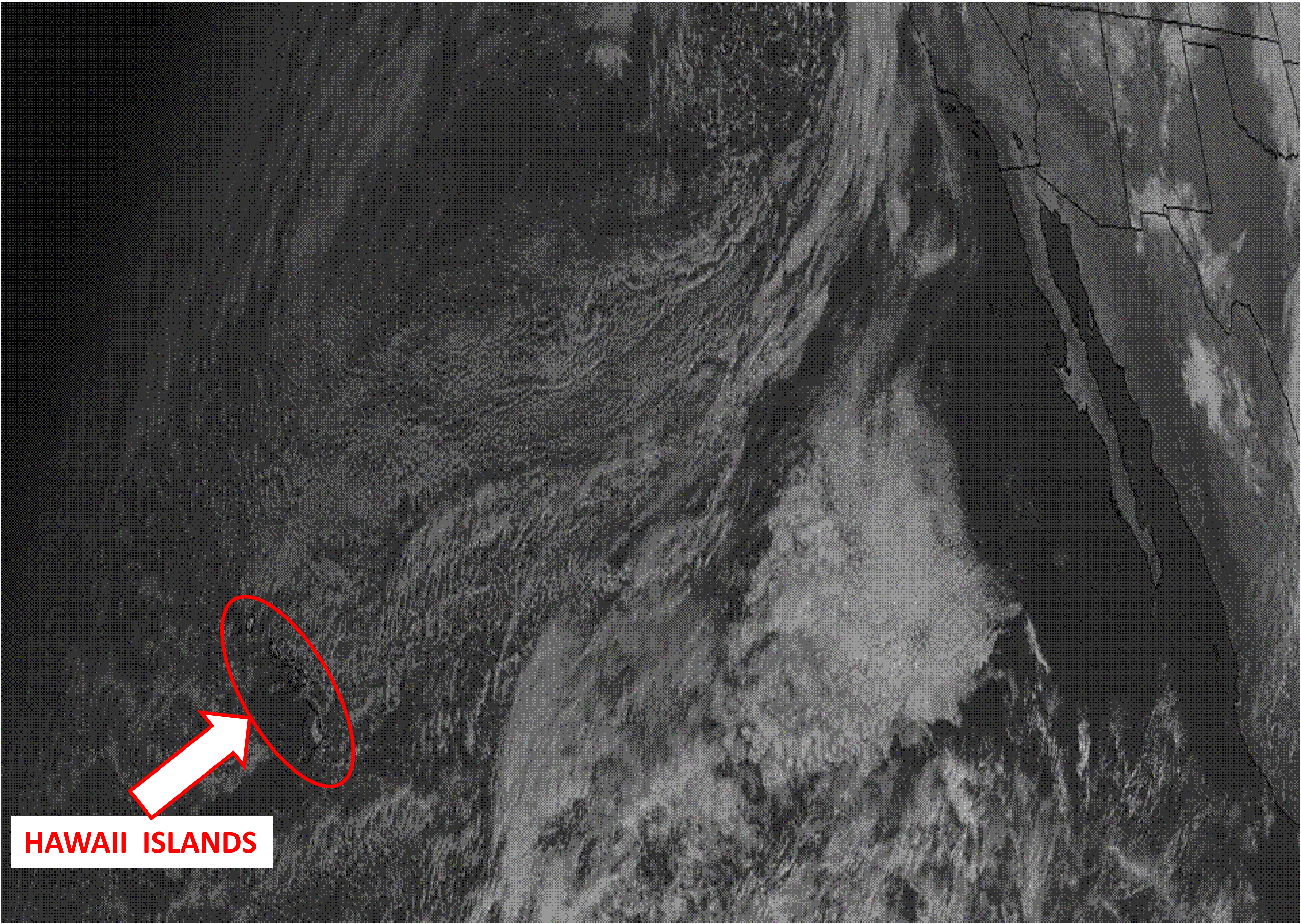
FOR COMPARISION

- MANY PLACES WITH ANNUAL HEAVY RAINS IN EXCESS OF 448 INCHES/YEAR
- Lloro, Colombia, averages 13,300mm (523.6 in) per year
- Mawsynram, Meghalaya, India, averages 11,873 mm (467 in)
- Mt Waialeale, Hawai'i, USA, annual average 11,684 mm (460 in)
- Cherrapunji, also in Meghalaya; yearly avg 11,430 mm (450 in)
- Tutunedo, Choco, Colombia, annual avg of 11394 (448 in)

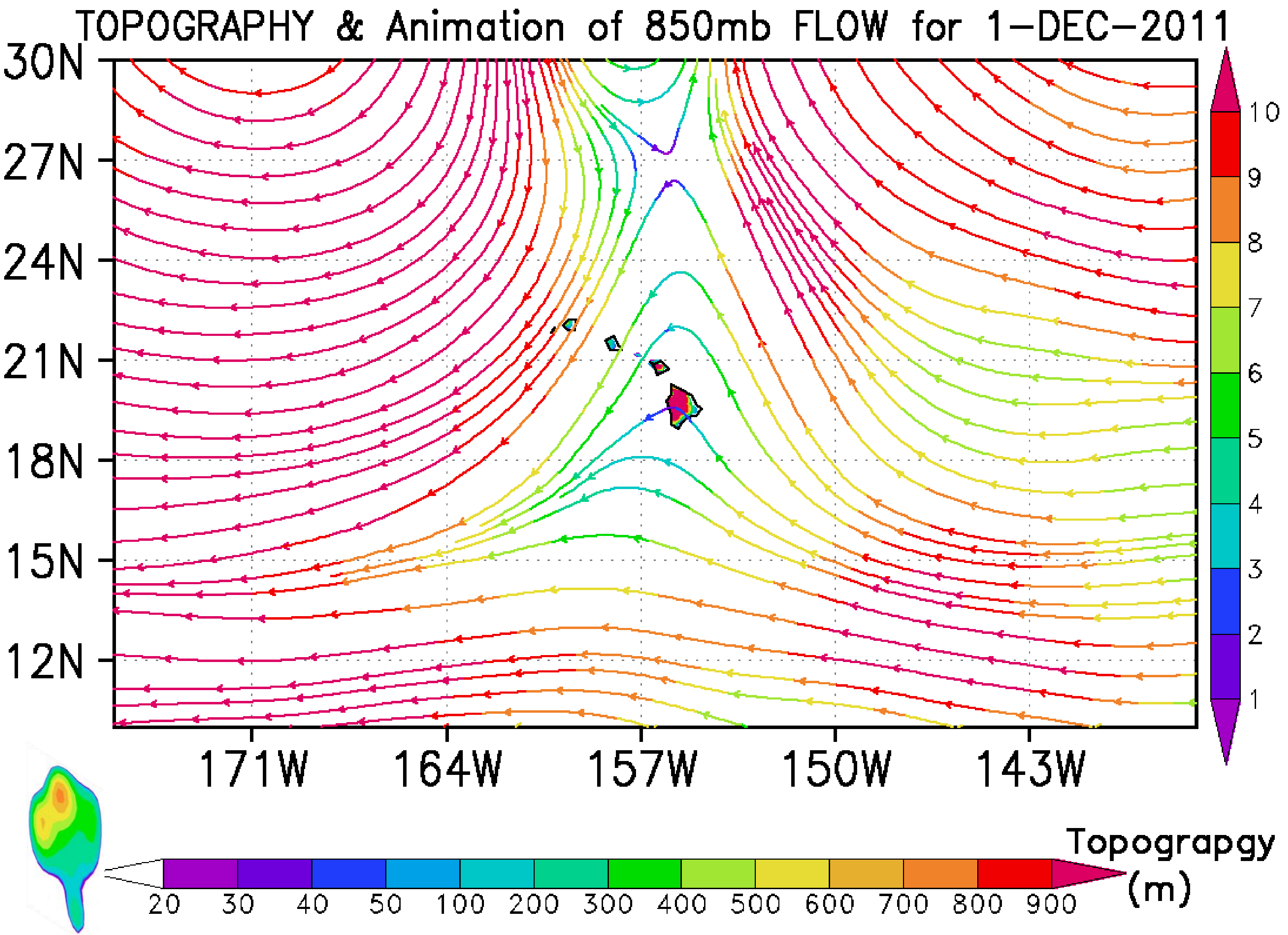
Cumulus Streets Animation over Hawaii region

http://www.geos.ed.ac.uk/abs/Weathercam/CumulusStreetsAnimation.html

GOES WEST NORTHERN HEMISPHERE VISIBLE 5 JAN 2013 8 frame : UV-MADISON

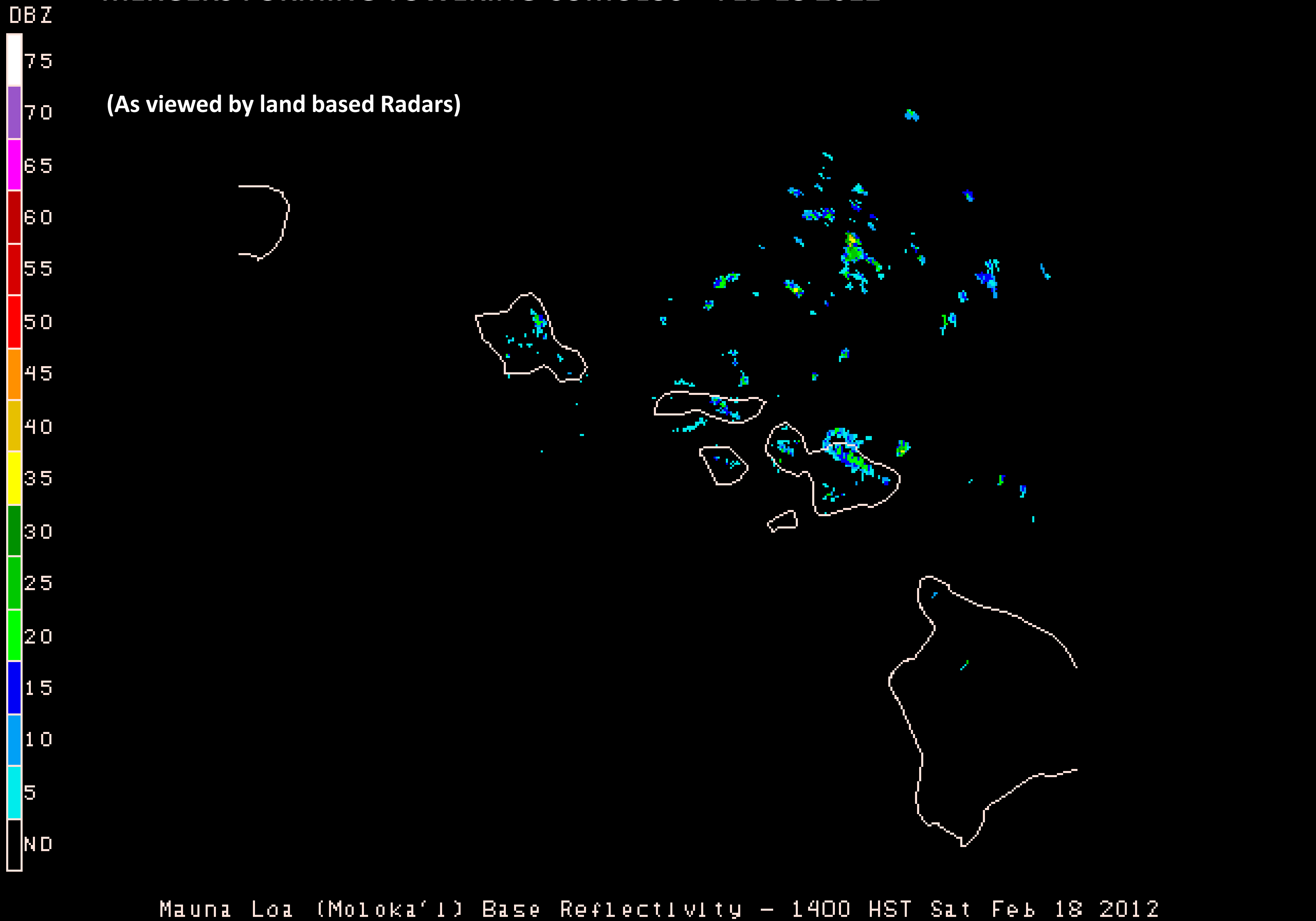


Waialeale Hill with clouds (Hawaii, USA)


TOPOGRAPHY & Animation of 850mb FLOW for 1-DEC-2011
30N
27N
24N
21N
18N
15N
12N
171W
164W
157W
150W
143W
10
9
8
7
6
5
4
3
2
1
Topograpgy
(m)
20 30 40 50 100 200 300 400 500 600 700 800 900

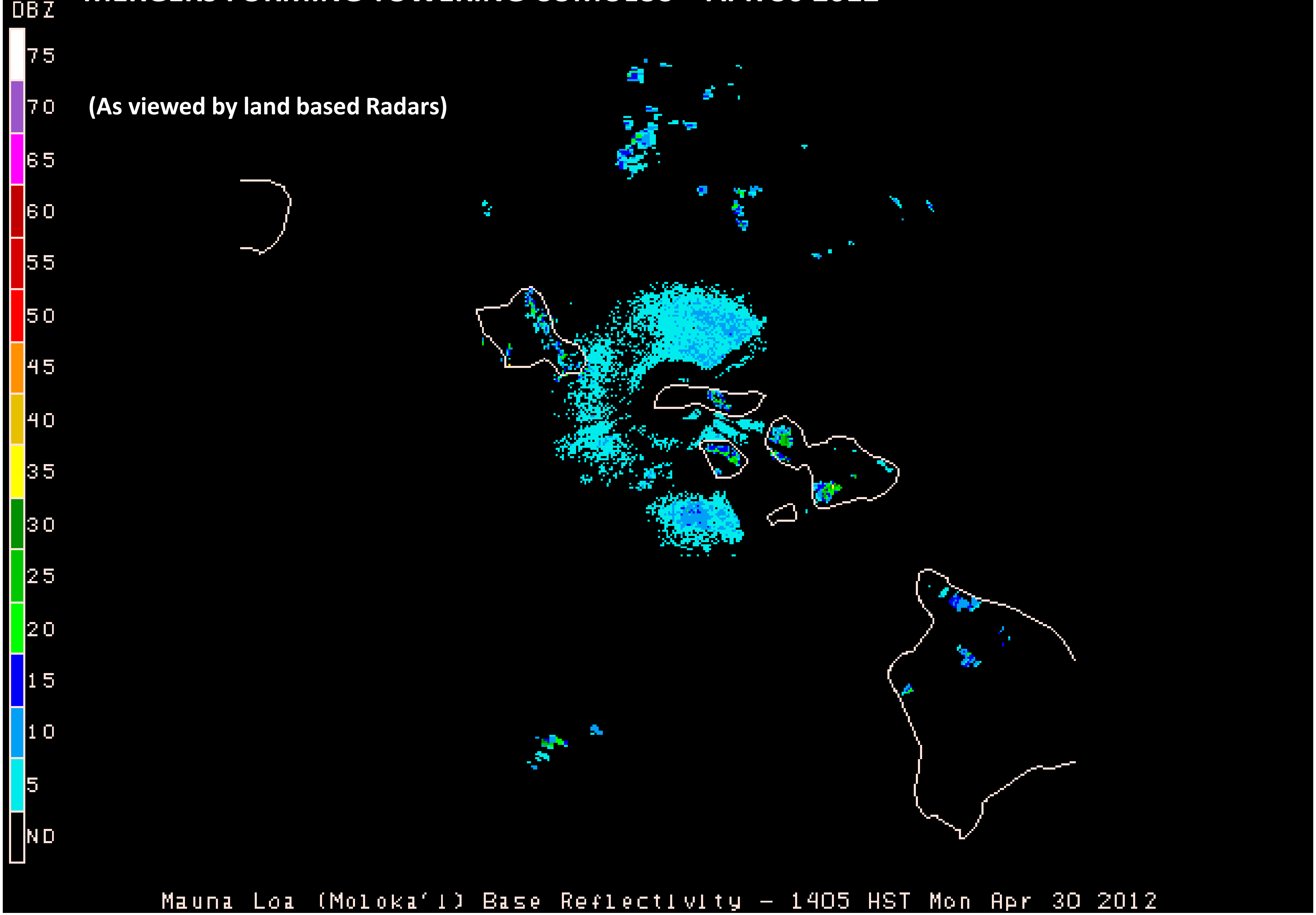
THE MARCH OF STRATOCUMULUS ACROSS THE HAWAIIAN ISLAND AND OCCASIONAL MERGERS FORMING TOWERING CUMULUS – FEB 18 2012

(As viewed by land based Radars)



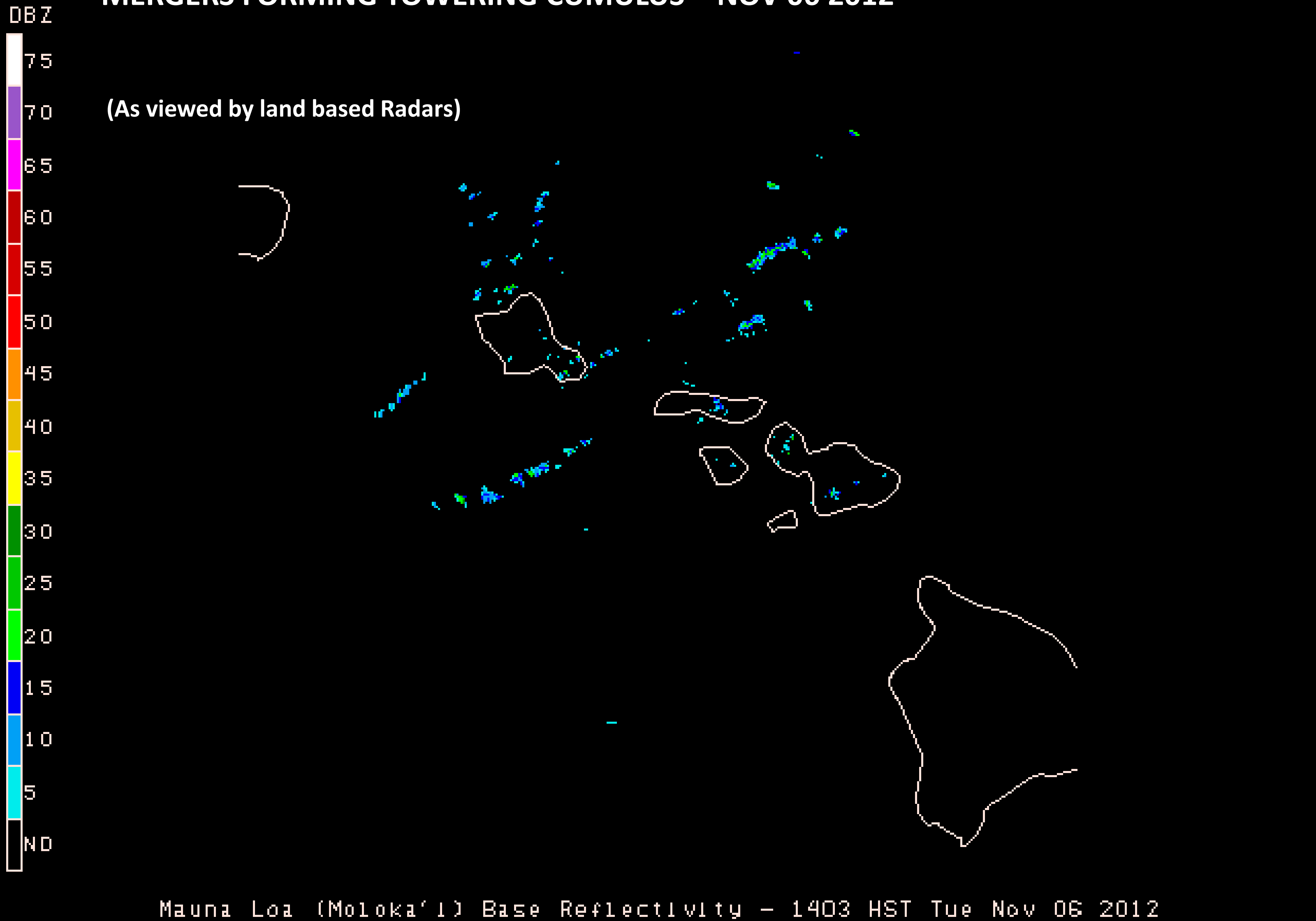
THE MARCH OF STRATOCUMULUS ACROSS THE HAWAIIAN ISLAND AND OCCASIONAL MERGERS FORMING TOWERING CUMULUS – APR 30 2012

(As viewed by land based Radars)

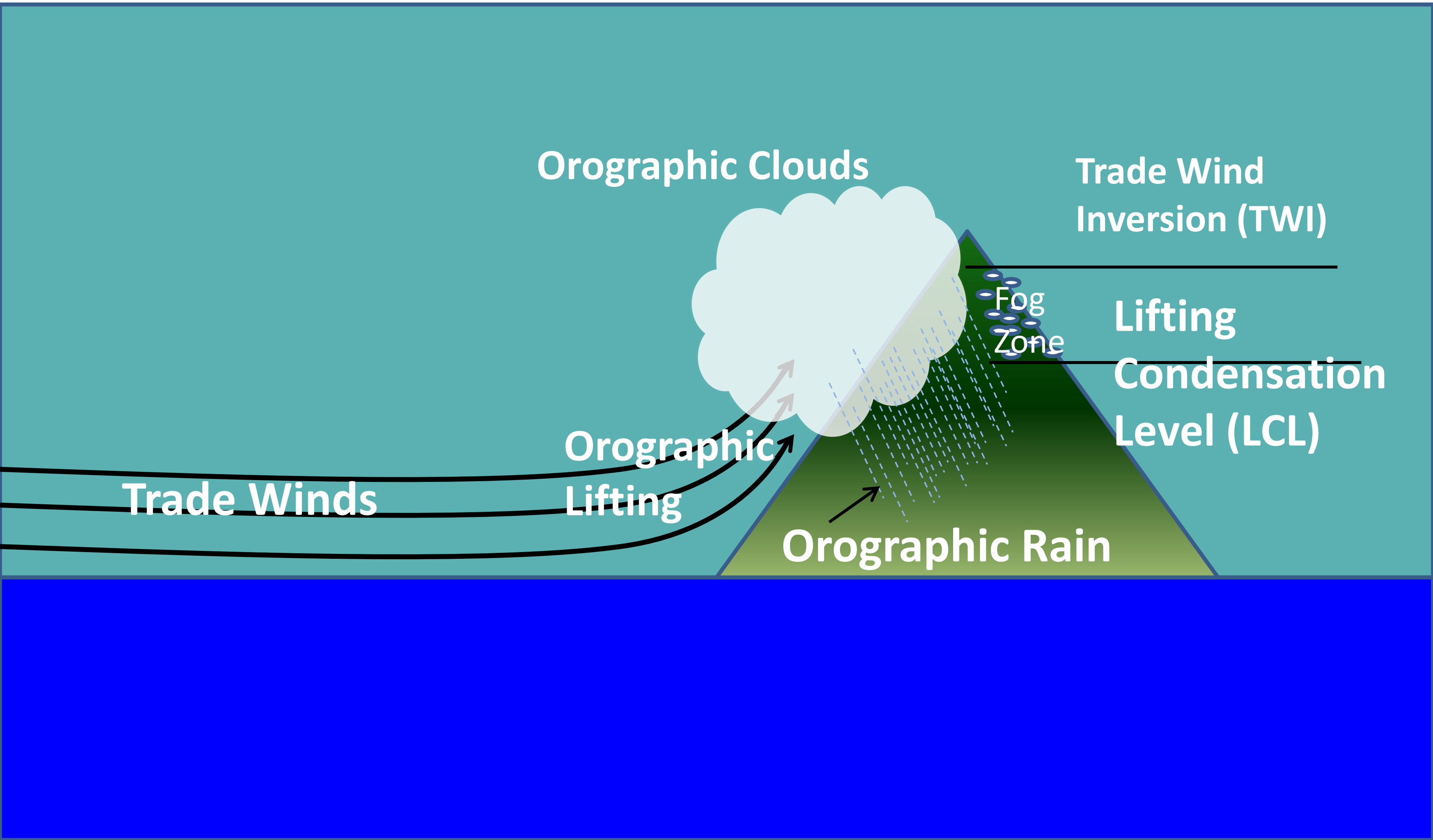


THE MARCH OF STRATOCUMULUS ACROSS THE HAWAIIAN ISLAND AND OCCASIONAL MERGERS FORMING TOWERING CUMULUS – NOV 06 2012

(As viewed by land based Radars)

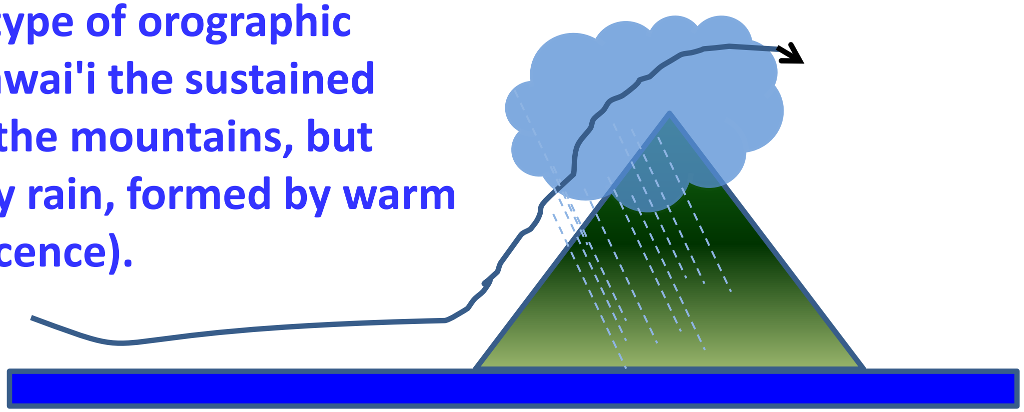


Sketch of mountain, flow and clouds



FLOW OVER OR AROUND THE MOUNTAIN

1. Stably stratified air can be forced to raise over a mountain ridge. The rising air cools, becomes saturated, and cloud and precipitation results. The rainrate can be estimated from upstream radiosonde data, i.e. the temperature, dewpoint and wind profiles. This is the most common type of orographic rainfall, especially in mid-latitudes. In Hawai'i the sustained uplift of marine boundary layer air over the mountains, but below the freezing level, results in steady rain, formed by warm rain processes (condensation and coalescence).



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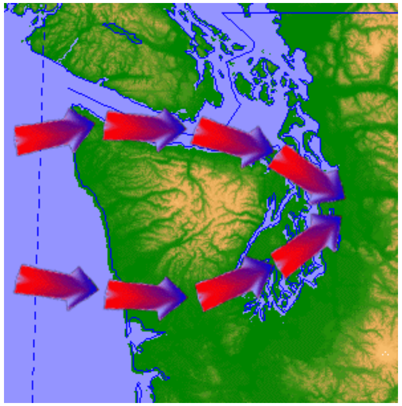
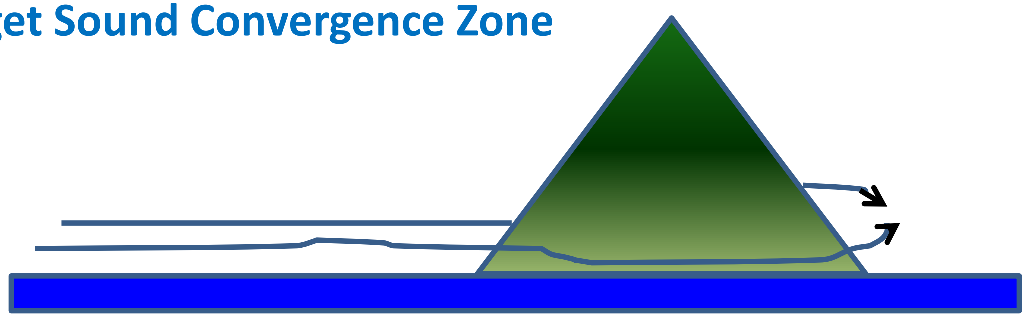
2. Stable air may be forced around an isolated mountain, rather than over it. In this case the leeside convergence of air may result in uplift and enhanced rainfall, possibly convective rainfall. An example is the Puget Sound Convergence Zone near Seattle, USA .





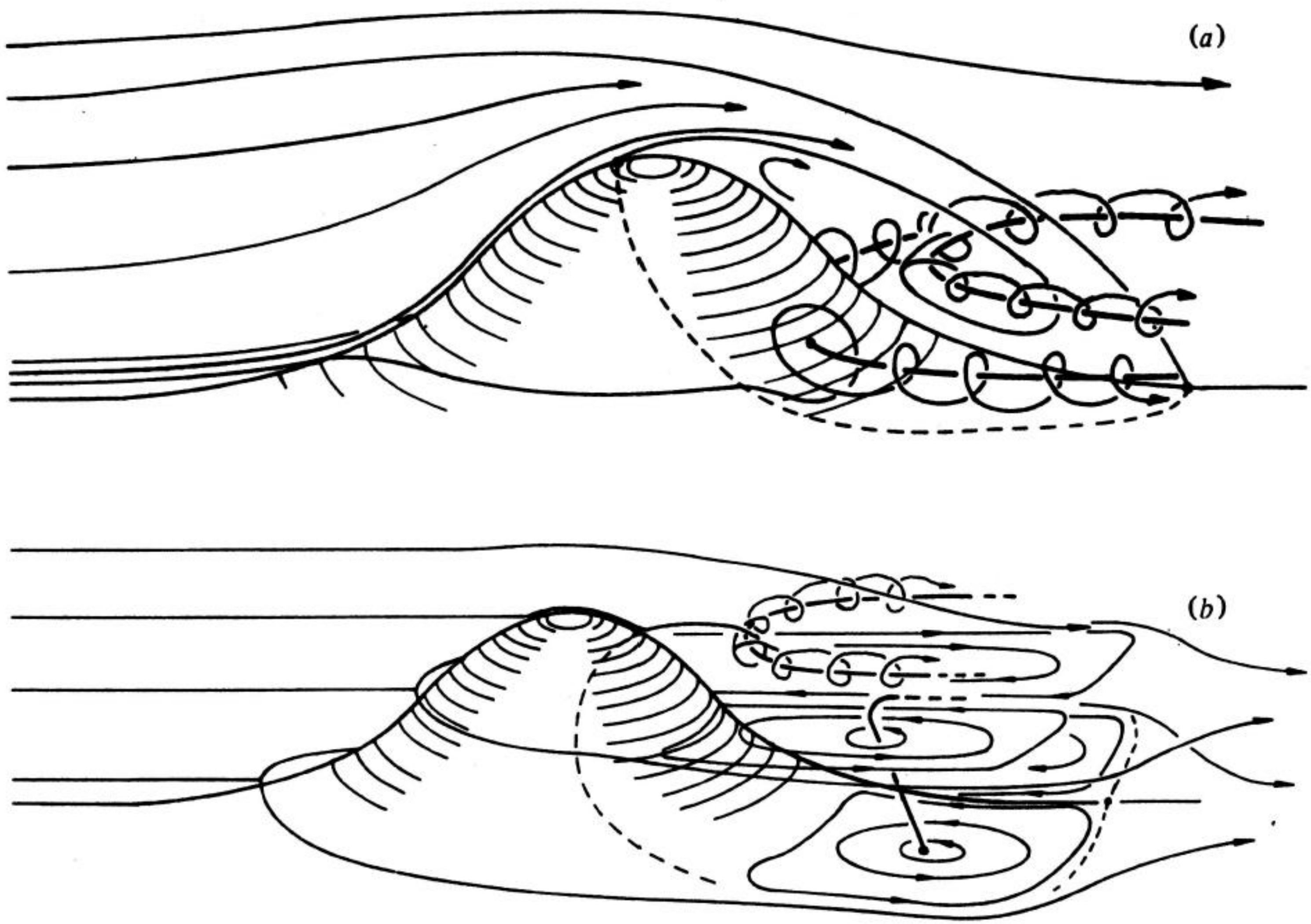


FIGURE 1. Sketch of flows over a three-dimensional hill in (*a*) neutral and (*b*) very stable stratification.

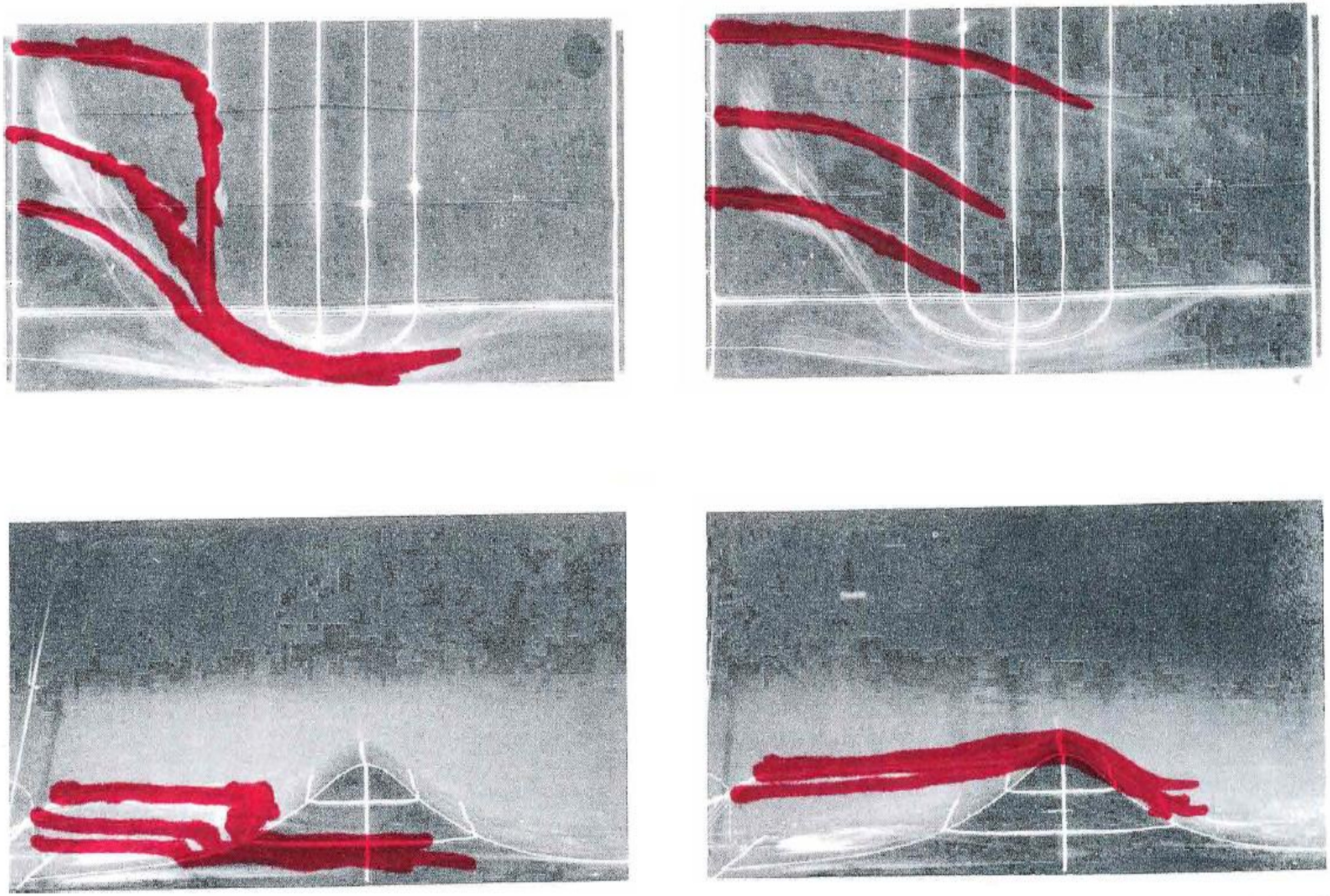
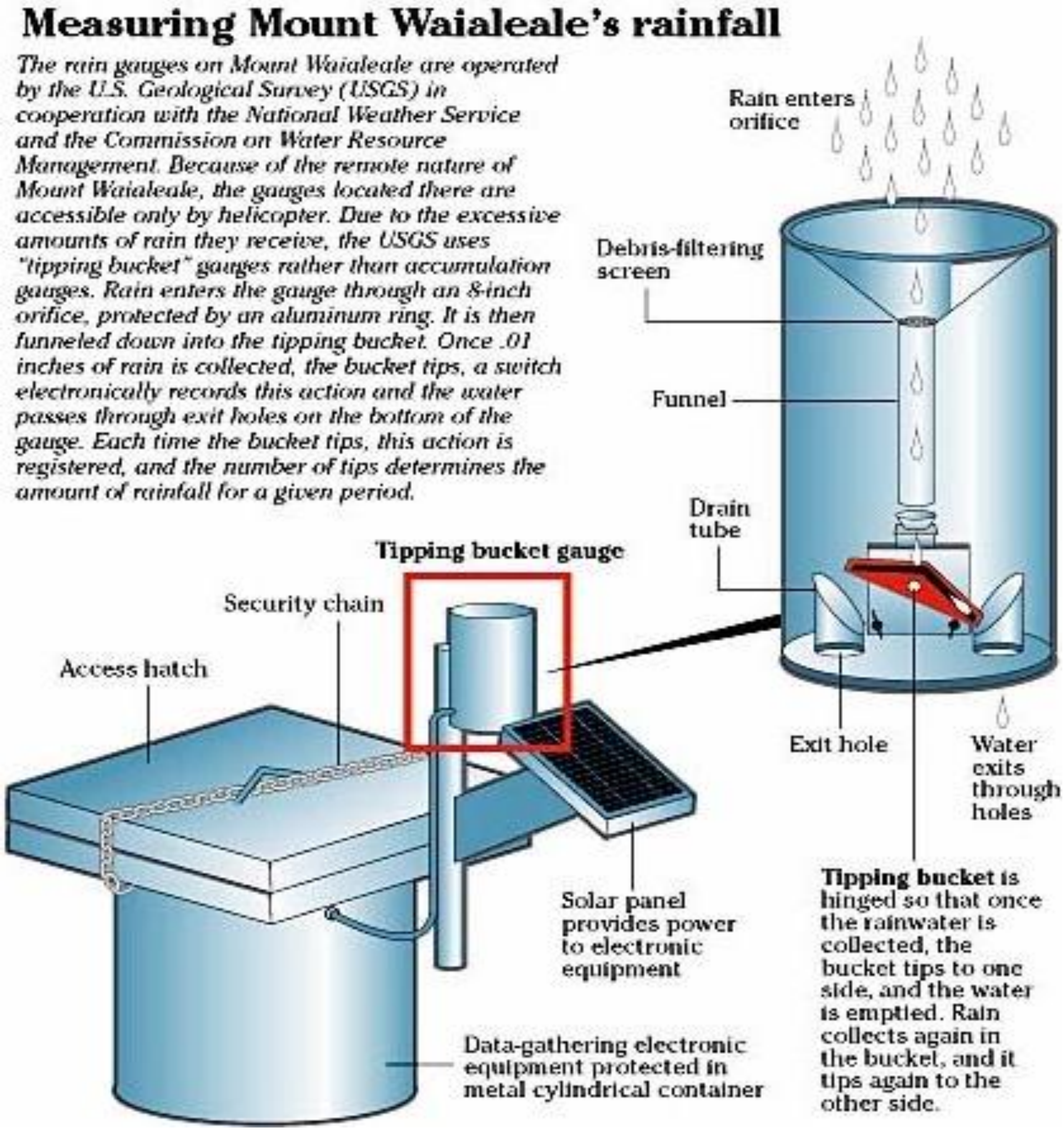


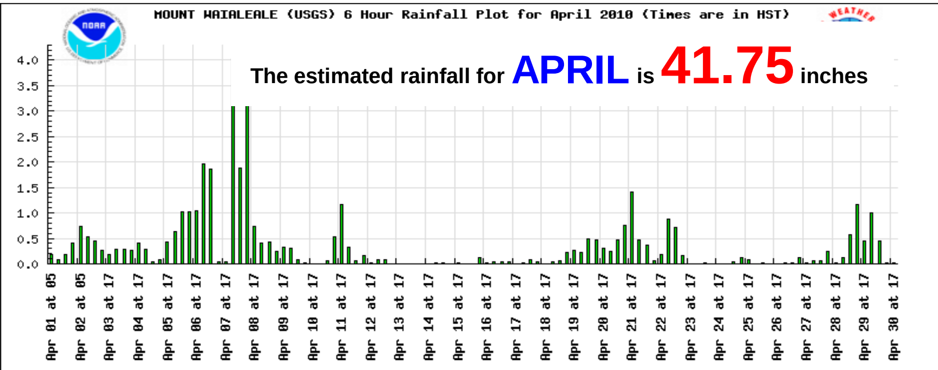
Figure 9 Plan (*upper*) and side (*lower*) views of uniformly stratified flow incident from the left on a barrier with a gap at one end with $Nh/U = 5.9$. The flow field is the same in both cases, but the dye is released from an upstream dye rake at a slightly higher level (9 mm higher, with a total obstacle height of 6.26 cm) in the right-hand frames. Flow in the left-hand frames passes around the obstacle, whereas flow in the right-hand frames passes over it, which demonstrates the abrupt change in flow character with height (from Baines 1979b).

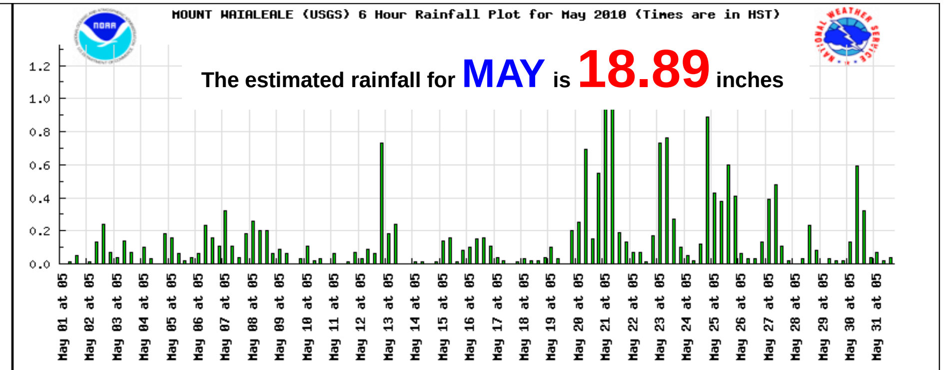


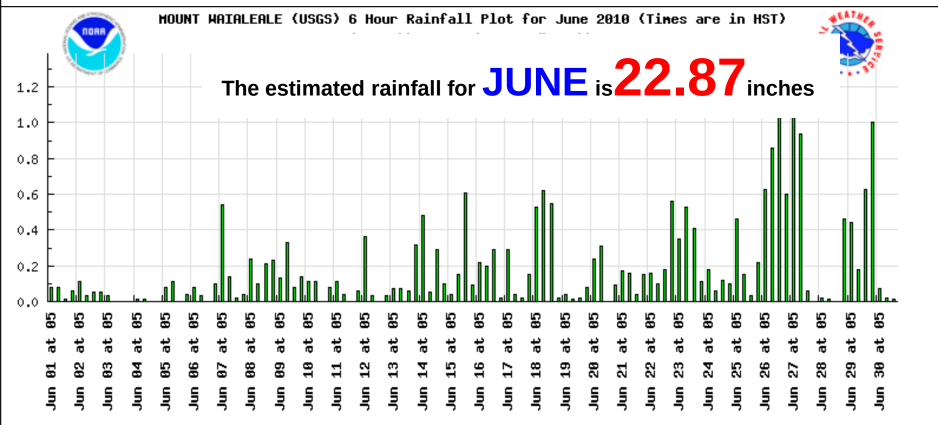
Tipping Bucket Rain Gauge

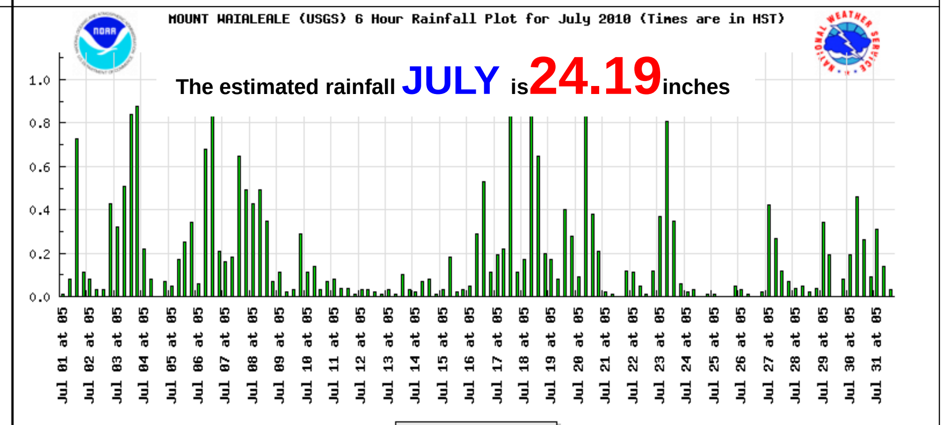
6 hour rainfall at MOUNT WAIALEALE (USGS) - 2010.

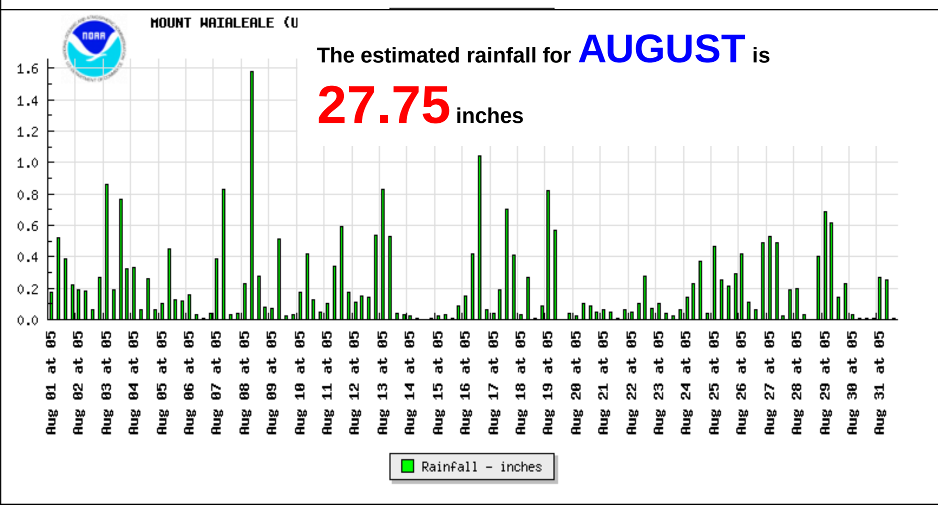
Negative values indicate missing or trace events.

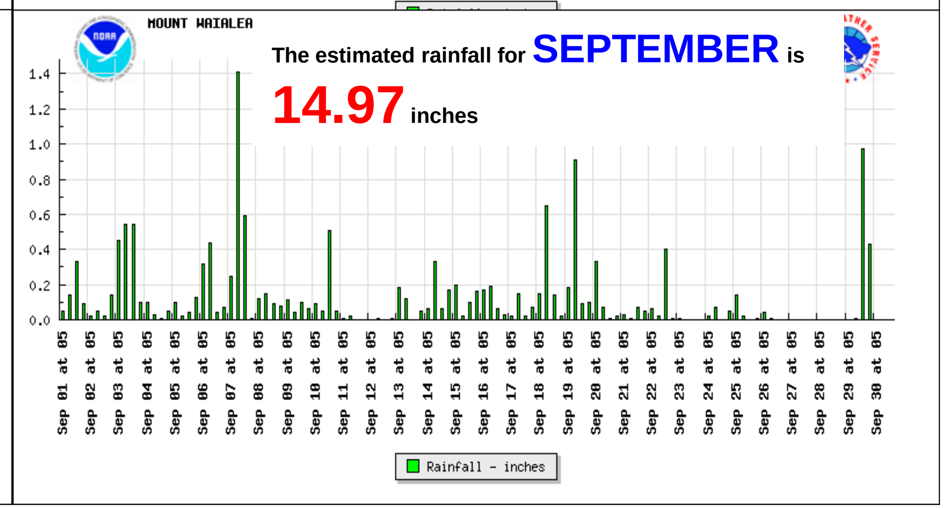










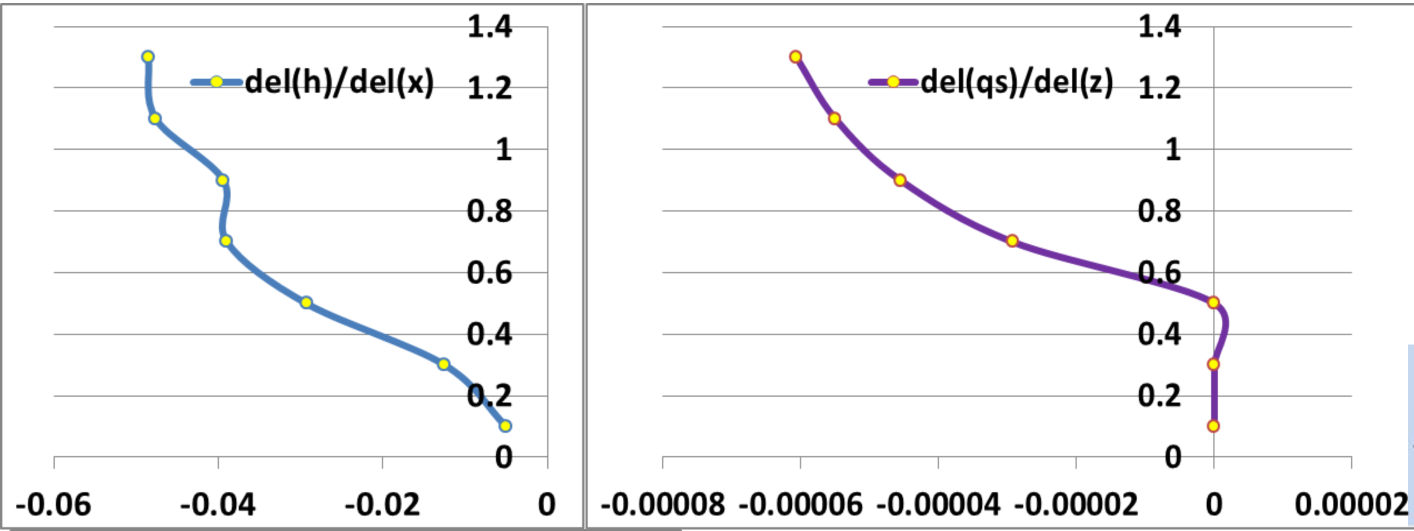


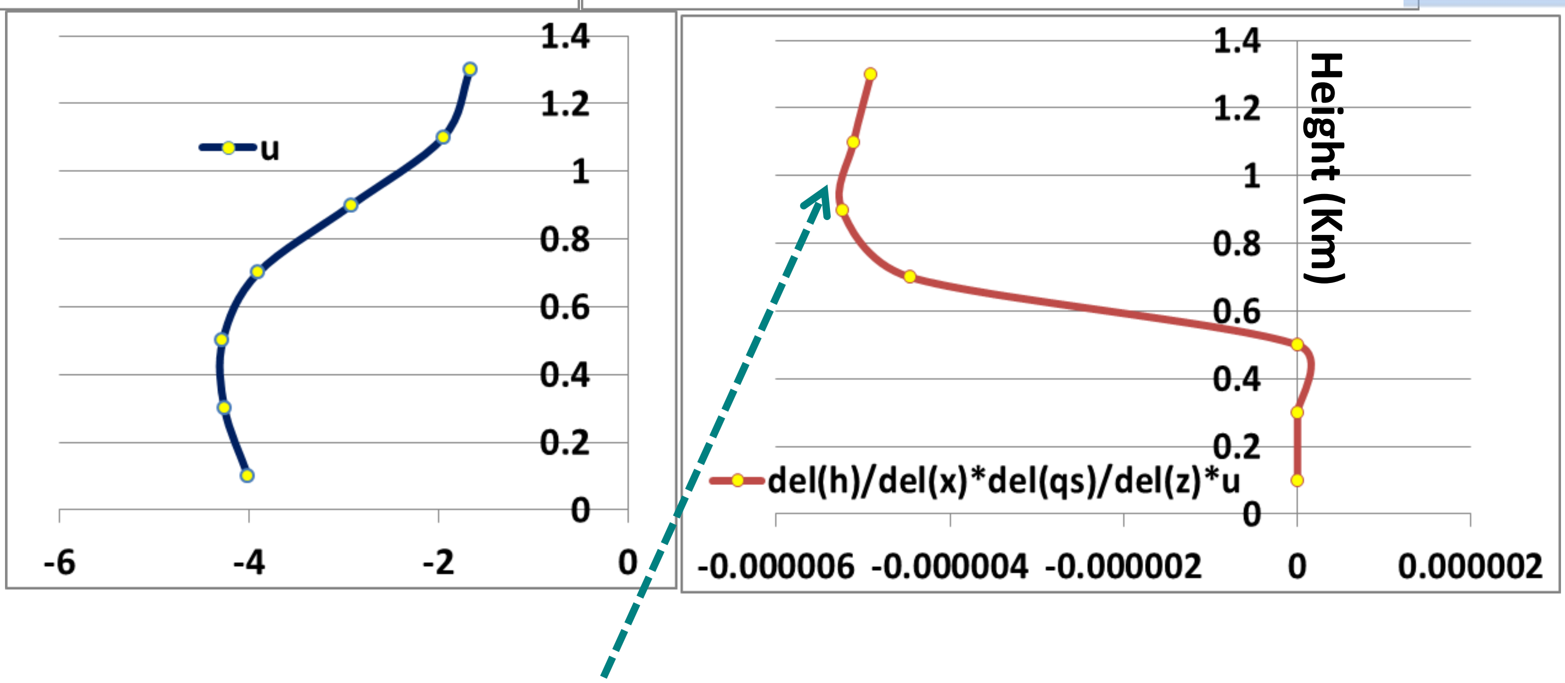
Orographic rain near Waialeale mountain (Hawaii)

$$Rain \approx \int_0^{TOP} W \frac{\partial q_s}{\partial z} dz$$

$$W \approx U \frac{\partial h}{\partial x}$$

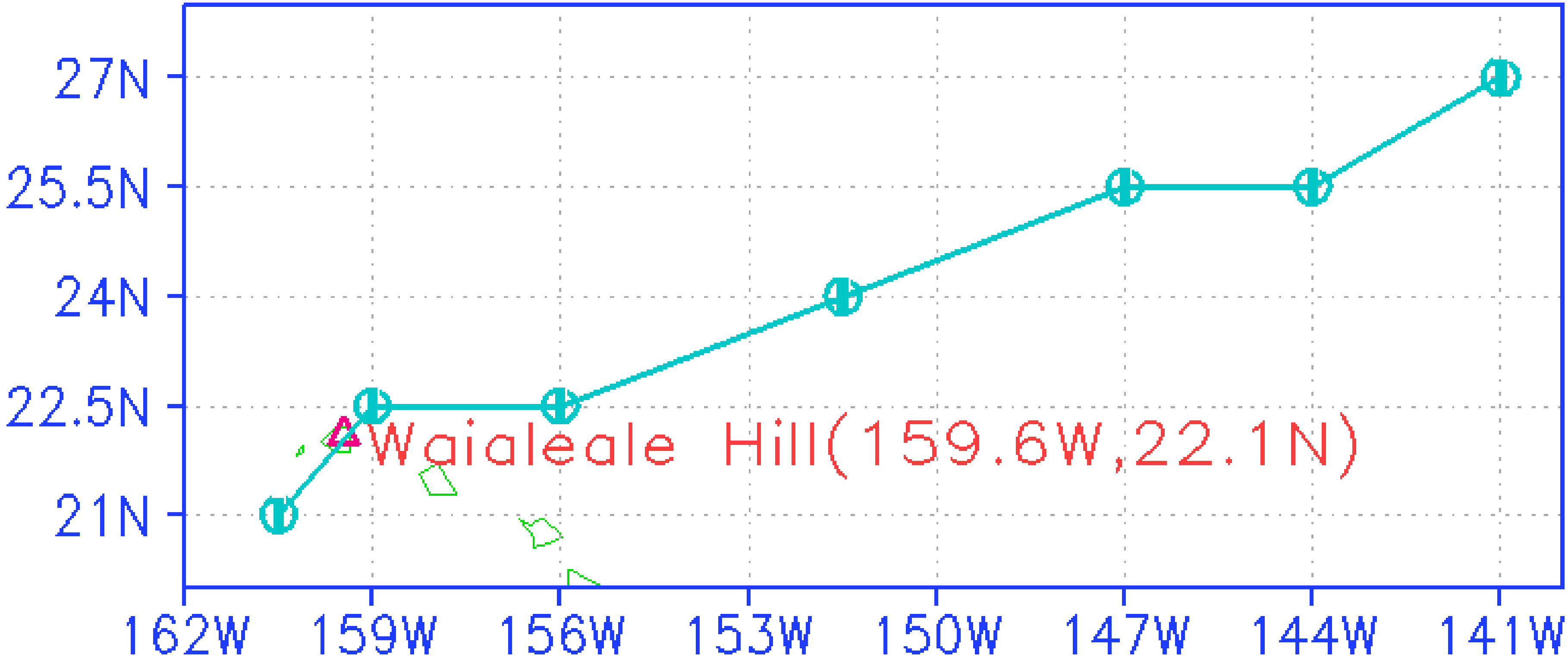
$$Rain \approx \int_0^{TOP} U \frac{\partial h}{\partial x} \frac{\partial q_s}{\partial z} dz$$



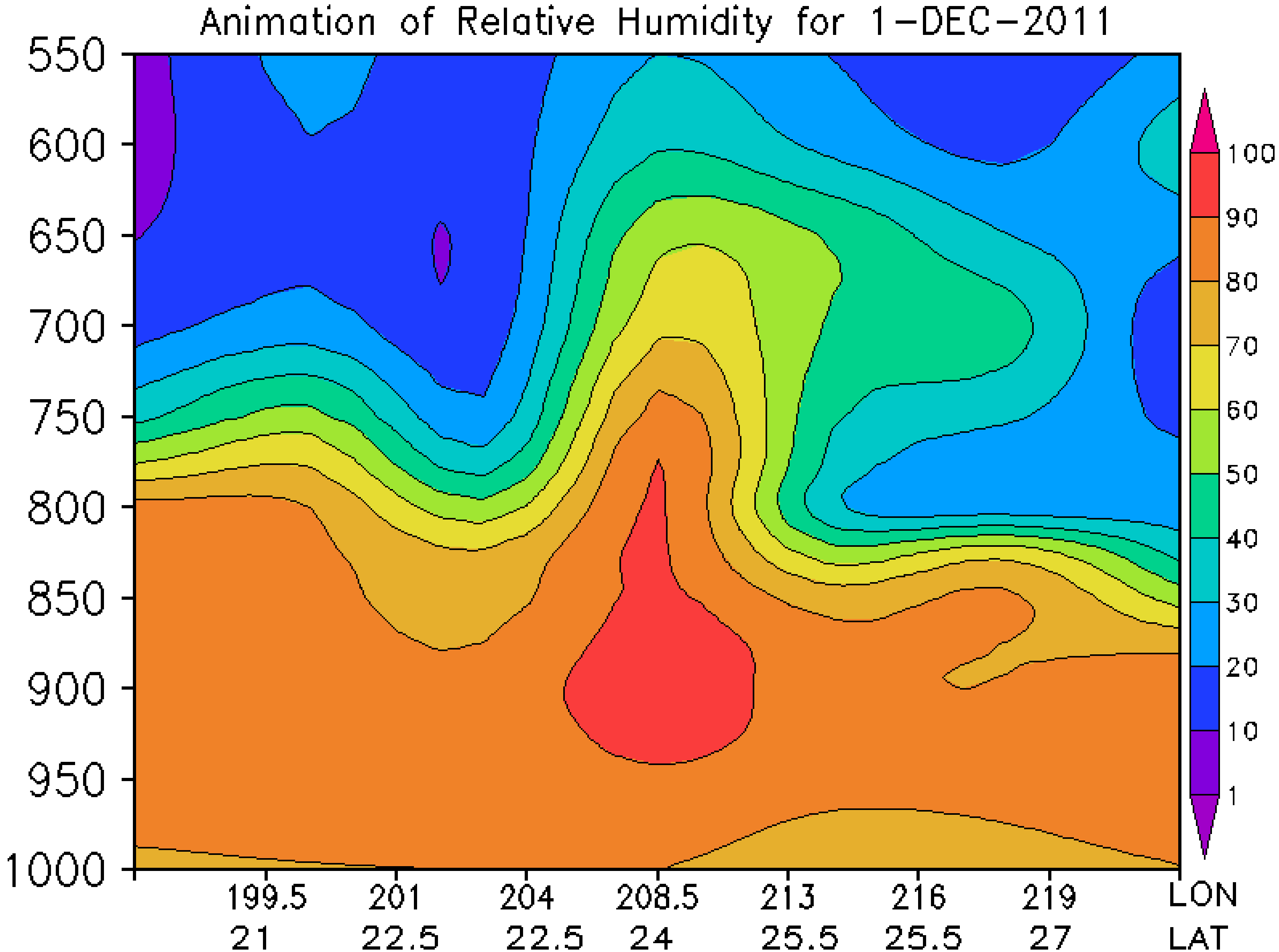


Maximum generation of orographic rain from disposition of Super Saturation

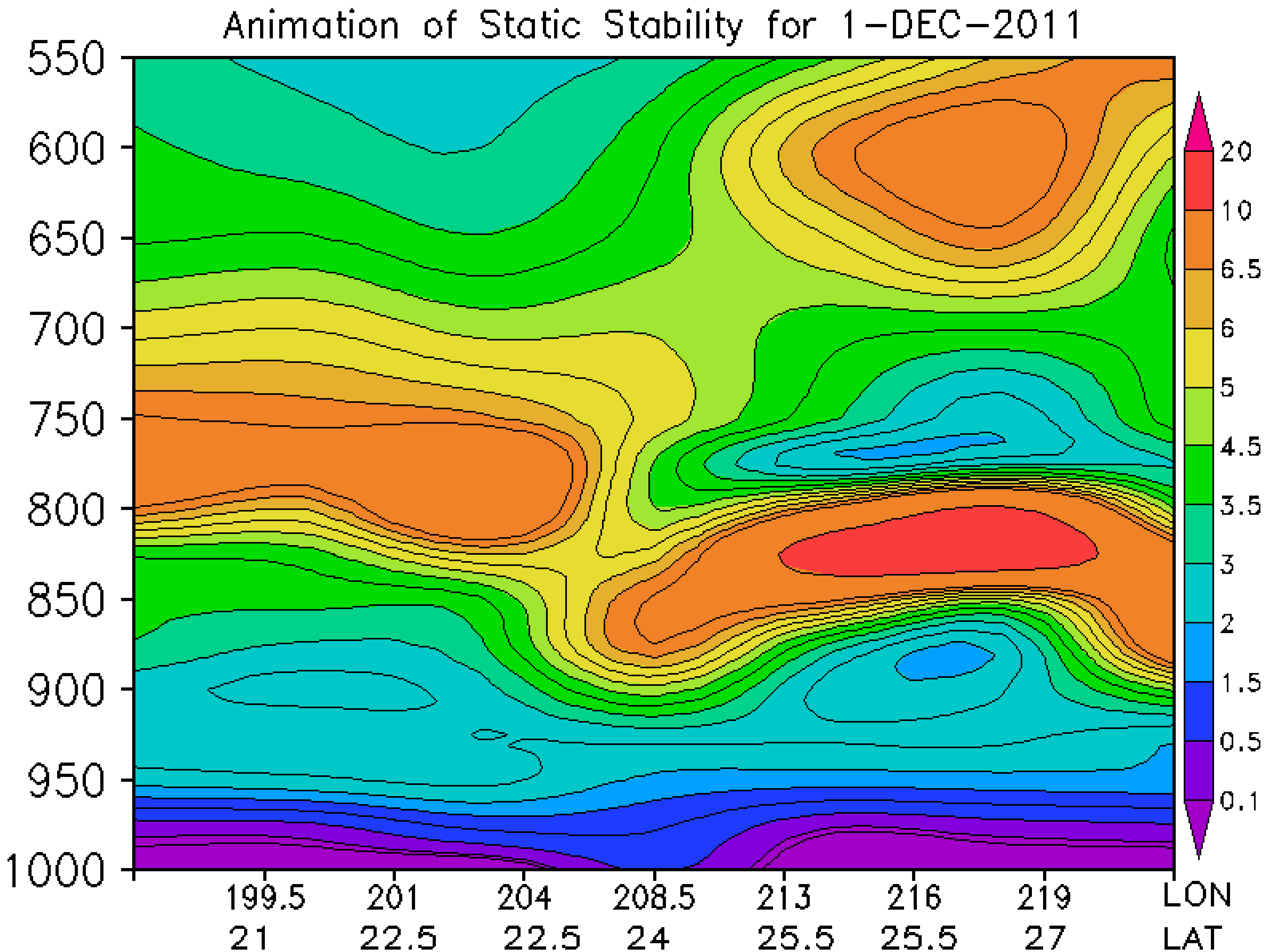
A CLIMATOLOGICAL BACK TRAJECTORY FROM WAIALEALE



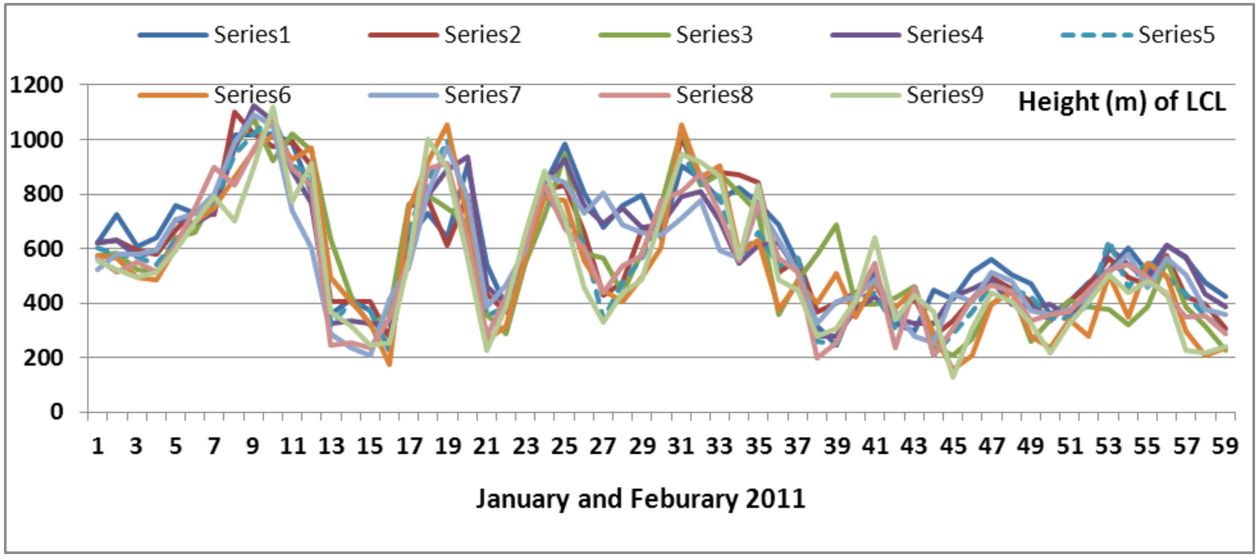
Relative Humidity along the flow (850mb) over Hawaii region

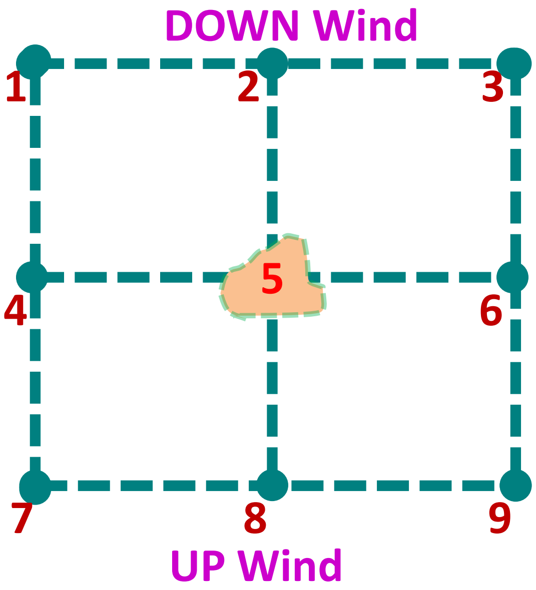


Static Stability (*x1000*) calculated Across mean flow over Hawaii



Cloud base (LCL) over Lihue (Waialeale)



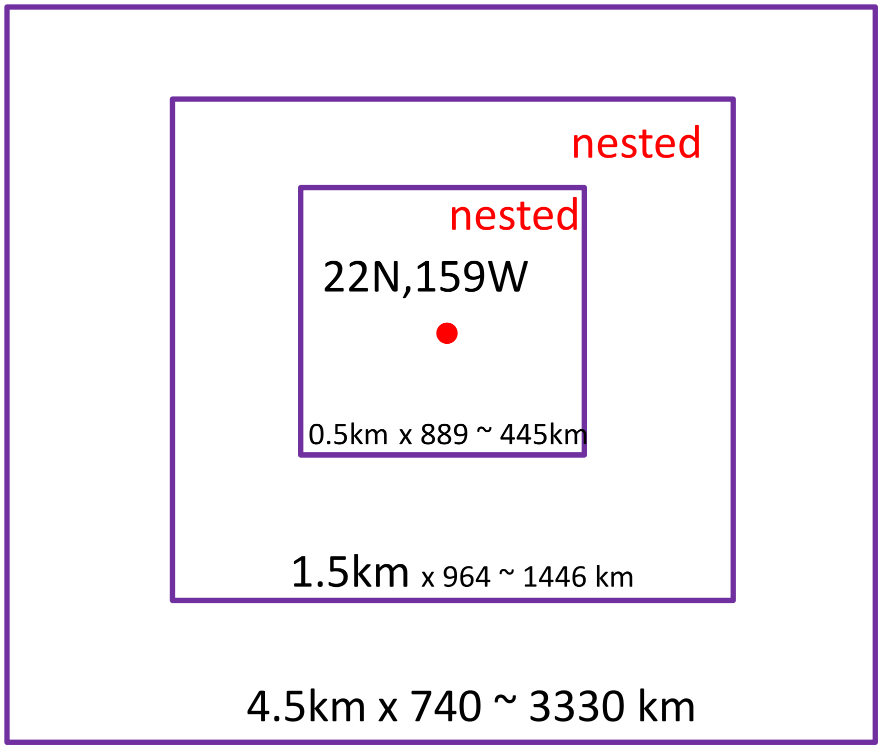


Lihue (Waialeale, Hawaii)

Data Source: ERAInterim resolution, 1.5x1.5 deg lon-lat

WRF-ARW OUTLINE

- 42 Vertical levels
- Microphysics : Goddard
- Longwave Radiation : Goddard
- Shortwave Radiation : Goddard
- Planetary boundary Physics : Yonsei Univerity Scheme
- Cumulus_parametrization : NIL Explicit clouds (resolved)
- Initial Conditions : GFS (1^0x1^0)
- Lateral Boundary Conditions: GFS (1^0x1^0)



Simple non precipitating stratocumulus modeling

Simple non precipitating stratocumulus modeling, Murray and Anderson (1965)

The vorticity equation is expressed by

$$\frac{\partial}{\partial t}\nabla^2\psi = -J(\psi,\nabla^2\psi) + \frac{g}{T_M}\frac{\partial T'}{\partial x} + \nu_M\nabla^4\psi \text{ , i.e.,} \qquad (11.12)$$

Local Change of Vorticity = *Vorticity Advection* + *Buoyancy Term* + *Friction*

$$\frac{\partial\psi}{\partial z} = u \qquad (11.13)$$

and

$$\frac{\partial\psi}{\partial x} = -w \text{ ,} \qquad (11.14)$$

so that the continuity equation

so that the continuity equation

$$\frac{\partial u}{\partial x} + \frac{\partial w}{\partial z} = 0 \qquad (11.15)$$

is satisfied.

According to equation (11.12), **The buoyancy field** $(\frac{\partial T'}{\partial x} > 0)$ contributes to **vorticity generation,** *i.e.*, to $\frac{\partial}{\partial t}\nabla^2\psi > 0$.

The thermal energy equation is taken as

$$\frac{dT}{dt} = -w\frac{g}{C_p} + \left(\frac{dT}{dt}\right)_{ph} + \nu_T \nabla^2 T\,, \tag{11.16}$$

where

$$T = T_M + T_0(z) + T'\,. \tag{11.17}$$

$T_0(z)$ is the initial stratification of temperature of the undisturbed state and is known, and T_M is the (constant) mean domain value. Equation (11.16) describes the change of temperature T from which the changes of T' can be deduced. $\left(\frac{dT}{dt}\right)_{ph}$ is the diabatic change of temperature due to phase change – either condensational heating or evaporative cooling. The changes **in liquid water and water vapor respectively** arising from phase changes and diffusion may be expressed by:

$$\frac{dq_l}{dt} = \left(\frac{dq_l}{dt}\right)_{ph} + \nu_q \nabla^2 q_l \tag{11.18}$$

$$\frac{dq_v}{dt} = \left(\frac{dq_v}{dt}\right)_{ph} + \nu_q \nabla^2 q_v \tag{11.19}$$

Equations (11.12) through (11.19) constitute a closed system provided the phase change terms are adequately defined. To that end, if $q_v > q_{vs}$, where q_{vs} is the saturation value, the disposition of supersaturation is parameterized from the relation

CHANGE OF PHASE

$$\left(\frac{dq_v}{dt}\right)_{ph} = -\frac{q_v - q_{vs}}{\Delta t} \qquad (11.20)$$

Once saturation is reached, the local change for equation (11.19) is set to zero. Furthermore, one sets

$$\left(\frac{dq_l}{dt}\right)_{ph} = -\left(\frac{dq_v}{dt}\right)_{ph} \qquad (11.19)$$

Thus saturation results in removal of water vapor and the formation of an equivalent amount of liquid water.

Liquid water in an unsaturated environment evaporates until the environment is saturated. This is expressed by

$$\left(\frac{dq_l}{dt}\right)_{ph} = -\frac{q_{vs} - q_v}{\Delta t} \qquad (11.20)$$

This is the parameterization for the evaporative process. Again, an equivalent increase in water vapor in the water vapor equation is defined by the relation

$$\left(\frac{dq_v}{dt}\right)_{ph} = -\left(\frac{dq_l}{dt}\right)_{ph} \qquad (11.21)$$

The condensation heating or evaporative cooling for the thermal equation is next defined by the statement

$$C_p\left(\frac{dT}{dt}\right)_{ph} = -L\left(\frac{dq_v}{dt}\right)_{ph} \quad \text{or} \quad C_p\left(\frac{dT}{dt}\right)_{ph} = +L\left(\frac{dq_l}{dt}\right)_{ph} \tag{11.22}$$

Here one must use the appropriate sign for heating or cooling within the first law of thermodynamics.

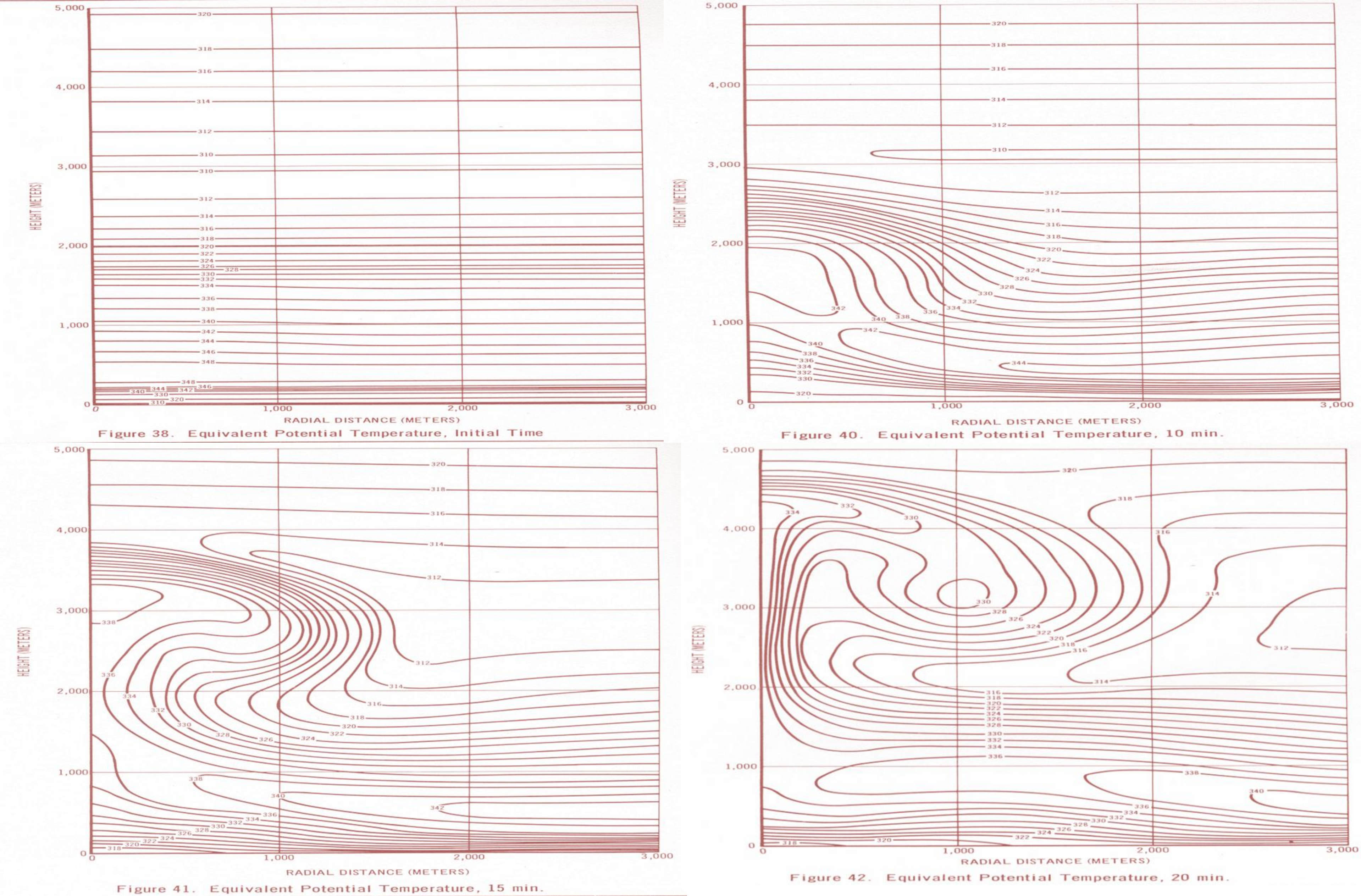


Fig. 11.3 x-z cross-sections of the model potential temperature at time a) 0, b) 10, c) 15, and d) 20 minutes illustrating the evolution of the model moist shallow convection. From Murray and Anderson (1965).

20 MINUTE GROWTH OF A CLOUD

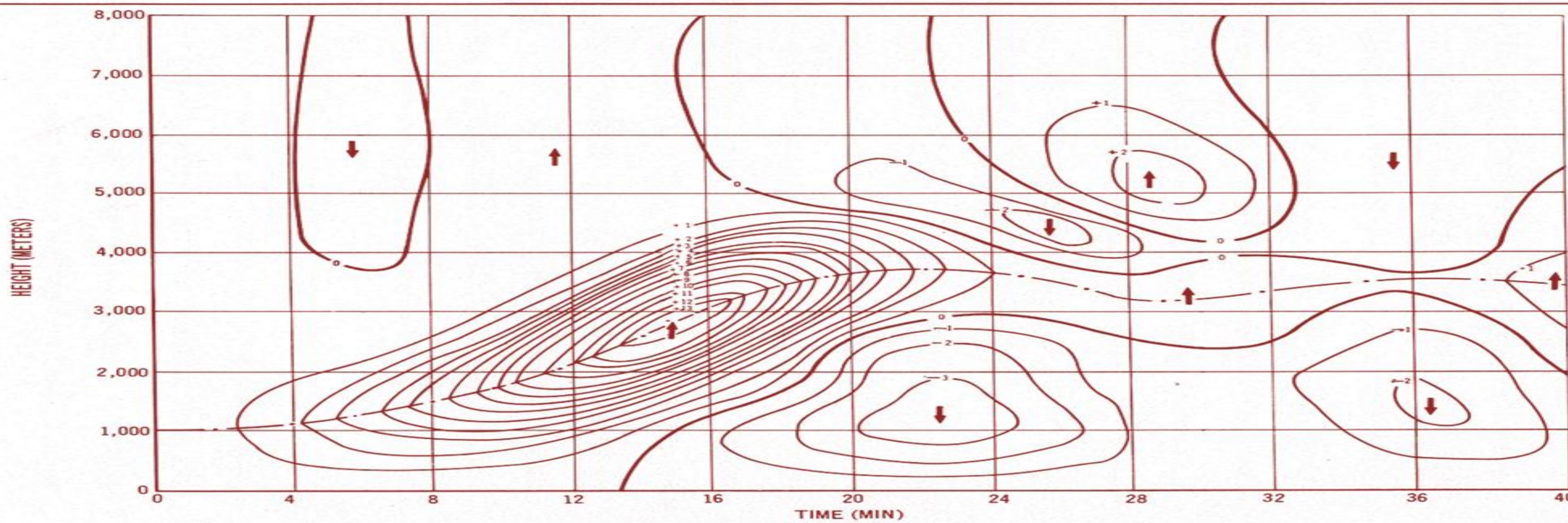


Figure 21. Time Section of Vertical Component of Velocity on the Central Axis

W

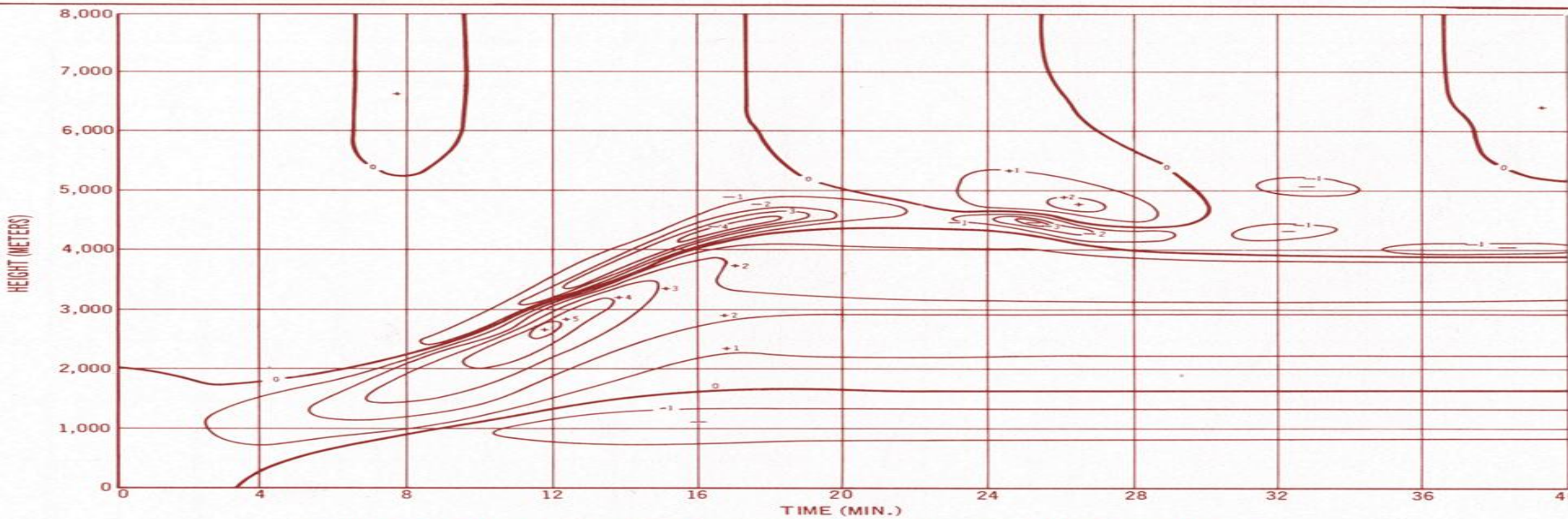


Figure 22. Time Section of Temperature Departure on the Central Axis

Fig. 11.5 Time-height cross-sections of a) vertical velocity, and b) temperature departure. Centered at x=0. From Murray and Anderson (1965). **OVER SHOOTING TIME** →

Goddard microphysics in WRF

The Water substance components of the model and their rates of growth includes a **drop size distribution** N(D) is assumed as

$$N(D) = N_0 e^{-\lambda D}$$

i.e. the number of drops N (per unit volume of space) of a given size D is inversely proportional to that size. N_0, the value of N at D=0, is called **an intercept parameter.** λ is called the slope of the particle size distribution and is empirically expressed by

$$\lambda = \left(\frac{\pi \rho_x N_0}{\rho q_x} \right)^{1/4} \quad (11.31)$$

where ρ_x and q_x are the density and mixing ratio of the specific hydrometeor.

The model uses values of the intercept parameter for graupel, snow and rain that are around 0.04, 0.04 and 0.08 cm^{-4} respectively. The densities for graupel, snow and rain are respectively 0.4 g cm^{-3}, 0.1 g cm^{-3} and 1 g cm^{-3}. For cloud ice, the model assumes a single value of size with diameter of 2x10^{-3} cm and a density of 0.917 g cm^{-3}.

The Prognostic equations for the components of the water substance include the following:

a) Cloud Water

$$\bar{\rho}\frac{\partial q_c}{\partial t} = -\frac{\partial}{\partial x}(\bar{\rho}uq_c) - \frac{\partial}{\partial y}(\bar{\rho}vq_c) - \frac{\partial}{\partial z}(\bar{\rho}wq_c) + \bar{\rho}(c - e_c) - T_{qc} + D_{qc} \tag{11.32}$$

b) Rain water

$$\bar{\rho}\frac{\partial q_r}{\partial t} = -\frac{\partial}{\partial x}(\bar{\rho}uq_r) - \frac{\partial}{\partial y}(\bar{\rho}vq_r) - \frac{\partial}{\partial z}[\bar{\rho}(w - V_r)q_r] + \bar{\rho}(-e_r + m - f_r) - T_{qr} + D_{qr} \tag{11.33}$$

c) Ice

$$\bar{\rho}\frac{\partial q_i}{\partial t} = -\frac{\partial}{\partial x}(\bar{\rho}uq_i) - \frac{\partial}{\partial y}(\bar{\rho}vq_i) - \frac{\partial}{\partial z}(\bar{\rho}wq_i) + \bar{\rho}(d_i - s_i) - T_{qi} + D_{qi} \tag{11.34}$$

d) Snow

$$\bar{\rho}\frac{\partial q_s}{\partial t} = -\frac{\partial}{\partial x}(\bar{\rho}uq_s) - \frac{\partial}{\partial y}(\bar{\rho}vq_s) - \frac{\partial}{\partial z}[\bar{\rho}(w - V_s)q_s] + \bar{\rho}(d_s - s_s - m_s + f_s) - T_{qs} + D_{qs} \tag{11.35}$$

e) Graupel

$$\bar{\rho}\frac{\partial q_g}{\partial t} = -\frac{\partial}{\partial x}(\bar{\rho}uq_g) - \frac{\partial}{\partial y}(\bar{\rho}vq_g) - \frac{\partial}{\partial z}[\bar{\rho}(w - V_g)q_g] + \bar{\rho}(d_g - s_g - m_g + f_g) - T_{qg} + D_{qg} \tag{11.36}$$

On the right hand side of the above equations there are terms of the kind $\bar{\rho}(c - e_c)$, $\bar{\rho}(-e_r + m - f_r)$, $\bar{\rho}(d_i - s_i)$, *etc.* Taking equation (11.33) as an example, $\bar{\rho}\frac{\partial q_r}{\partial t} = \ldots + \bar{\rho}(-e_r + m - f_r) + \ldots$, the right hand side is interpreted as follows – evaporation (e_r) and freezing (f_r) reduce the mixing ratio of rain water q_r, therefore they figure in the equation with a minus sign; melting (m) increases the mixing ratio of rain water, therefore it figures in the equation with a plus sign. Similar interpretation applies to the terms of this kind in all the above equations.

The transfer rates among the different hydrometeor species are denoted by T with the relevant subscript. These are expressed by the following equations:

$$T_{qc} = -\left(P_{sacw} + P_{raut} + P_{racw} + P_{sf\,w} + D_{gacw} + Q_{sacw}\right) - P_{ihom} - P_{imlt} - P_{idw} \quad (11.37)$$

$$T_{qi} = -\left(P_{saut} + P_{saci} + P_{raci} + P_{sf\,i} + D_{gaci} + W_{gaci}\right) + P_{ihom} - P_{imlt} + P_{idw} \quad (11.38)$$

$$T_{qr} = Q_{sacw} + P_{raut} + P_{racw} + Q_{gacw} - \left(P_{iacr} + D_{gacr} + W_{gacr} + P_{sacr} + P_{gf\,r}\right) \quad (11.39)$$

$$\begin{aligned} T_{qs} &= P_{saut} + P_{saci} + P_{sacw} + P_{sf\,w} + P_{sf\,i} + \delta_3 P_{raci} + \delta_3 P_{iacr} + \delta_2 P_{sacr} \\ &\quad - \left[P_{gacs} + D_{gacs} + W_{gacs} + P_{gaut} + \left(1 - \delta_2 P_{racs}\right)\right] \end{aligned} \quad (11.40)$$

$$\begin{aligned} T_{qg} &= \left(1-\delta_3\right)P_{raci} + D_{gaci} + W_{gaci} + D_{gacw} + \left(1-\delta_3\right)P_{iacr} + P_{gacs} + D_{gacs} \\ &\quad + W_{gacs} + P_{gaut} + \left(1-\delta_2\right)P_{racs} + D_{gacr} + W_{gacr} + \left(1-\delta_2\right)P_{sacr} + P_{gf\,r} \end{aligned} \quad (11.41)$$

In these equations,

$$W_{gacr} = P_{wet} - D_{gacw} - W_{gaci} - W_{gacs}\,. \quad (11.42)$$

If the temperature is above freezing,

$$\begin{aligned} P_{saut} &= P_{saci} = P_{sacw} = P_{raci} = P_{iacr} = P_{sf\,i} = P_{sf\,w} = D_{gacs} = W_{gacs} \\ &= P_{gacs} = D_{gacr} = P_{gwet} = P_{racs} + P_{sacr} = P_{gf\,r} = P_{gaut} = P_{imlt} = 0\,, \end{aligned} \quad (11.43)$$

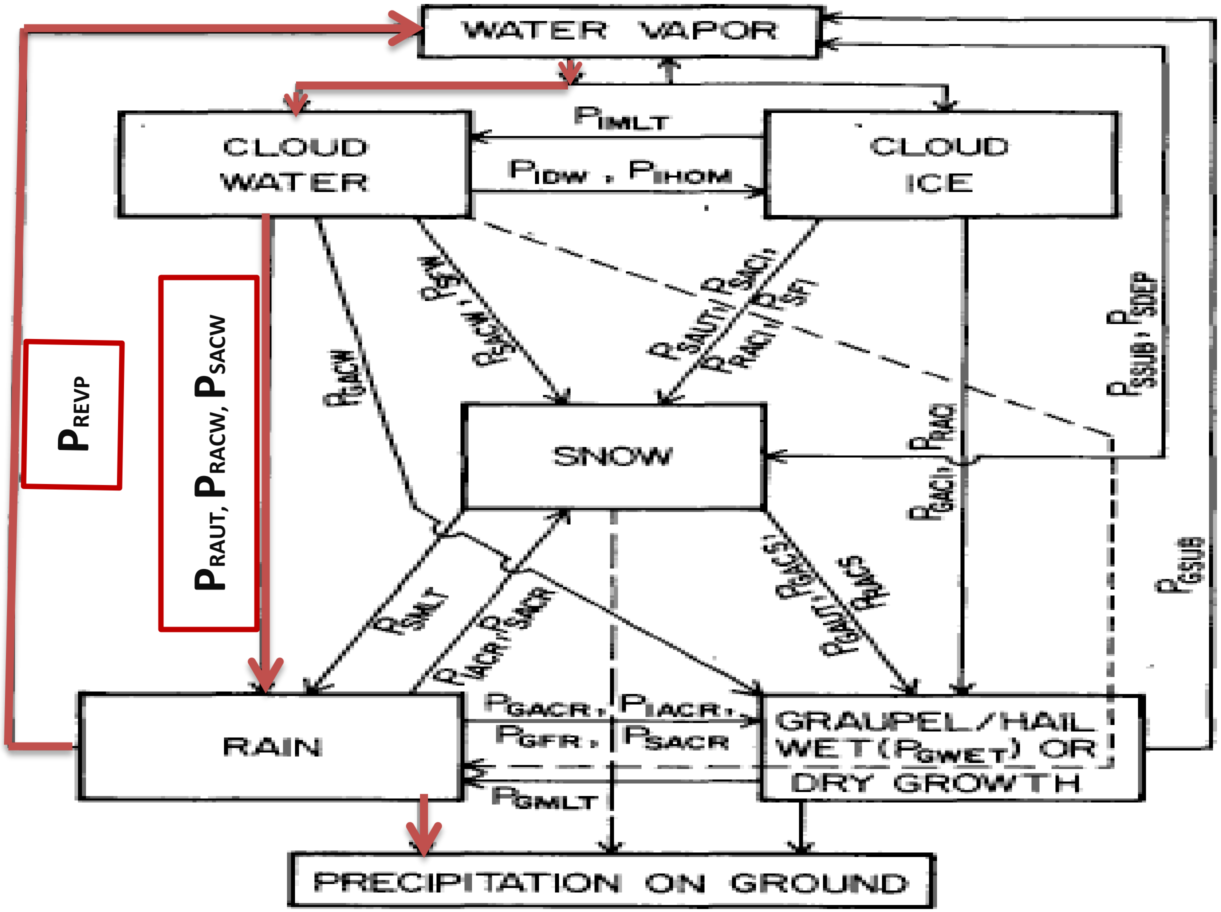
otherwise

$$Q_{sacw} = Q_{gacw} = P_{gacs} = P_{idw} = P_{ihom} = 0 \quad (11.44)$$

The symbols on the right hand sides of the equations for the transfer rates among different hydrometeor species (11.37 through 11.41) and in equations 11.42 – 11.43 represent different processes as explained in Table 11.1 and illustrated schematically in Fig. 11.7. Each of these is explained in greater detail in Lin *et. al.* (1983) and Tao and Simpson (1993).

Symbol	Meaning
P_{depi}	Depositional growth of cloud ice
P_{int}	Initiation of cloud ice.
P_{imlt}	Melting of cloud ice to form cloud water.
P_{idw}	Depositional growth of cloud ice at the expense of cloud water.
P_{ihom}	Homogeneous freezing of cloud water to form cloud ice.
P_{iacr}	Accretion of rain by cloud ice; producing snow or graupel depending on the amount of rain.
P_{raci}	Accretion of cloud ice by rain; producing snow or graupel depending on the amount of rain.
P_{raut}	Auto conversion of cloud water by rain
P_{raew}	Accretion of cloud water by rain
P_{revp} (e_r)	Evaporation of rain
P_{racs}	Accretion of snow by rain; producing graupel if rain or snow exceeds threshold and $T<273.16$ or rain if $T>273.16$.
$P(Q)_{sacw}$	Accretion of cloud water by snow; producing snow (P_{sacw}) if $T<273.16$ or rain (Q_{sacw}) if $T>273.16$.
P_{sacr}	Accretion of rainby snow; producing graupel if rain or snow exceeds threshold; if not, produces snow.
P_{saci}	Accretion of cloud ice by snow.
P_{saut}	Autoconversion (aggregation) of cloud ice to form snow
P_{sfw}	Bergeron process (deposition and rimming) – transfer of cloud water to form snow.
P_{sfi}	Bergeron process embryos (cloud ice) used to calculate transfer rate of cloud water to snow (P_{sfw}).
P_{sdep} (d_s)	Deposition growth of snow.
P_{ssub} (s_s)	Sublimation of snow.
P_{smlt} (m_s)	Melting of snow to form rain, $T>273.16$.

P_{sfi}	Bergeron process embryos (cloud ice) used to calculate transfer rate of cloud water to snow (P_{sfw}).
P_{sdep} (d_s)	Deposition growth of snow.
P_{ssub} (s_s)	Sublimation of snow.
P_{smlt} (m_s)	Melting of snow to form rain, T>273.16.
P_{wacs}	Accretion of snow by cloud water to form rain, T>273.16.
P_{gaut}	Autoconversion (aggregation) of snow to form graupel.
P_{gfr} (f_g)	Probabilistic freezing of rain to form graupel.
$D(Q)_{gacw}$	Accretion of cloud water by graupel
$D(W)_{gaci}$	Accretion of cloud ice by graupel.
$D(W)_{gacr}$	Accretion of rain by graupel.
P_{gsub} (s_g)	Sublimation of graupel.
P_{gmlt} (m_g)	Melting of graupel to form rain, T>273.16. (in this regime Q_{gacw} is assumed to be shed as rain).
P_{gwet}	Wet growth of graupel; may involve W_{gacs} and W_{gaci} and must include D_{gacw} or W_{gacr}, or both. The amount of W_{gacw} which is not able to freeze is shed to rain.



LIN DIAGRAM

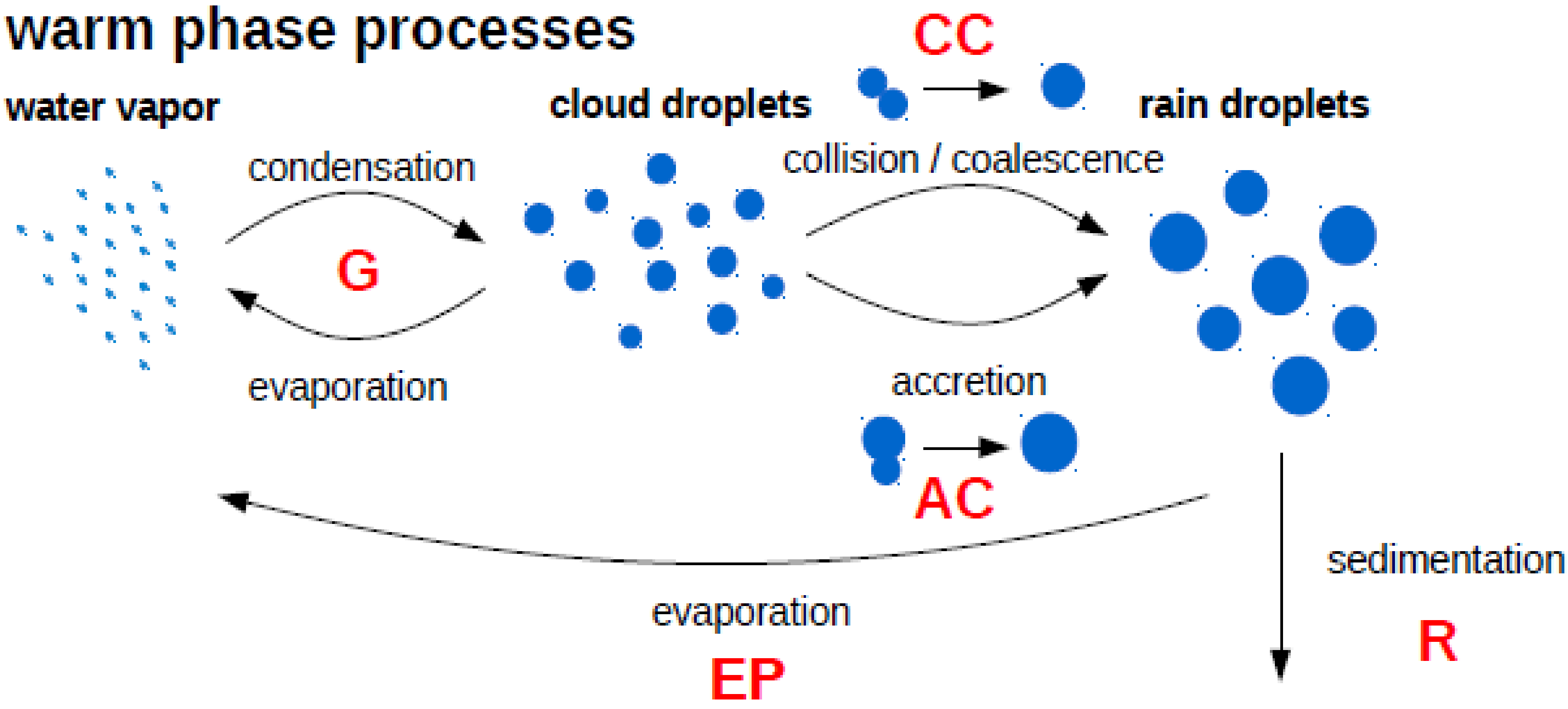
Fig. 11.7: Cloud microphysical processes of the (after Lin et al. 1983).

Goddard Cumulus Ensemble model

The three momentum equation (for u, v, w), the first law of thermodynamics (θ), the water vapor equation for (q_v) and the five microphysical process equation (q_c, q_r, q_I, q_s and q_g) constitute 10 prognostic equations. The mass continuity and the equation of state bring in two more variables – the Exner pressure π (which is related to the pressure p) and the density of air $\overline{\rho}$. In order to close this system of equations, the transfer rates that account for all conversion processes need to be calculated, usually by using suitable empirical parameterizations.

Warm-phase microphysics

warm phase processes



- cloud and rain droplets vary in size
- effectiveness of collision and accretion strongly depends on size of droplets

From: Tutorial-5, ETH by Lukas Papritz

Conversion processes

There are a number of conversion processes transforming one form of water within a cloud into another, as seen in equations 11.37 through 11.41 and Table 1. The transfer processes are generally modeled empirically based on microphysical field experiment results. The degree of empiricism and the number of parameters controlling the transfer are quite large. Cloud growth or decay in modeling studies is very sensitive to the modeled values of these transfer processes. For illustrative purposes, parameterizations for three of these processes are described below.

a) Auto-conversion (cloud water to rainwater, Praut) :

This process consists of transforming the liquid water from cloud droplets to raindrops. Kessler (1969) formulated a simple parameterization of the role of autoconversion of liquid water from raindrops with water content m (mass/volume) to raindrops with water content *M*. The autoconversion is formulated as

$$c_1 = \left[\frac{\Delta q_l}{\Delta t}\right]_{auto} = k_a(q_c - q_{cr}) \qquad (11.43)$$

and allows autoconversion process to take place only if the cloud water mixing ratio q_c is greater than a critical value q_{cr}. The values of q_{cr} and k_a used by Kessler are q_{cr} =0.05 g kg^{-1} and k_a=0.001s^{-1}

b) Accretion (cloud water to rainwater, P_{racw}) :

The formulation of accretion follows Kessler (1969) and that of terminal velocity follows Srivastava (1967). After the embryonic rainfall droplets have been formed it is assumed that the water content converts into rain following an inverse exponential distribution function (Marshall-Palmer, 1948) $N(D) = N_0 e^{-\lambda D}$, where $N(D)$ is the number of raindrops per unit volume of diameter D, and $\lambda = 3.67 / D_0$, where D_0 is a threshold smallest diameter for the start of this process.

The cross-sectional area of the raindrop is $\pi D^2 / 4$ and its terminal velocity is v_{TD} hence the volume swept by this raindrop per unit time is $v_{TD} \rho \, q_c \pi D^2 / 4$. The increase of mass of drops at each diameter is given by

$$\left[\frac{\Delta q}{\Delta t}\right]_{acc} = \int_0^\infty v_{TD} \rho \, q_c \frac{\pi D^2}{4} N(D) dD \qquad (11.44)$$

Assuming $v_{TD} = 1500 D^{1/2} \text{cm s}^{-1}$ and integrating for all diameters, the relation used for the computation of accretion process is obtained as an exact solution of the integral above,

$$c_2 = \left[\frac{\Delta q_l}{\Delta t}\right]_{acc} = \frac{1500\pi}{4} N_0 \rho \frac{\Gamma(3.5)}{\lambda^{3.5}} q_c \qquad (11.45)$$

The rainwater mixing ratio is defined as

$$q_r = \int_0^\infty q_{rD} dD = \int_0^\infty N_0 e^{-\lambda D} \left[\pi \frac{D^3}{6} \rho_w \right] dD \tag{11.46}$$

After integrating $q_r = \pi \rho_w N_0 / \lambda^4$, where ρ_w is the density of liquid water, the value of λ is obtained as an exact solution

$$\lambda = \left(\frac{4\pi \rho_w N_0}{q_r} \right)^{1/4} \tag{11.47}$$

Finally, from

$$v_T = \frac{\int_0^\infty q_{rD} v_{TD} dD}{\int_0^\infty q_{rD} dD} = \frac{\int_0^\infty q_{rD} v_{TD} dD}{q_r} \tag{11.48}$$

Substituting from (11.46) one finally obtains the final fall speed of raindrops as

$$v_T = \frac{1}{\pi \rho_w N_0 \lambda^{-4}} \int_0^\infty N_0 e^{-\lambda D} \left(\frac{\pi D^3}{6} \right) \rho_w 1500 D^{1/2} dD \tag{11.49}$$

Or, after solving the above integral exactly,

$$v_T = 1500 \Gamma(4.5) / \lambda^{1/2} \Gamma(4) \tag{11.50}$$

c) *Evaporation (cloud water to vapor, P_{revp}):*

The evaporation process follows to some extent the format of Murray and Anderson (1965) If the air is saturated the rate of change of the saturation mixing ratio of water vapor is the same as the rate of change of the saturation mixing ratio. On the basis of conservation of equivalent potential temperature under conditions of saturation mixing ratio is

$$\frac{dq_{vs}}{dt} = -Bw \tag{11.51}$$

$$B = \frac{1 - \frac{1}{\varepsilon L}\left(C_p T - L q_{vs}\right)}{L + \frac{C_p R T^2}{L q_{vs}\left(\varepsilon + q_{vs}\right)}} g \tag{11.52}$$

where $\varepsilon = 0.62195$ is the molecular weight of water vapor/molecular weight of dry air, $L = 2.5 \times 10^6$ J kg^{-1} is the latent heat of evaporation, and C_p = 1004 J kg^{-1} K^{-1} is the specific heat capacity of dry air. The amount of local change in the water vapor mixing ratio is then

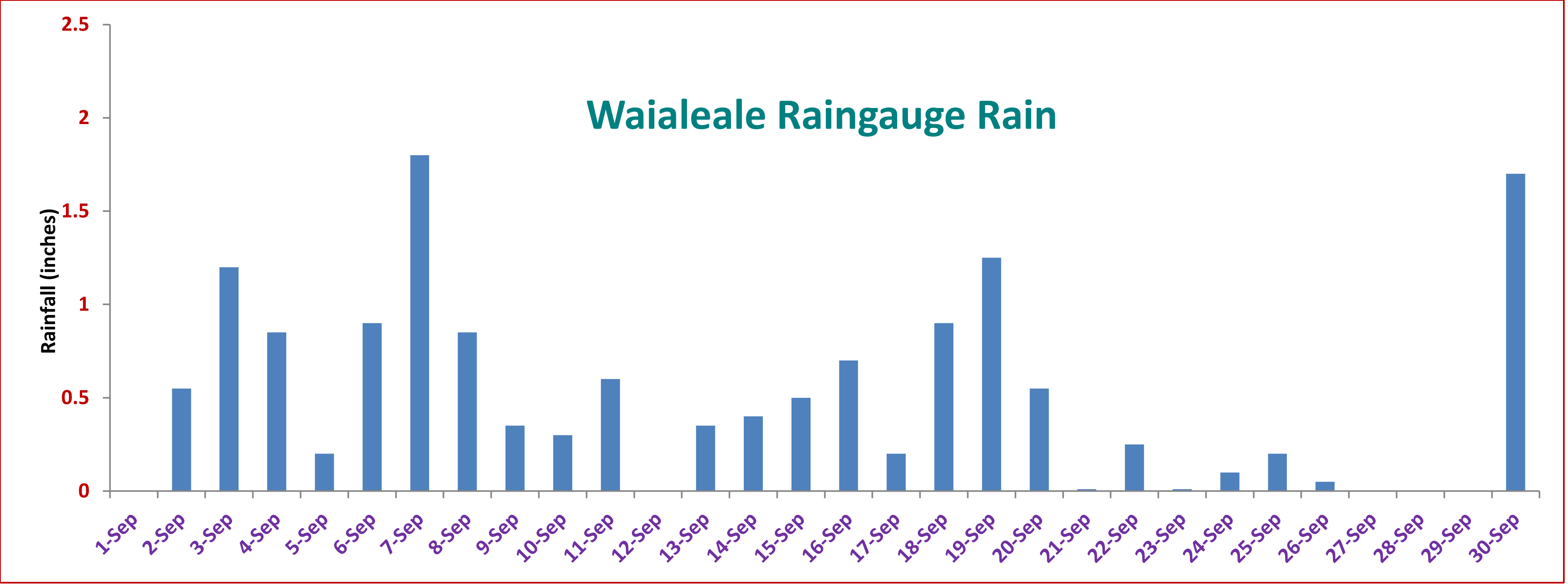
$$\Delta q_v = -Bw\Delta t \tag{11.53}$$

In the case of upward motion this represents condensation and is accompanied by an equal and opposite change in cloud water mixing ratio and an increase in temperature, i.e.,

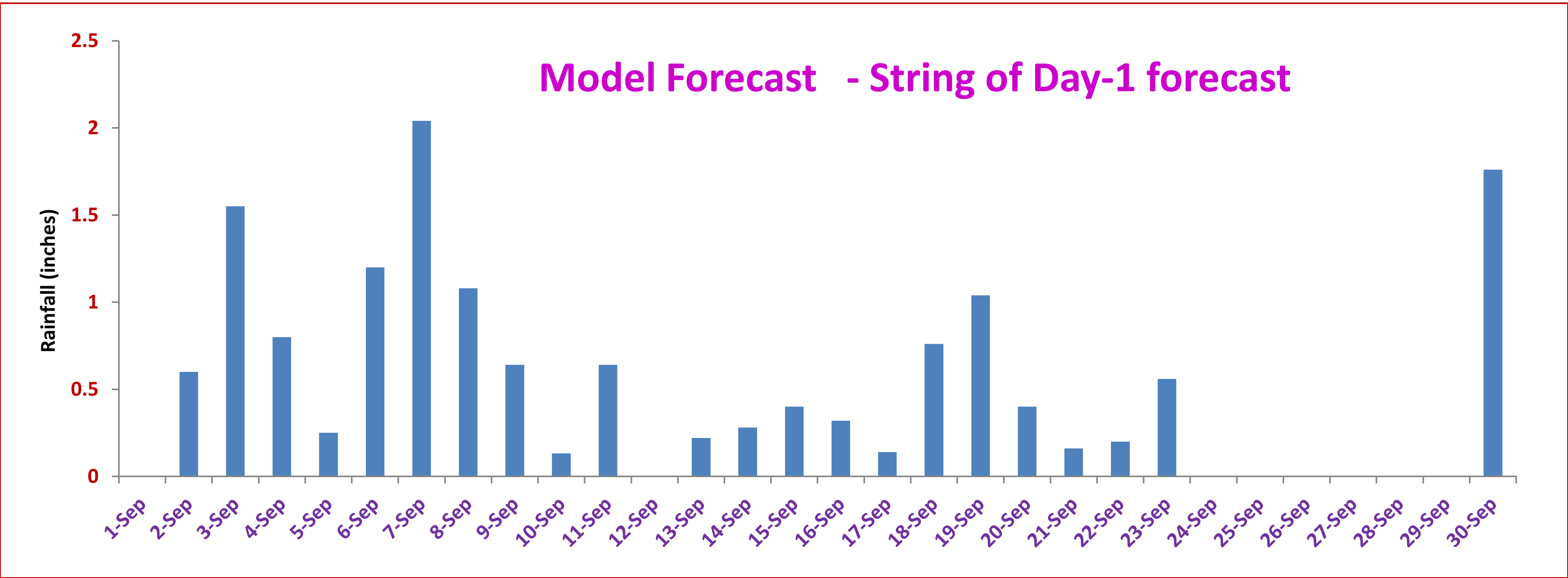
$$\Delta q_c = -\Delta q_v \tag{11.54}$$

$$\Delta T = \frac{L}{C_p}\Delta q_c \tag{11.55}$$

In the case of downward motion of saturated air, the same treatment is used. The increase of mixing ratio, however, accompanying this change is done through evaporation of cloud and/or rain. If cloud water is sufficient to accomplish this change, no rainwater is evaporated. If the cloud water is insufficient some rainwater is evaporated until the sum of cloud water and rainwater evaporation is enough to accomplish the change computed in equation (11.53).

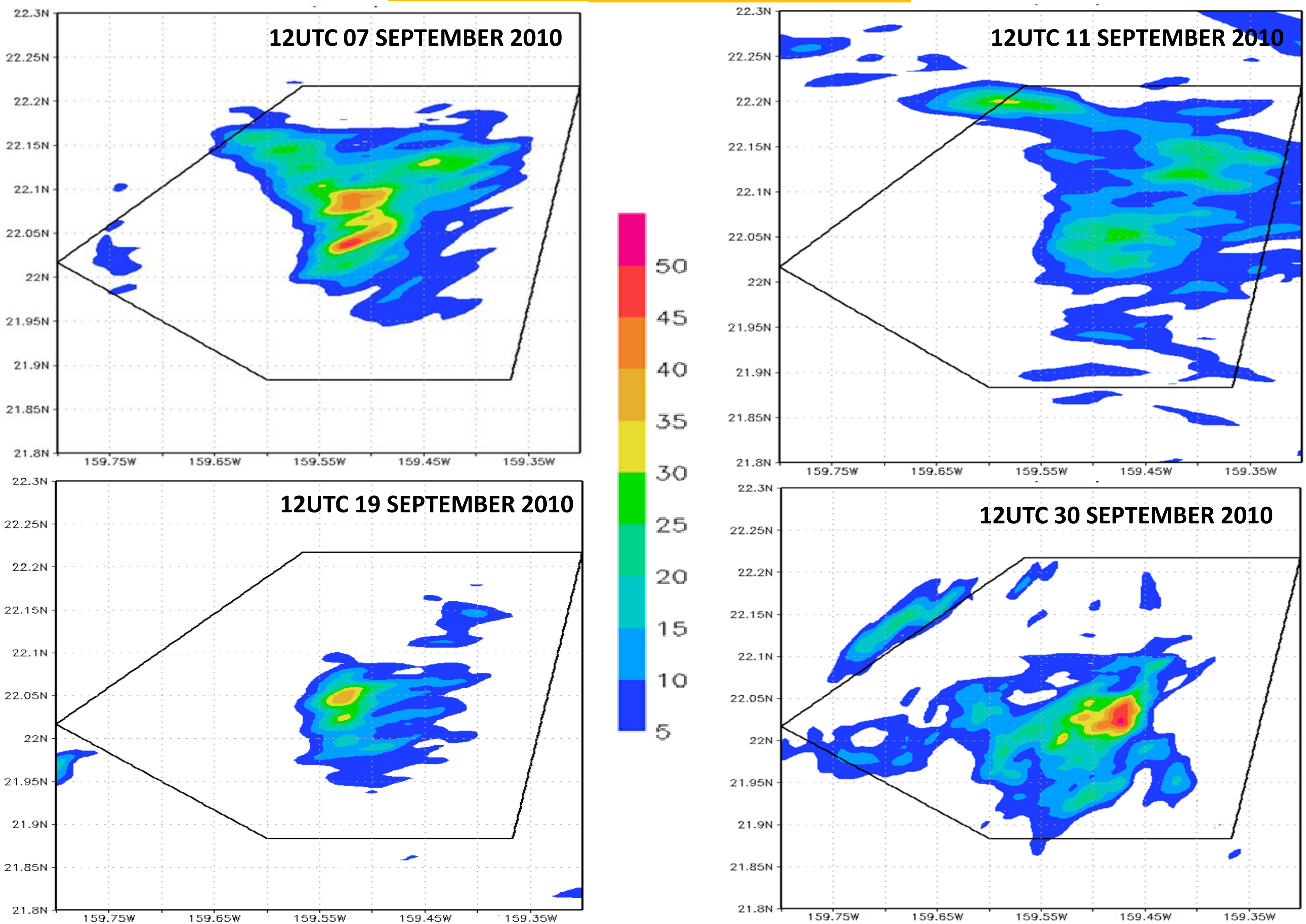


Waialeale Raingauge Rain
Rainfall (inches)
2.5
2
1.5
1
0.5
0
1-Sep
2-Sep
3-Sep
4-Sep
5-Sep
6-Sep
7-Sep
8-Sep
9-Sep
10-Sep
11-Sep
12-Sep
13-Sep
14-Sep
15-Sep
16-Sep
17-Sep
18-Sep
19-Sep
20-Sep
21-Sep
22-Sep
23-Sep
24-Sep
25-Sep
26-Sep
27-Sep
28-Sep
29-Sep
30-Sep

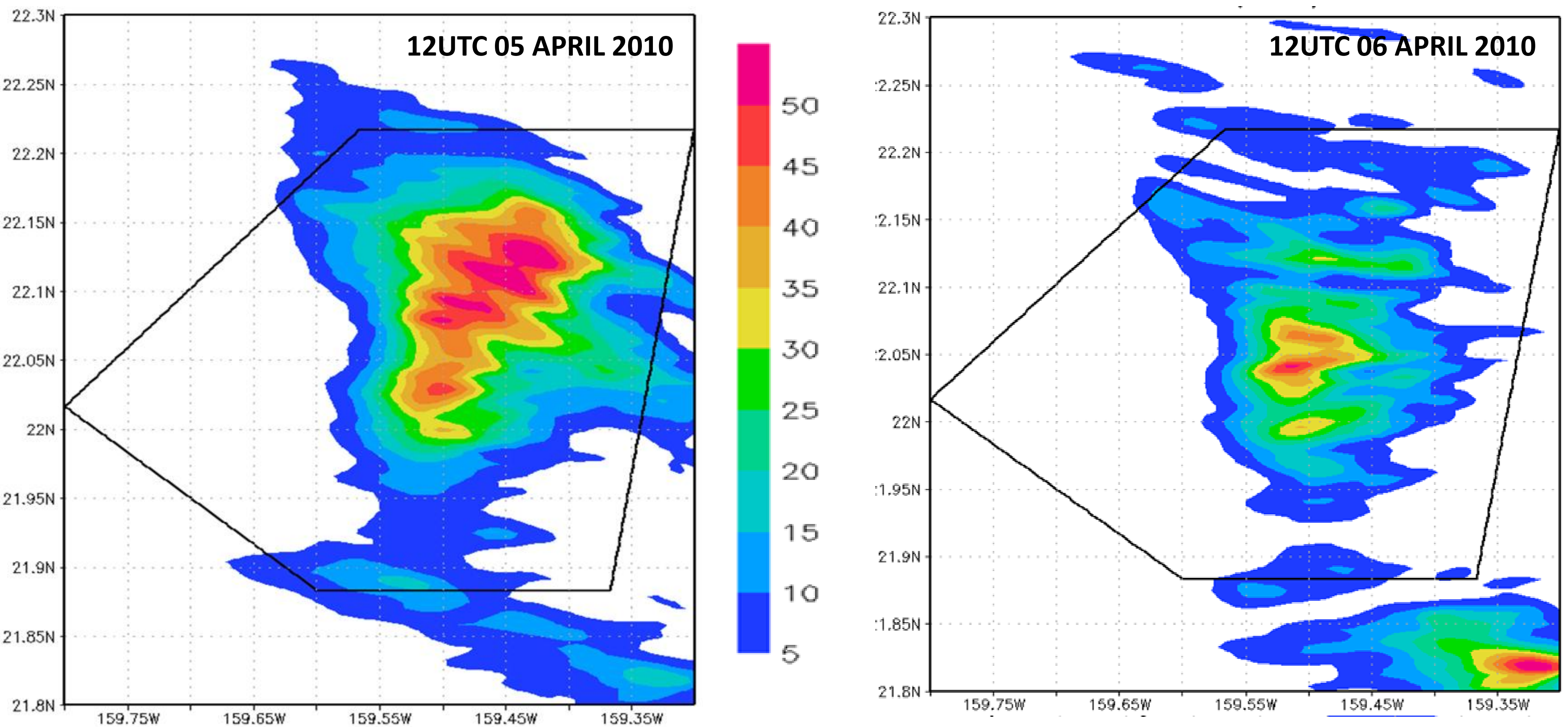


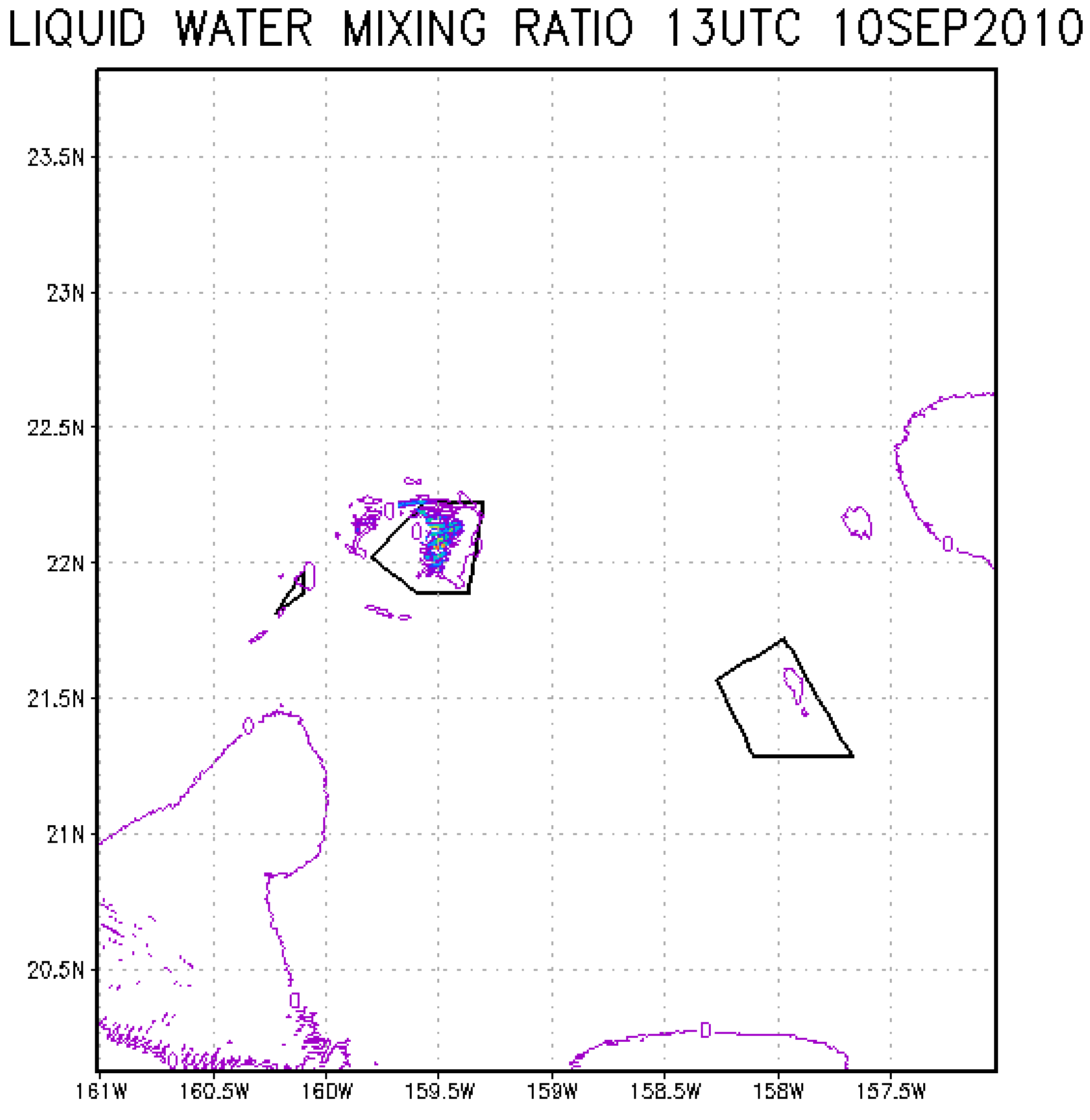
Model Forecast - String of Day-1 forecast
Rainfall (inches)
2.5
2
1.5
1
0.5
0
1-Sep
2-Sep
3-Sep
4-Sep
5-Sep
6-Sep
7-Sep
8-Sep
9-Sep
10-Sep
11-Sep
12-Sep
13-Sep
14-Sep
15-Sep
16-Sep
17-Sep
18-Sep
19-Sep
20-Sep
21-Sep
22-Sep
23-Sep
24-Sep
25-Sep
26-Sep
27-Sep
28-Sep
29-Sep
30-Sep

MOUNT WAIALEALE RAINFALL(mm)



MOUNT WAIALEALE RAINFALL(mm)



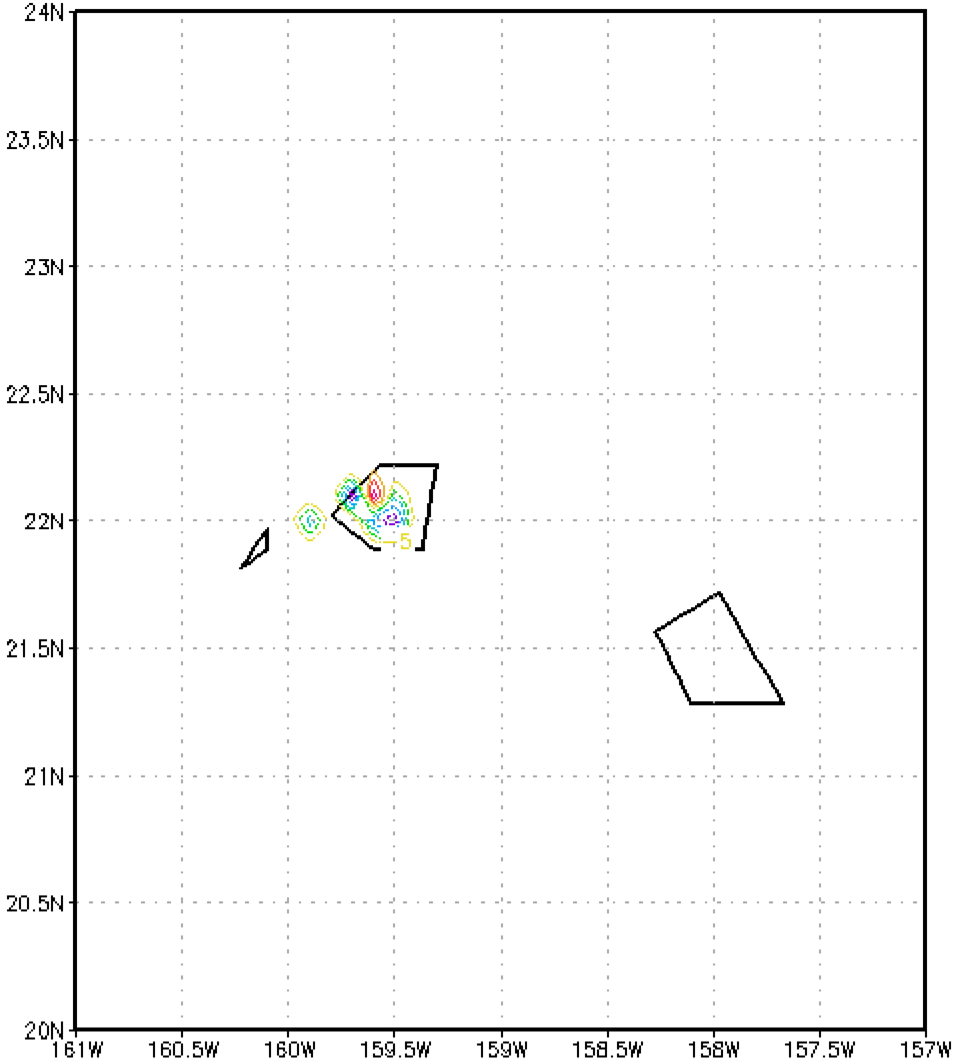


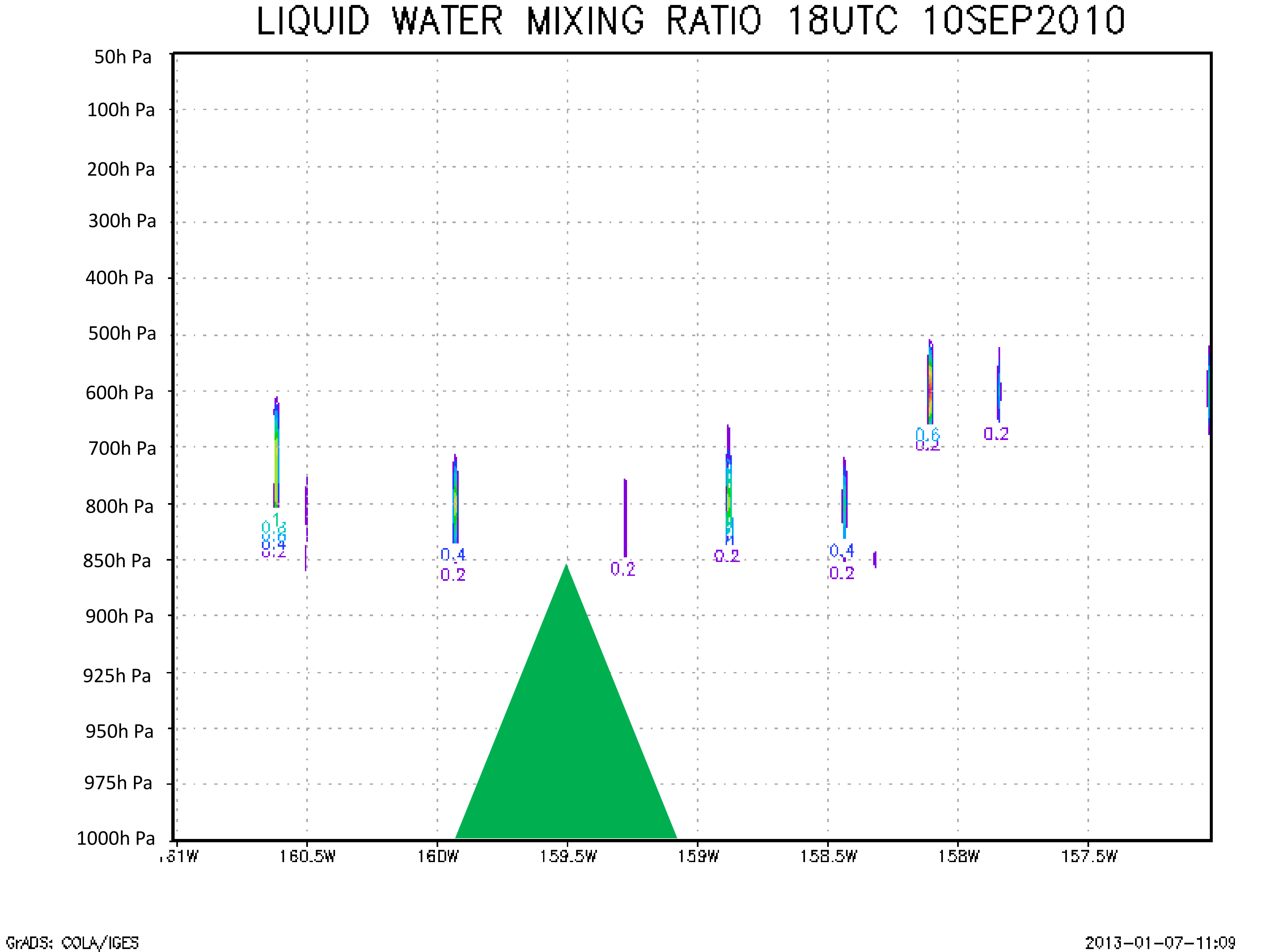
GrADS: COLA/IGES

2013-01-02-15:51

CLOUD RESOLVING MODEL BASED

RADAR REFLECTIVITY 850hPa 13UTC 10SEP2010





LIQUID WATER MIXING RATIO 18UTC 10SEP2010
50h Pa
100h Pa
200h Pa
300h Pa
400h Pa
500h Pa
600h Pa
700h Pa
800h Pa
850h Pa
900h Pa
925h Pa
950h Pa
975h Pa
1000h Pa
161W
160.5W
160W
159.5W
159W
158.5W
158W
157.5W
0.4
0.2
0.2
0.2
0.4
0.2
0.6
0.2
0.2
GrADS: COLA/IGES
2013-01-07-11:09

The Buoyancy field

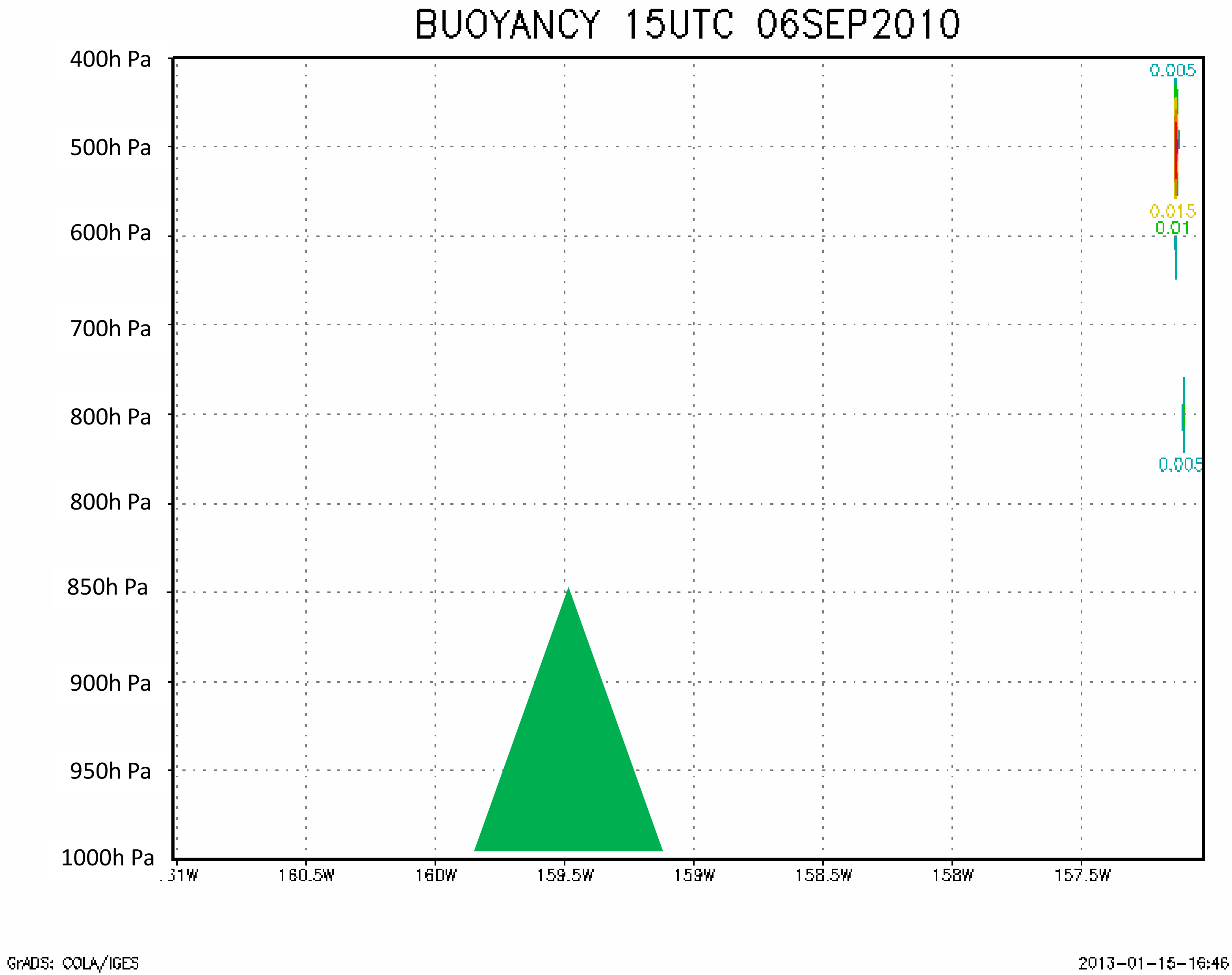
The Buoyancy is defined as follows:

$$B = g\left(\frac{T_v'}{\overline{T_v}} - r_l\right) \quad (3)$$

where r_l is the liquid water mixing ratio, and T_v' and $\overline{Tv}$ respectively denote virtual temperature values inside a cloud (where $r_l > 0.1$ g/kg) and outside a cloud (where $r_l < 0.1$ g/kg). T is the virtual temperature and T_v is defined as

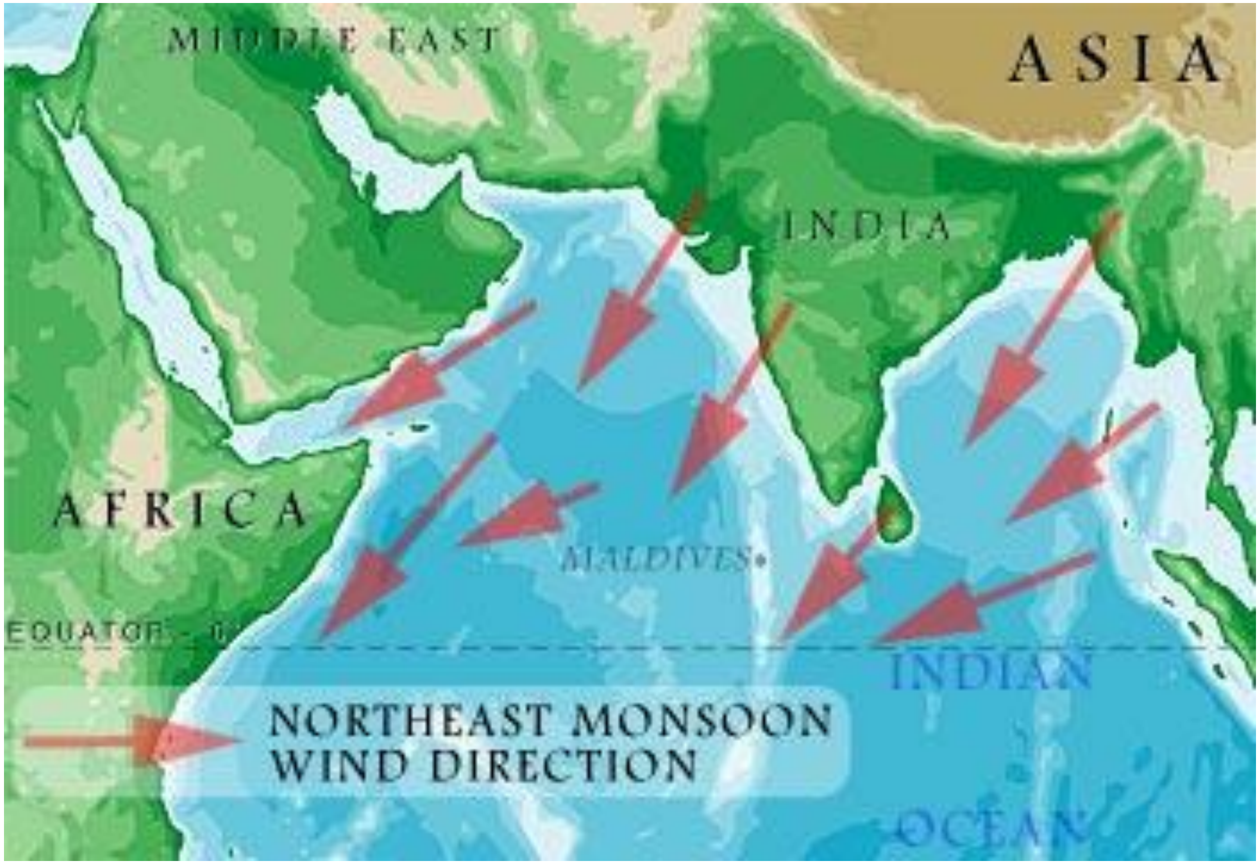
$$T_v^* = 1+(r_v/\varepsilon)/(1+r_v)T,$$

where T denotes air temperature, r_v is the mixing ratio of water vapor, and ε is the ratio of molecular weights of water vapor and dry air (ε = 0.622).



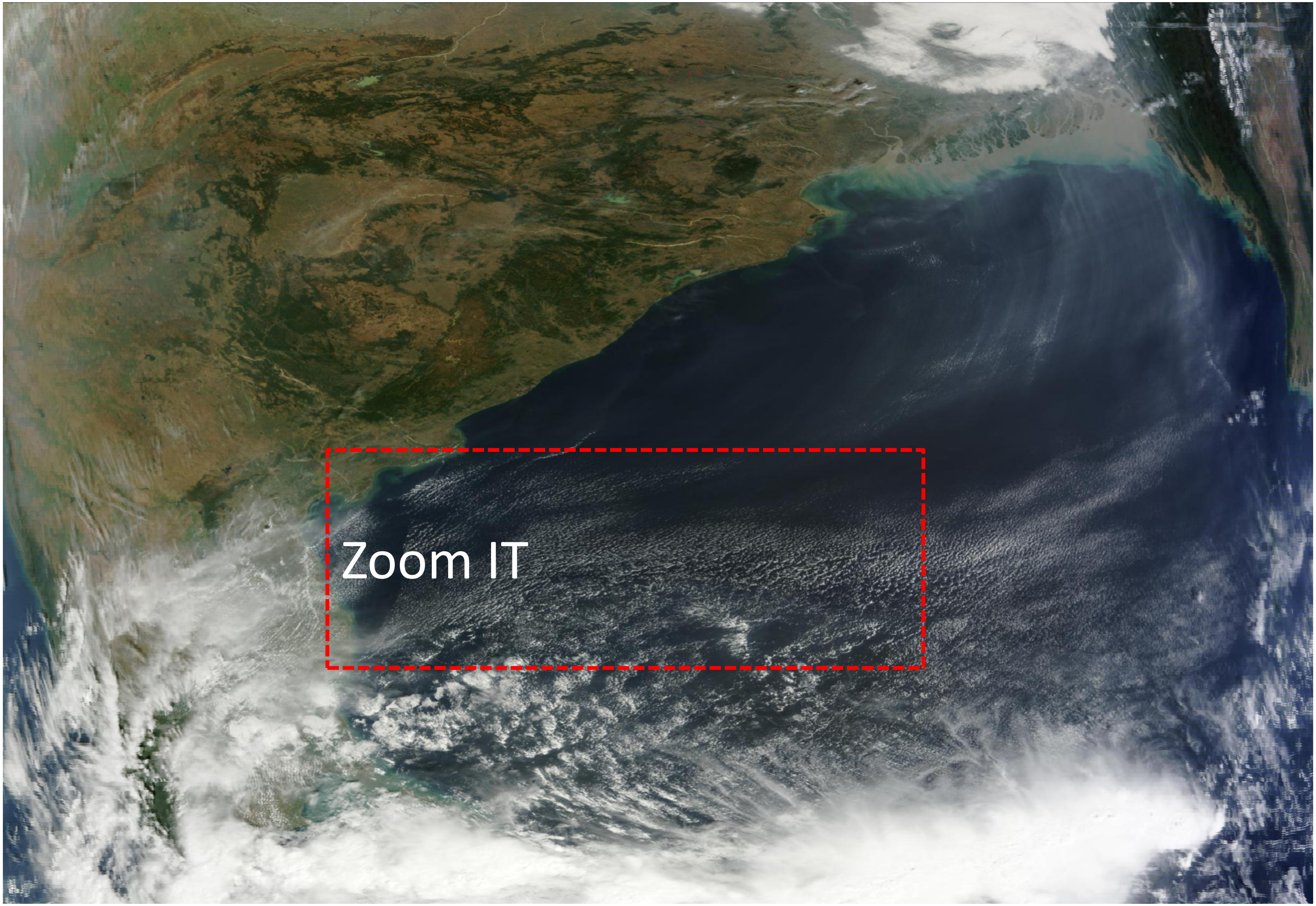
BUOYANCY 15UTC 06SEP2010
400h Pa
500h Pa
600h Pa
700h Pa
800h Pa
800h Pa
850h Pa
900h Pa
950h Pa
1000h Pa
.31W
160.5W
160W
159.5W
159W
158.5W
158W
157.5W
0.005
0.015
0.01
0.005
GrADS: COLA/IGES
2013-01-15-16:46

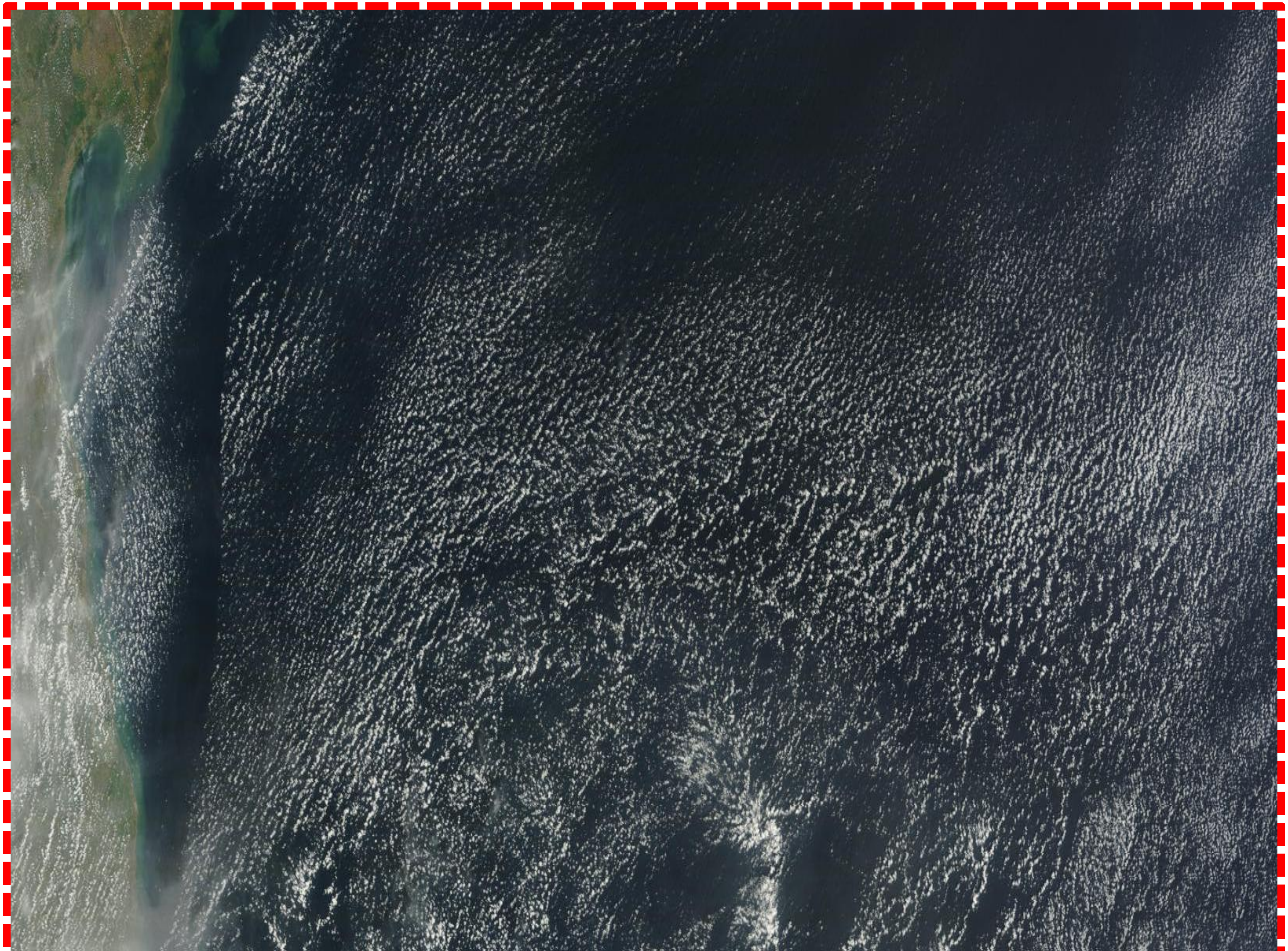
NORTH-EAST MONSOON

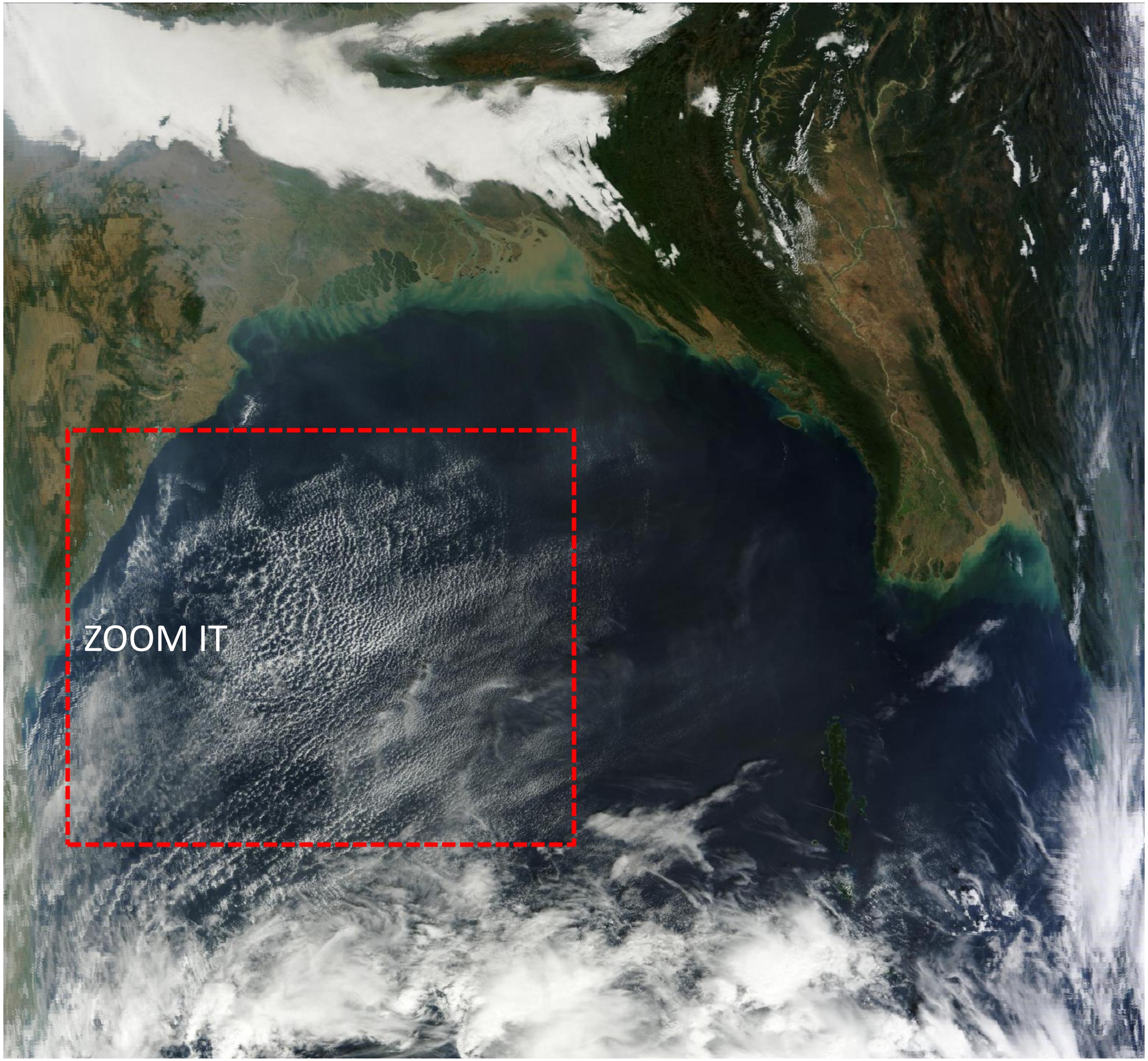


Visible Image from TERRA/MODIS (18th Dec 2012, 04.35UTC)

Resolution: 500m

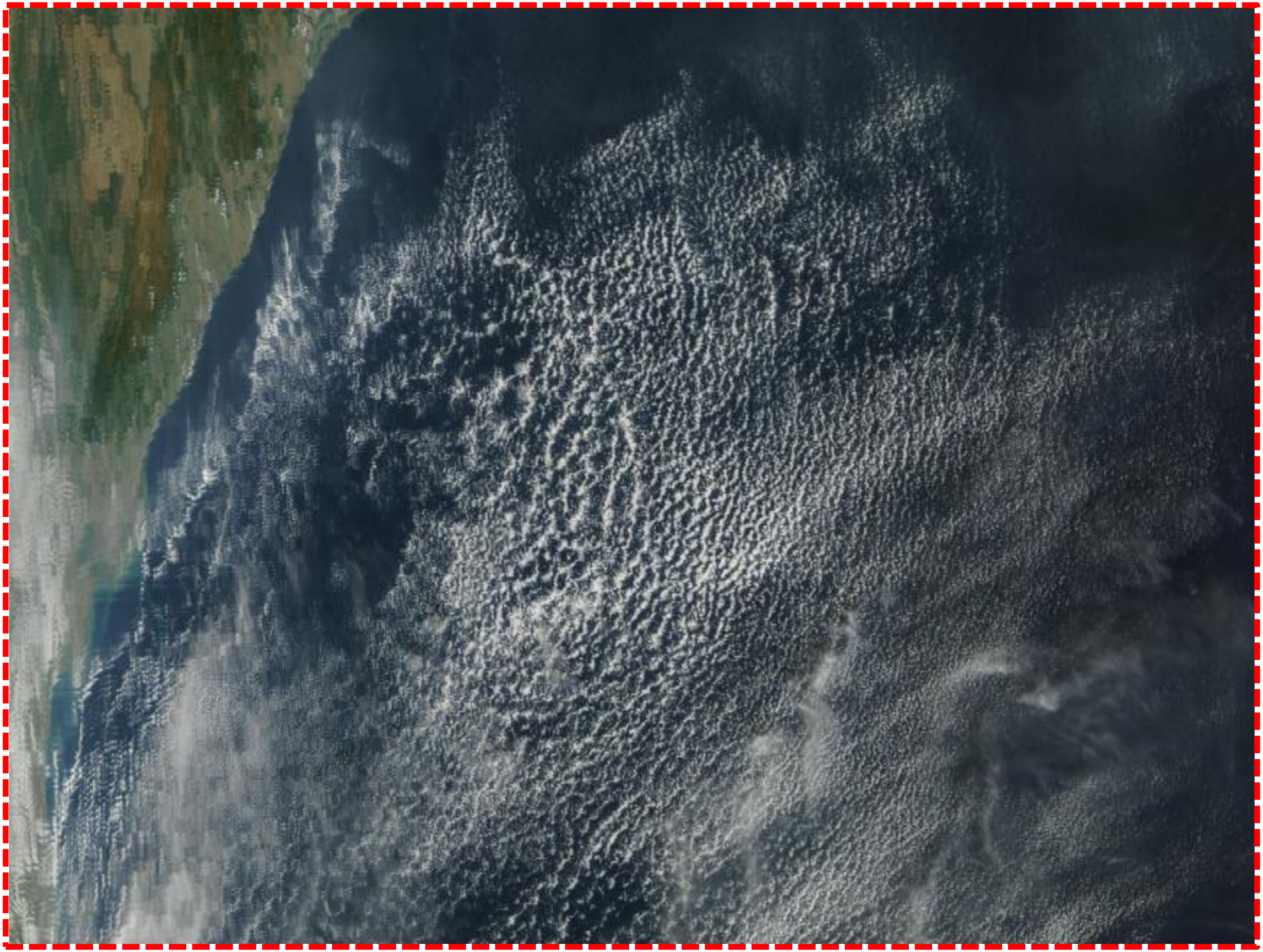


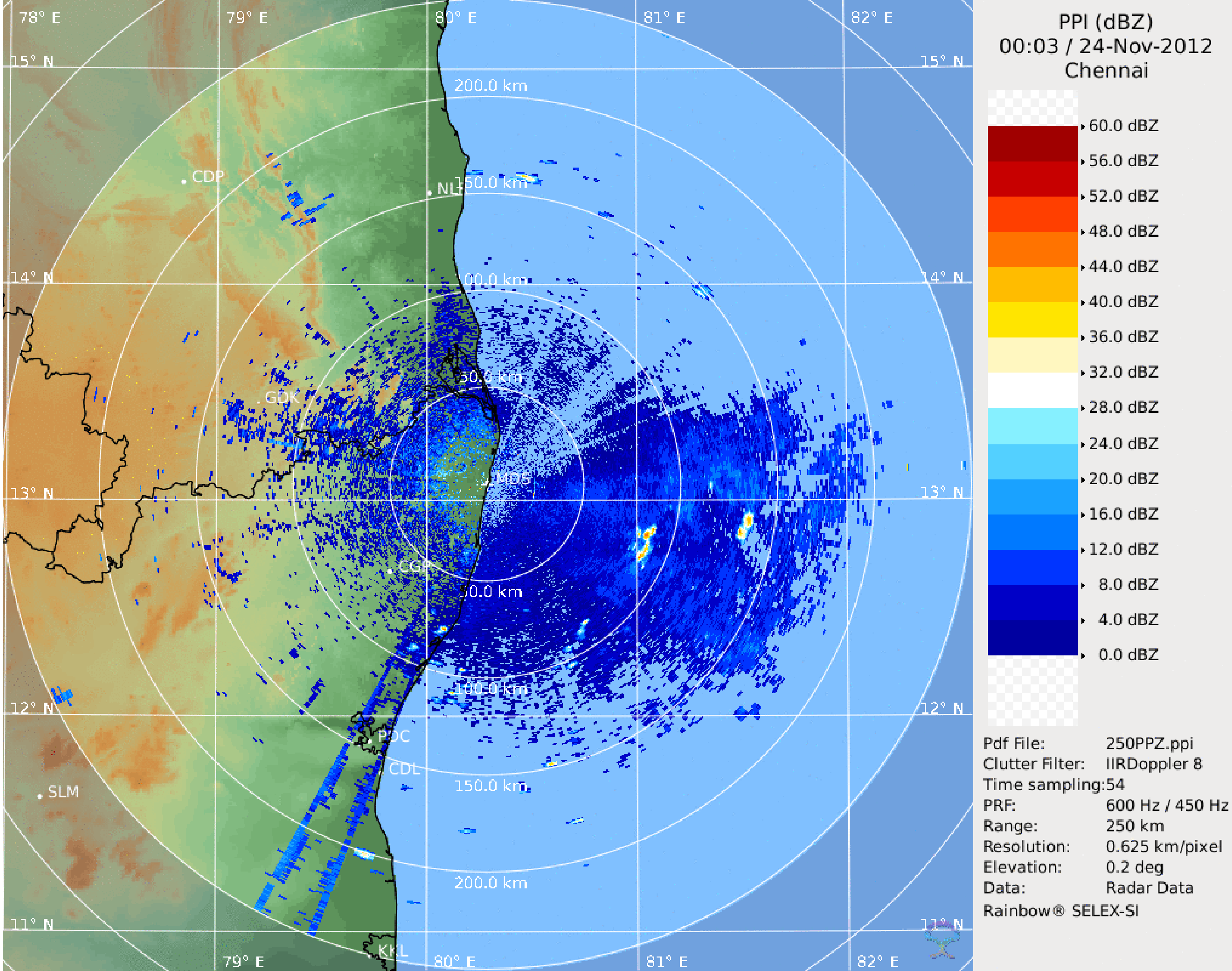


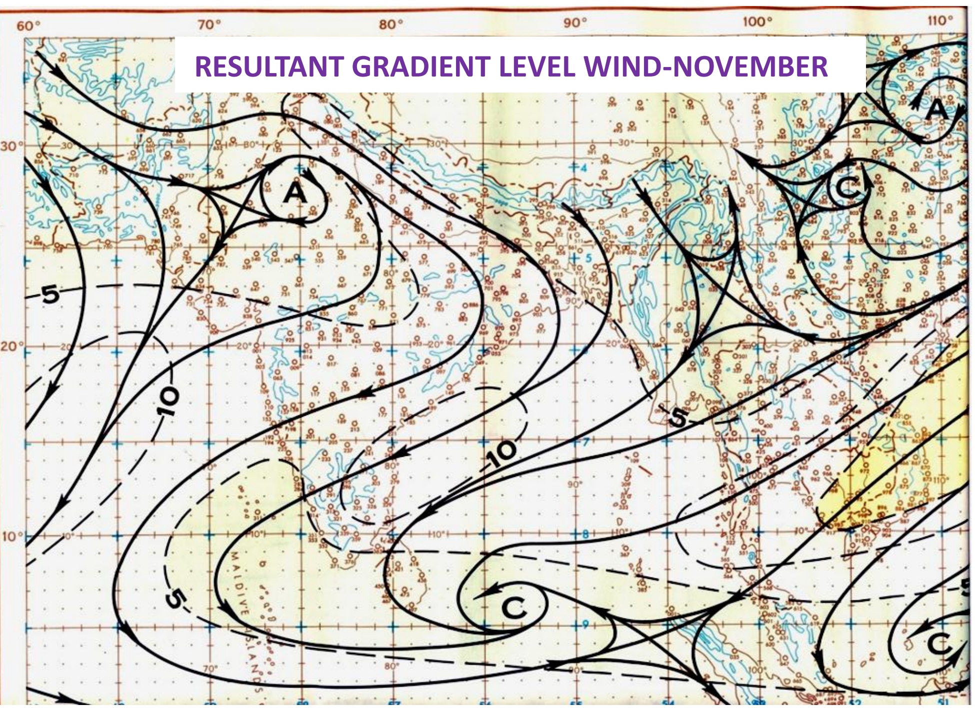


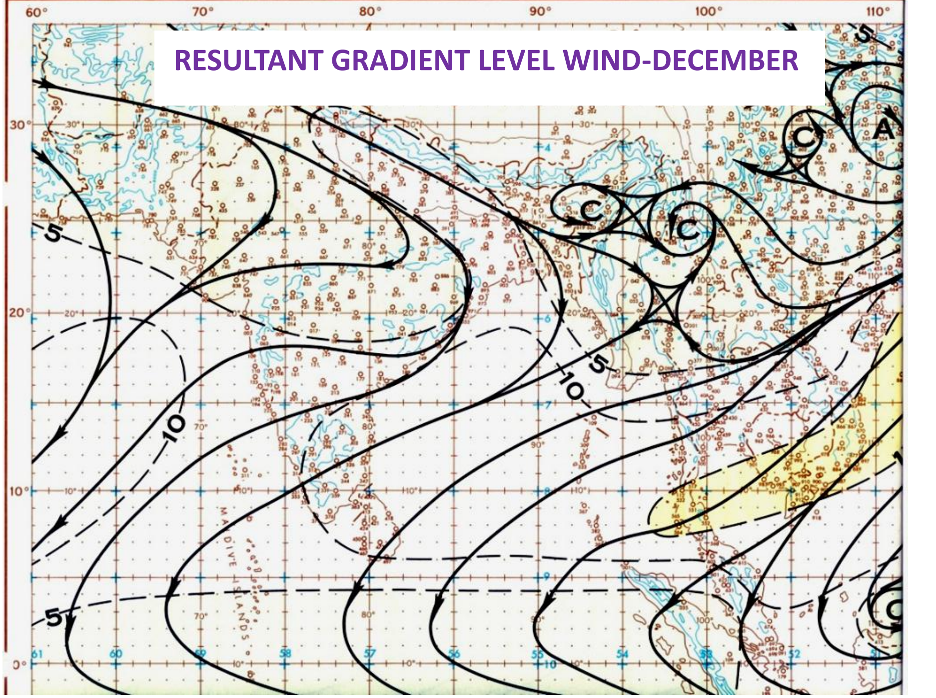
Visible Image from TERRA/MODIS (22nd Dec 2012, 05.00UTC)

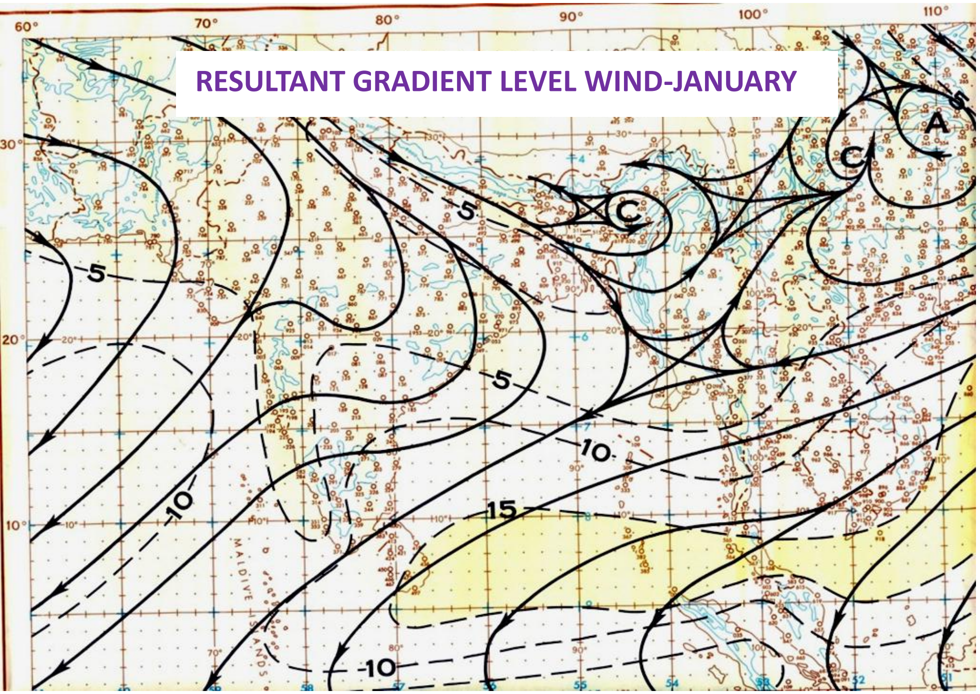
Resolution: 500m

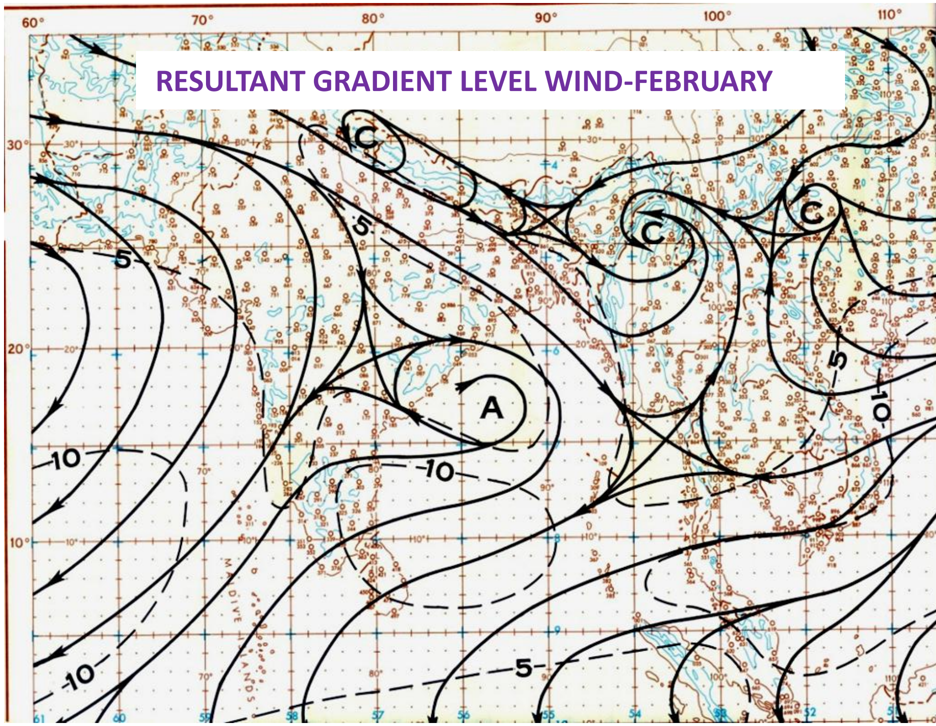


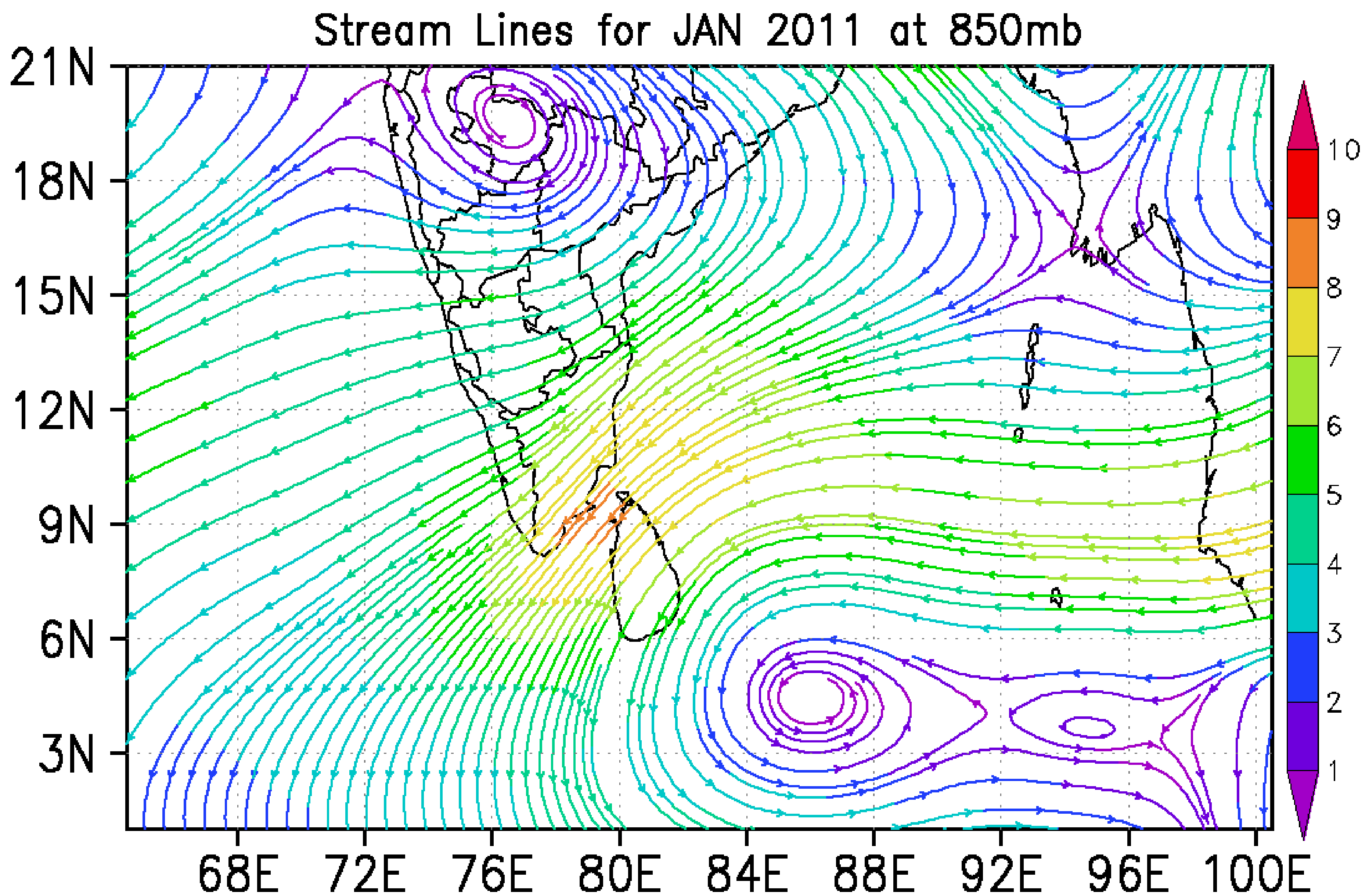

PPI (dBZ)
00:03 / 24-Nov-2012
Chennai
60.0 dBZ
56.0 dBZ
52.0 dBZ
48.0 dBZ
44.0 dBZ
40.0 dBZ
36.0 dBZ
32.0 dBZ
28.0 dBZ
24.0 dBZ
20.0 dBZ
16.0 dBZ
12.0 dBZ
8.0 dBZ
4.0 dBZ
0.0 dBZ
Pdf File: 250PPZ.ppi
Clutter Filter: IIRDoppler 8
Time sampling:54
PRF: 600 Hz / 450 Hz
Range: 250 km
Resolution: 0.625 km/pixel
Elevation: 0.2 deg
Data: Radar Data
Rainbow® SELEX-SI
78° E
79° E
80° E
81° E
82° E
15° N
14° N
13° N
12° N
11° N
200.0 km
150.0 km
100.0 km
50.0 km
CDP
NLR
GDK
MDS
CGP
PDC
CDL
SLM
KKL


RESULTANT GRADIENT LEVEL WIND-NOVEMBER


RESULTANT GRADIENT LEVEL WIND-DECEMBER


RESULTANT GRADIENT LEVEL WIND-JANUARY


RESULTANT GRADIENT LEVEL WIND-FEBRUARY

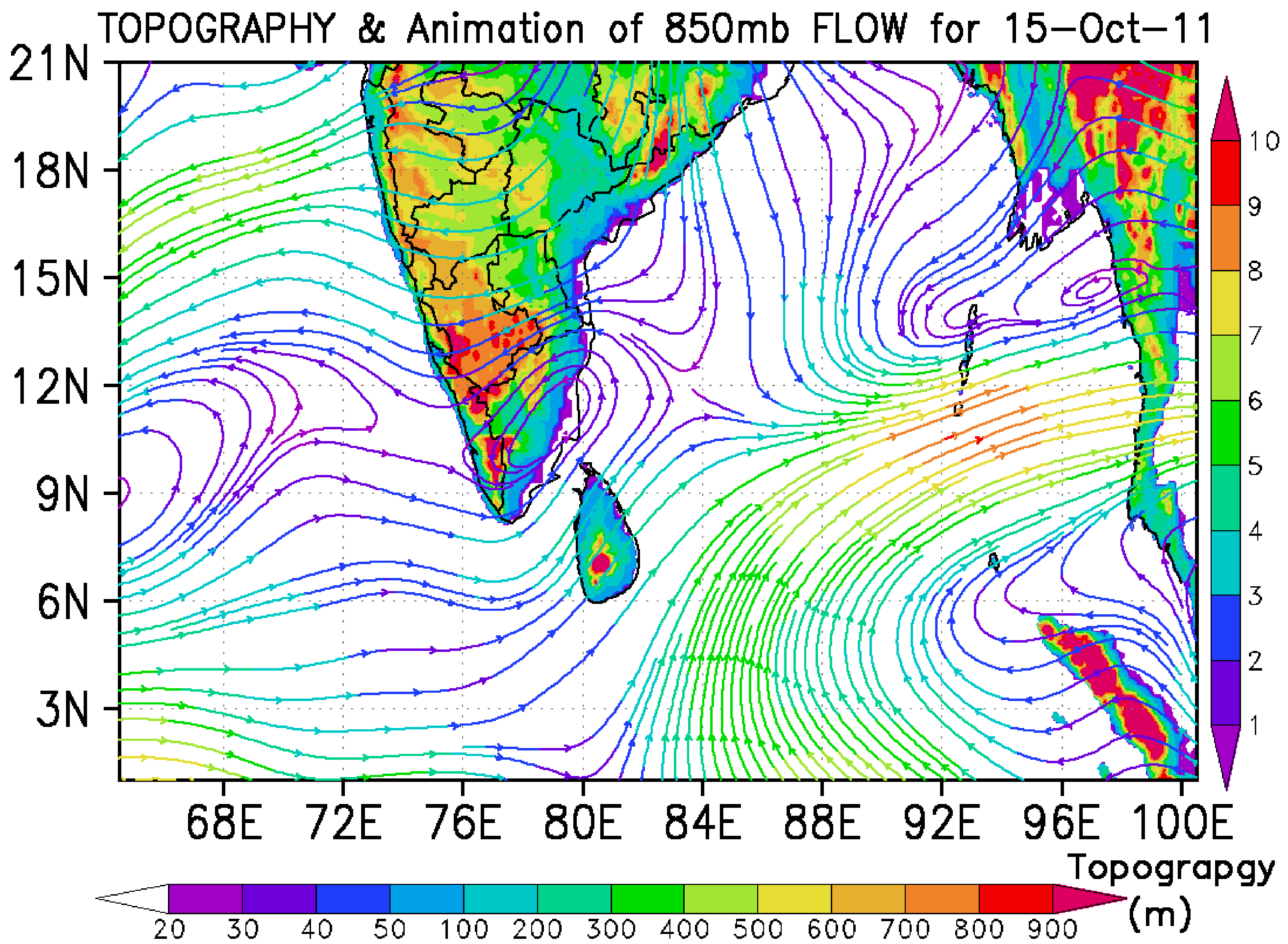


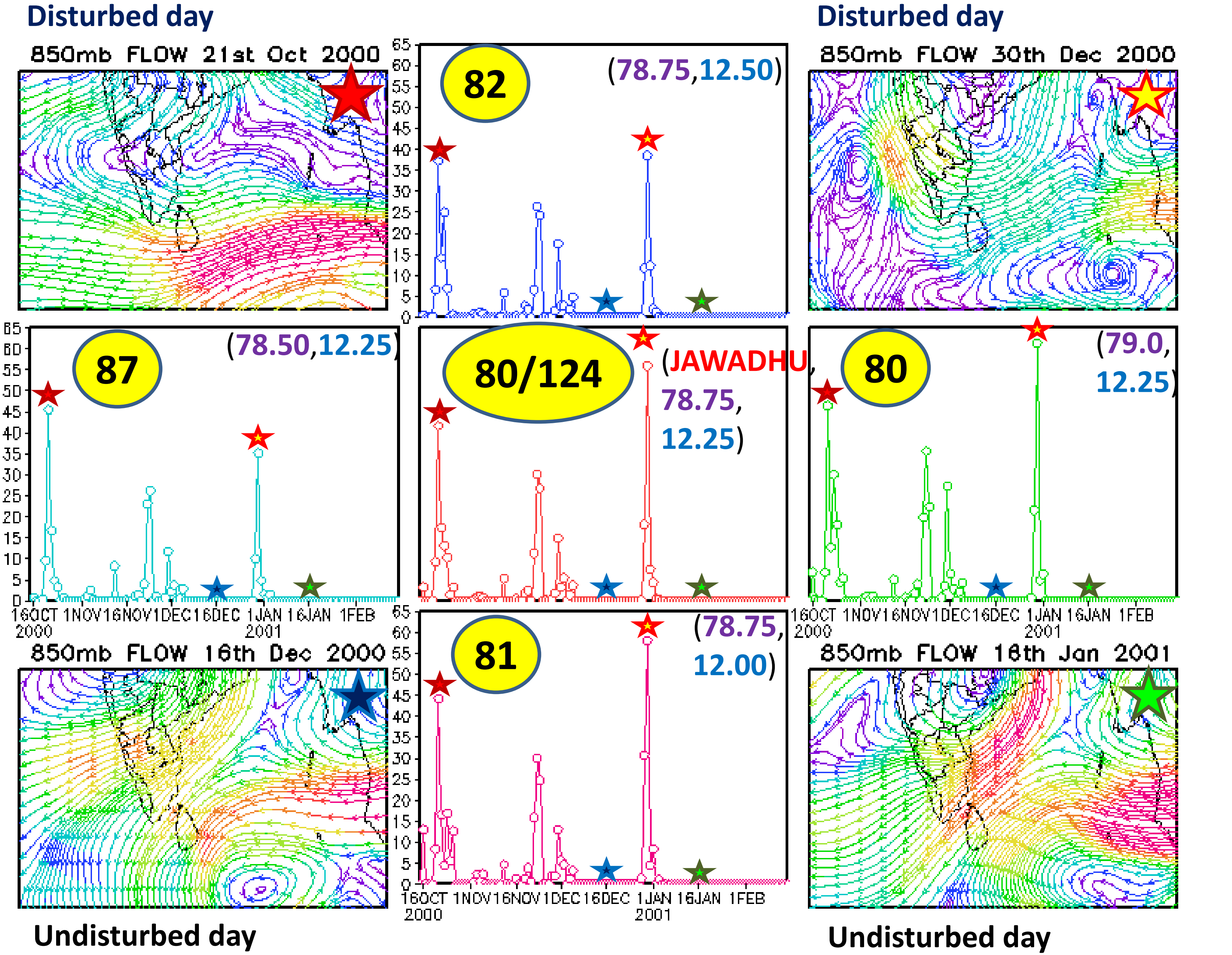
Stream Lines for JAN 2011 at 850mb
21N
18N
15N
12N
9N
6N
3N
68E
72E
76E
80E
84E
88E
92E
96E
100E
10
9
8
7
6
5
4
3
2
1

Jawadhu Hills & Pudupalayam RF (Near Polur)

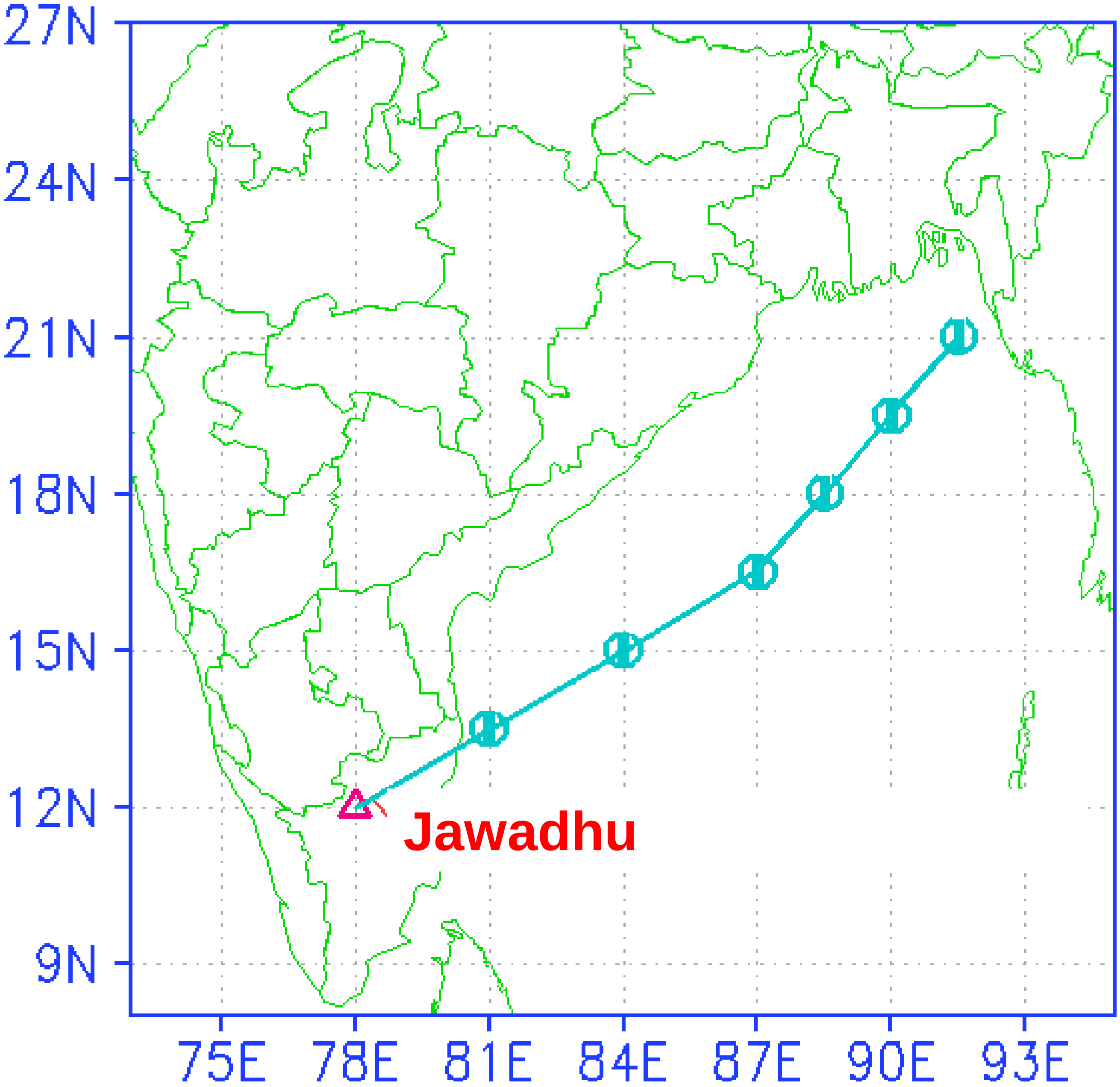
LOOKING FROM THE WEST

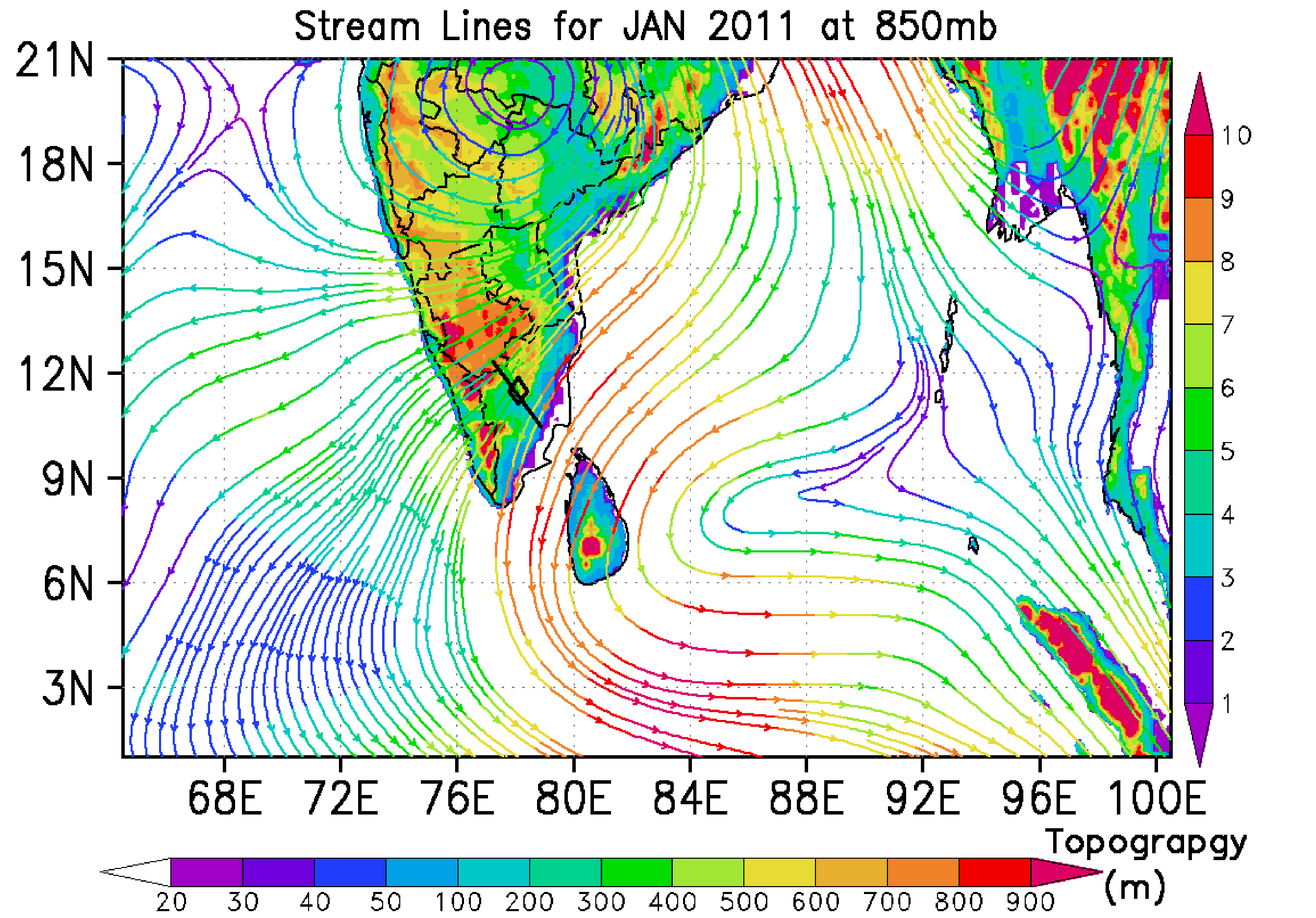
Width = 20km (Approx)
Height = 0.8 Km (Approx)


TOPOGRAPHY & Animation of 850mb FLOW for 15-Oct-11
21N
18N
15N
12N
9N
6N
3N
68E 72E 76E 80E 84E 88E 92E 96E 100E
1 2 3 4 5 6 7 8 9 10
20 30 40 50 100 200 300 400 500 600 700 800 900
Topograpgy (m)


Disturbed day
850mb FLOW 21st Oct 2000
Disturbed day
850mb FLOW 30th Dec 2000
82
(78.75,12.50)
87
(78.50,12.25)
80/124
(JAWADHU, 78.75, 12.25)
80
(79.0, 12.25)
81
(78.75, 12.00)
16OCT 1NOV 16NOV 1DEC 16DEC 1JAN 16JAN 1FEB
2000
2001
850mb FLOW 16th Dec 2000
850mb FLOW 16th Jan 2001
Undisturbed day
Undisturbed day

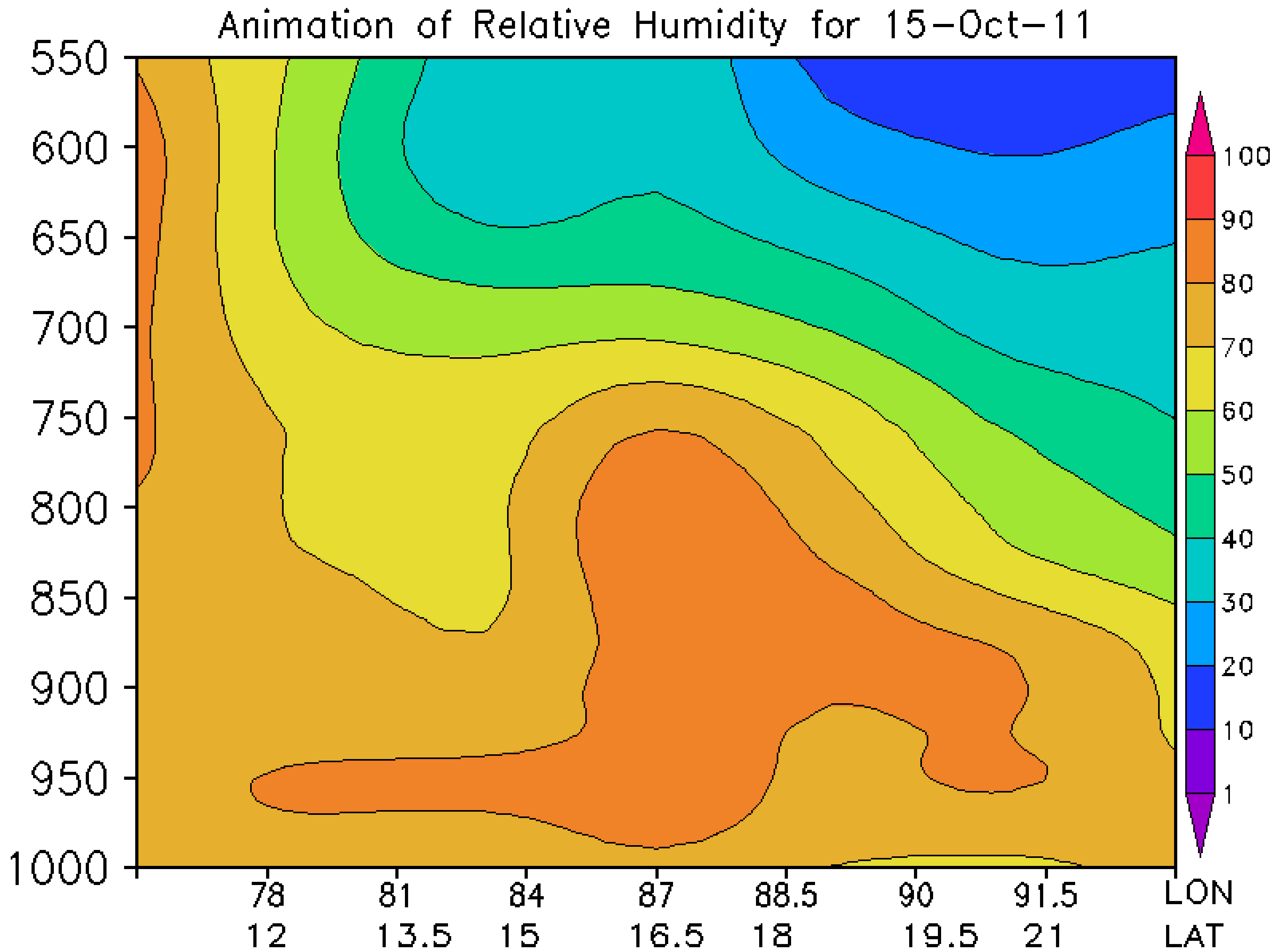
A CLIMATOLOGICAL BACK TRAJECTORY FROM JAWADHU



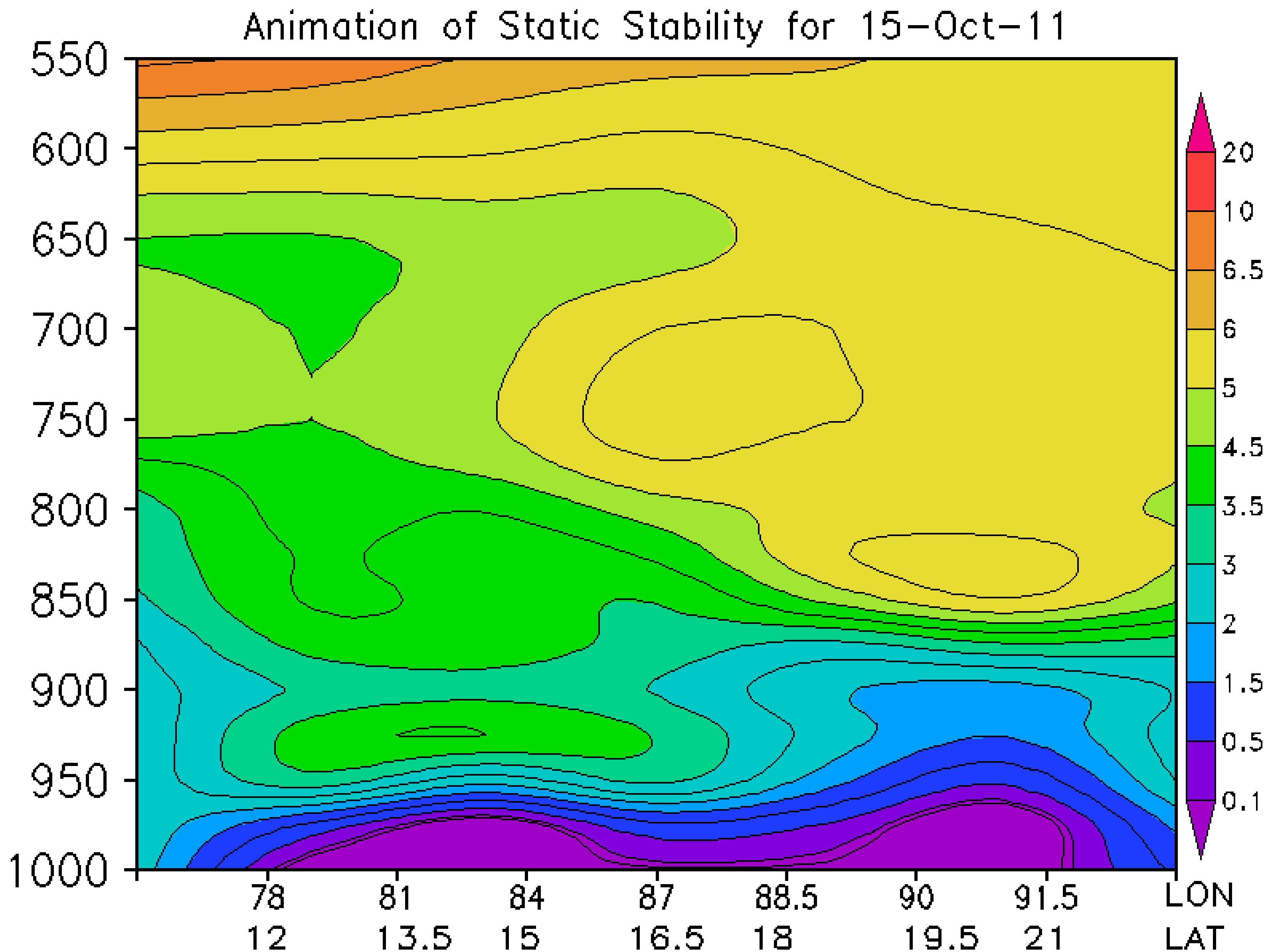


Stream Lines for JAN 2011 at 850mb
21N
18N
15N
12N
9N
6N
3N
68E
72E
76E
80E
84E
88E
92E
96E
100E
10
9
8
7
6
5
4
3
2
1
Topograpgy
(m)
20
30
40
50
100
200
300
400
500
600
700
800
900

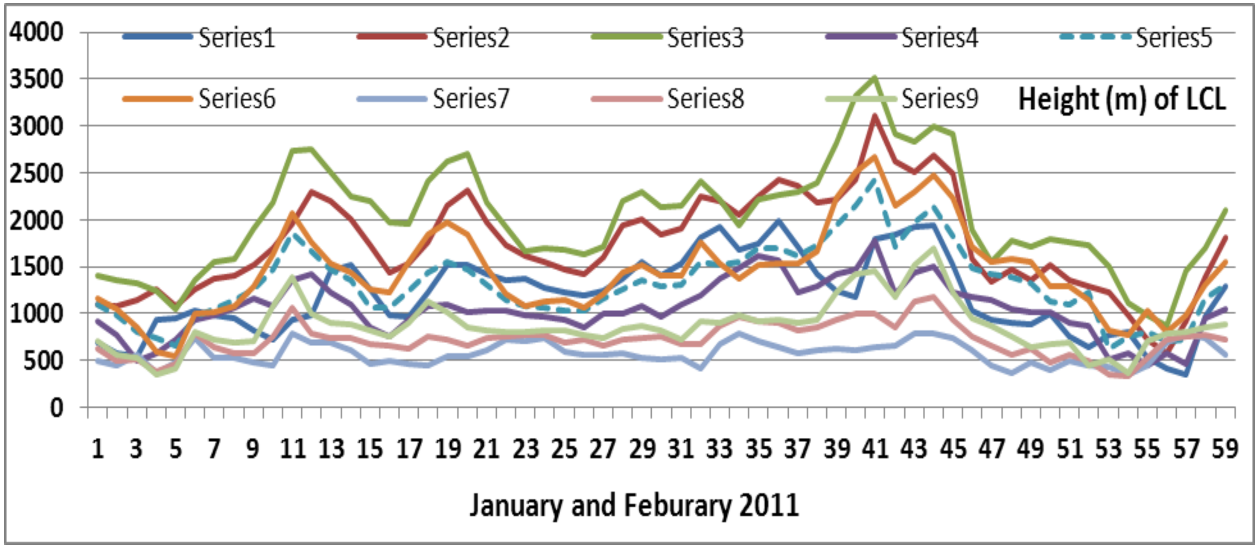
Relative Humidity along the flow (850mb) over Bay of Bengal

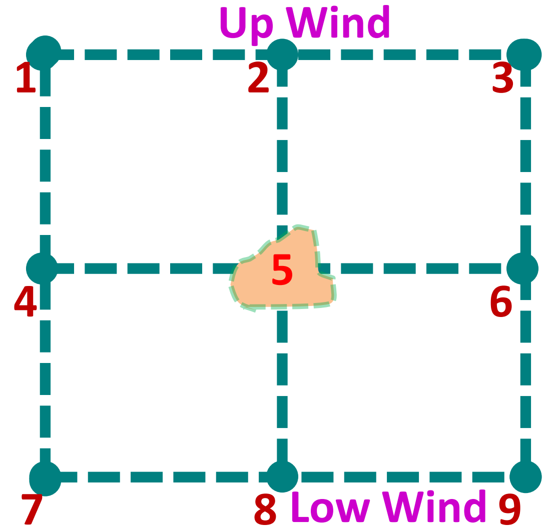


Static Stability (*x1000*) calculated Across mean flow over Bay of Bengal

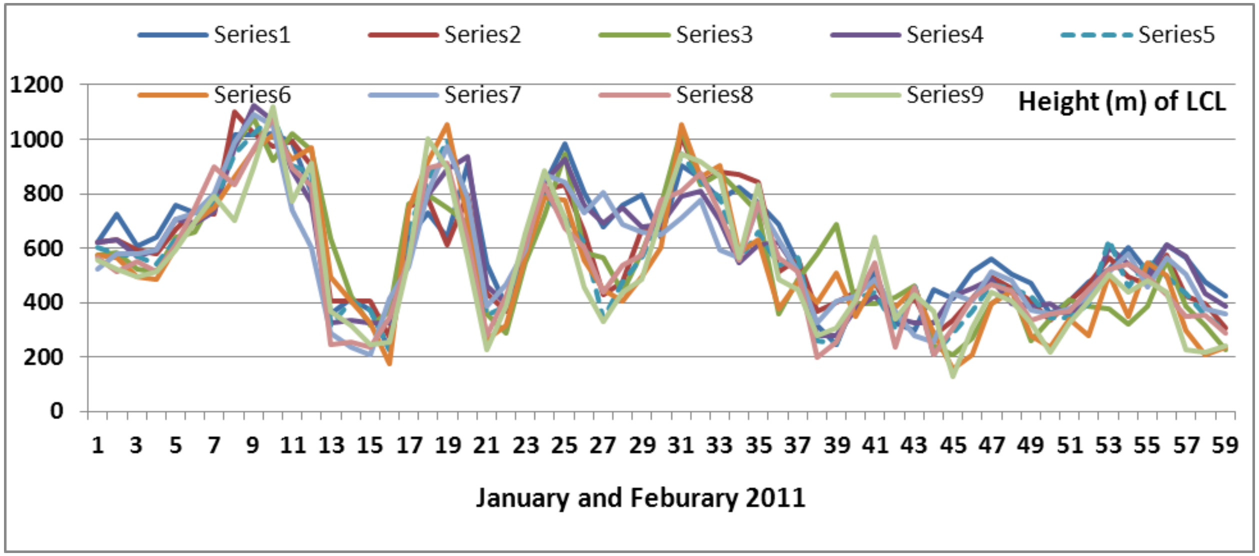


Cloud base (LCL) near Jawadhu (Tamilnadu) and Lihue (Waialeale)





Data Source: ERAInterim resolution 1.5x1.5 deg lon-lat



Lihue (Waialeale, Hawaii)

HANDLING OF THE TERRAIN IN WRF

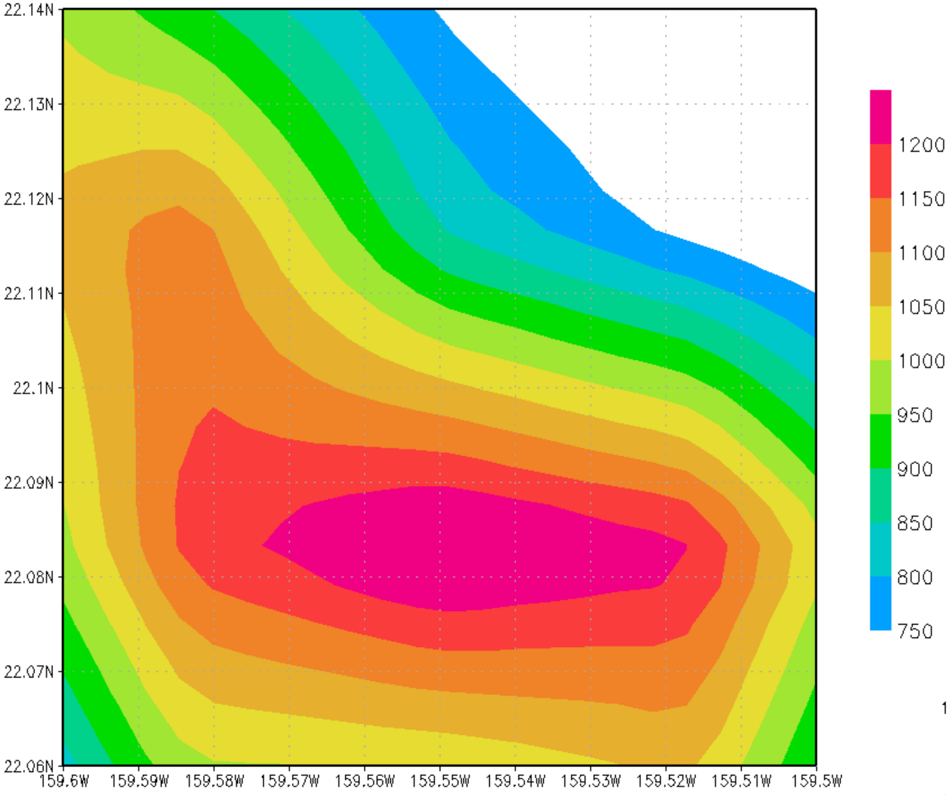
THE WRF UTILIZES A SIGMA COORDINATE SYSTEM WITH SIGMA EQUAL TO ONE SURFACE CARRYING THE HEIGHT OF THE EARTHS SURFACE.

IN OUR WORK WE USE THE USGS TERRAIN HEIGHTS (WHICH IS COMPATIBLE WITH THE WRF TOPOGRAPHY). THE USGS DATA COMES AT A 2 METER RESOLUTION, THOSE ARE INTERPOLATED TO OUR INNER WRF GRIDS RESOLUTION OF 500 METERS.

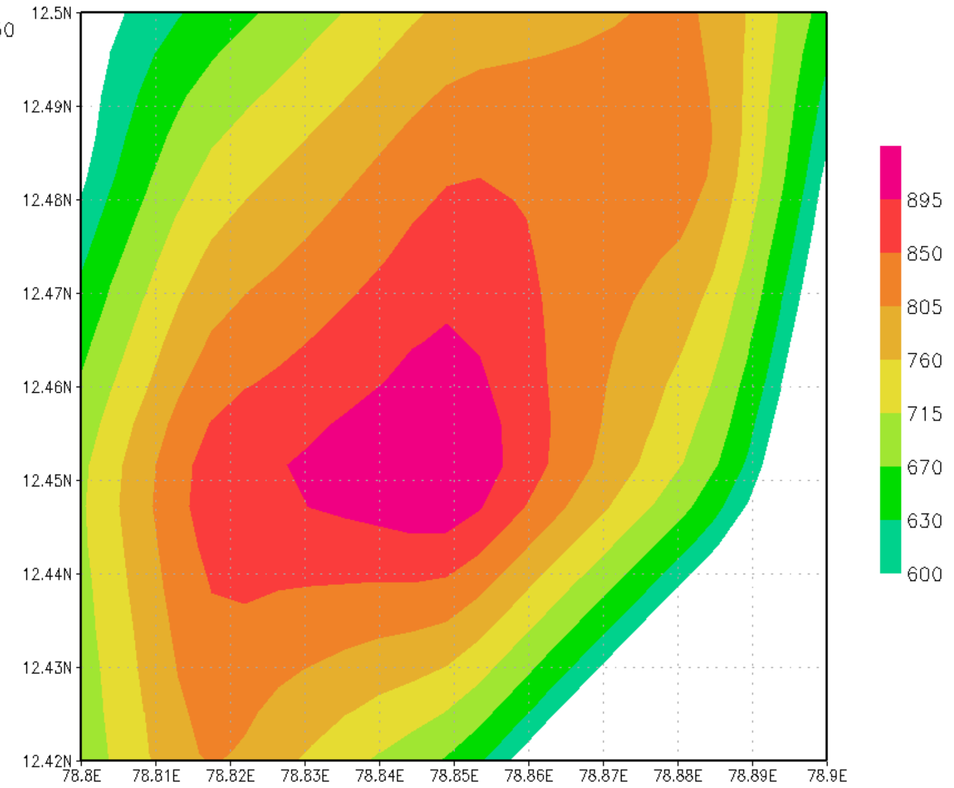
THE RAW DATA OF USGS IS GLOBAL, HENCE ONCE WE MOUNT THE HAWAIIAN (WAIALEALE) ON TO THE POLUR REGION, WE SIMPLY SUBSTITUTE GRID POINT BY GRID POINT THE HAWAIIAN TOPOGRAPHY ON TO THE RESPECTIVE POLUR INNER NEST. FOR LAND USE THE PREVIOUS POLUR LAND SURFACE DATA IS STILL RETAINED. TRIGONOMETRIC RELATIONS ARE USED FOR THE ROTATION OF THE FRONT FACE OF THE HAWAIIAN MOUNTAIN THAT REPLACES THE FRONT FACE OF THE POLUR MOUNTAIN. SOME SMOOTHING WAS NECESSARY FOR THE BLENDING OF THE BACK SIDE OF THIS NEW CONFIGURATION.

BY THE FRONT FACE WE MEAN THE TOPOGRAPHY OF THOSE GRID POINTS IN THREE DIMENSIONS THAT WOULD FIRST SEE A NORMAL IMPACT OF THE CLIMATOLOGICAL WINTER MONSOON WINDS.

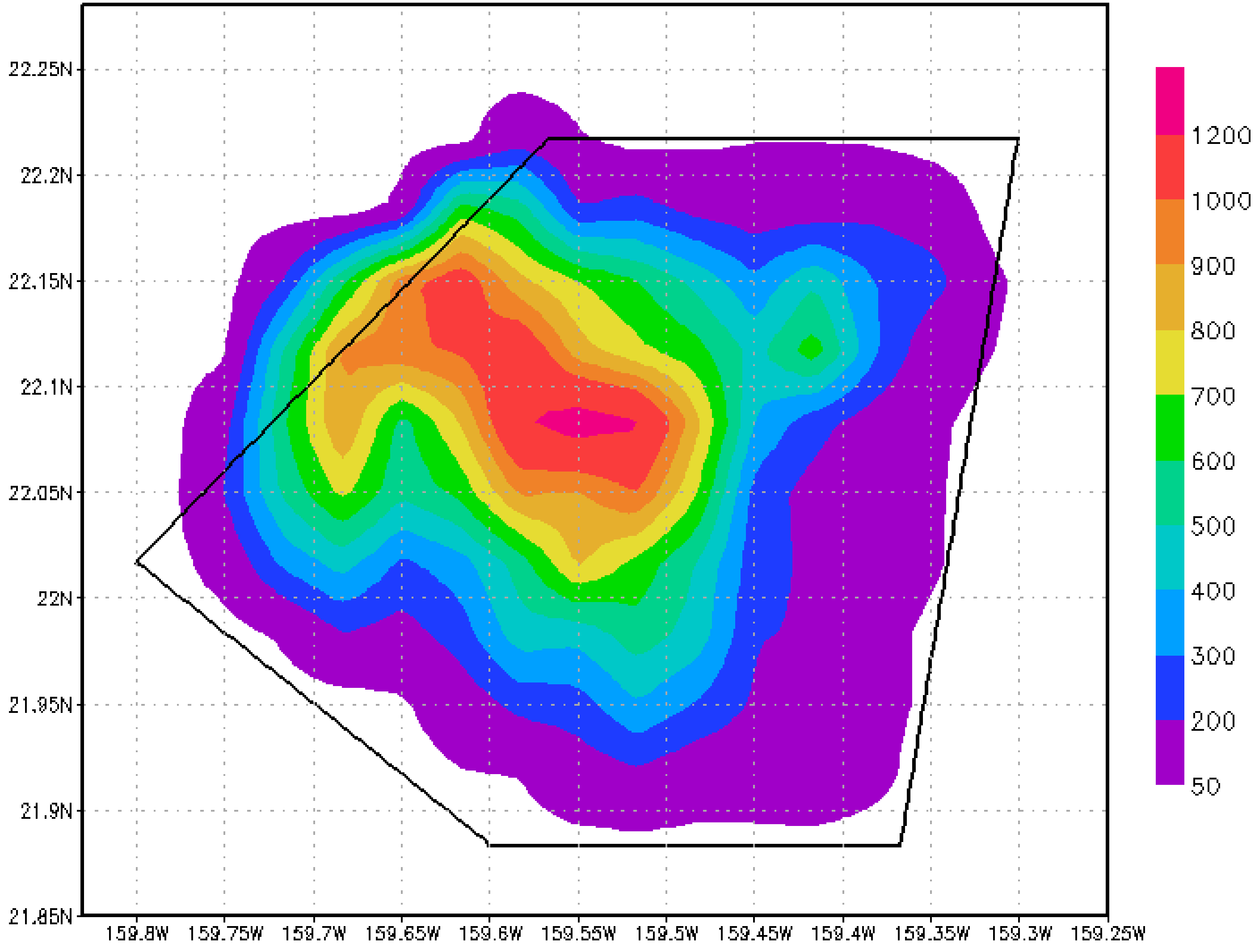
OROGRAPHY AROUND WAIALEALE HAWAII (500m)



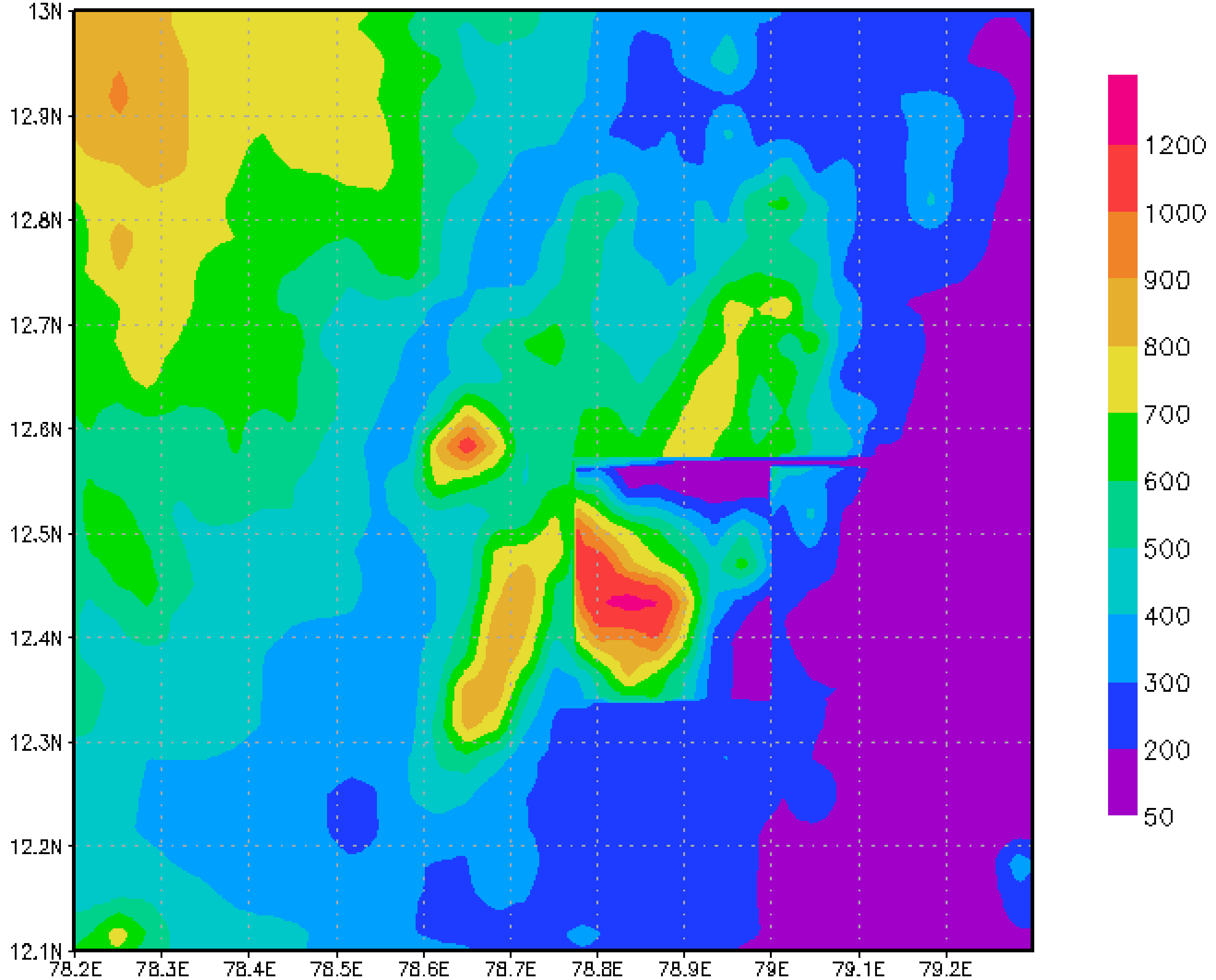
OROGRAPHY AROUND JAWADHU HILLS, TAMILNADU (500m)



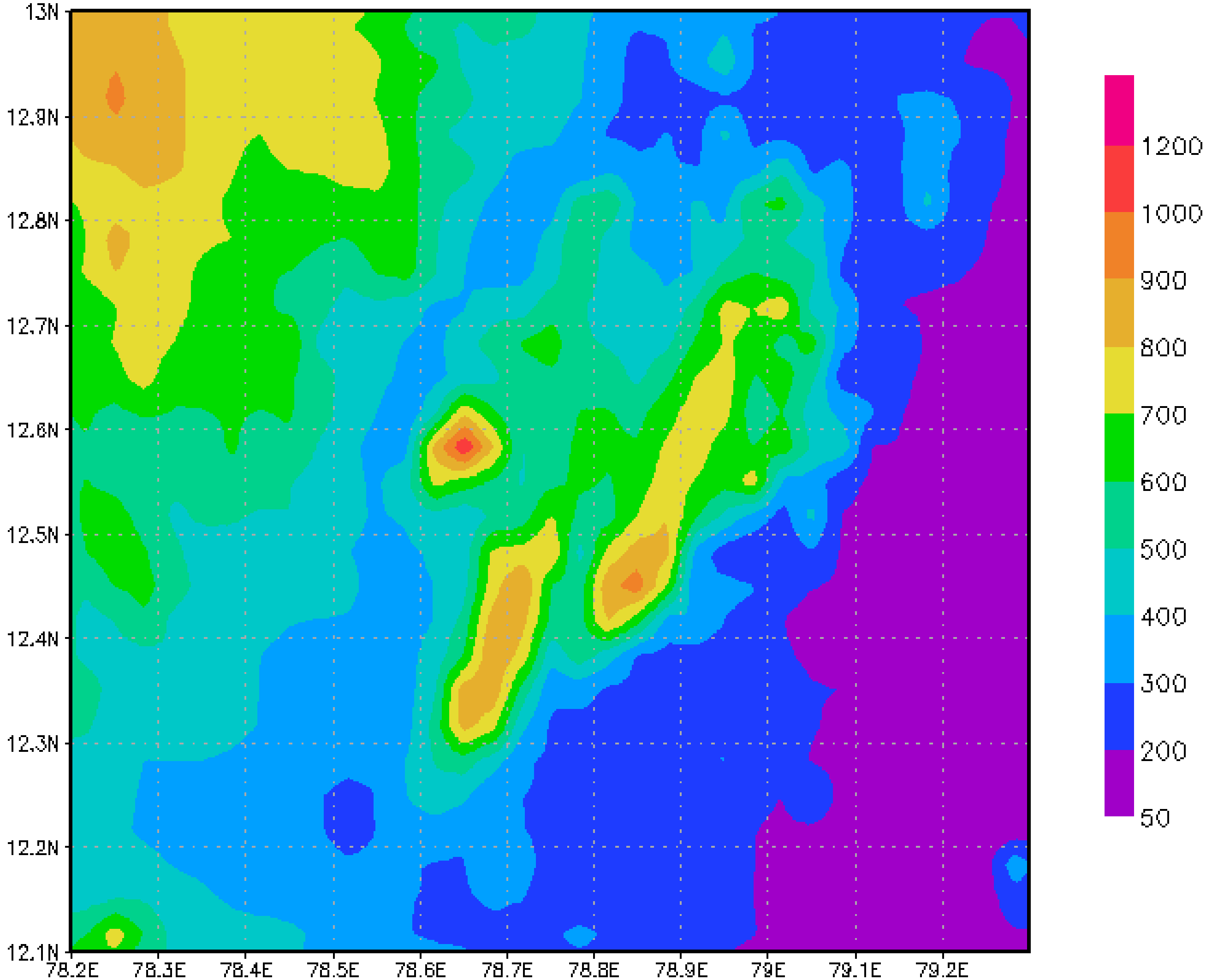
HAWAII MOUNTAIN PLACED ON THE JAWADHU HILLS , TAMILNADU



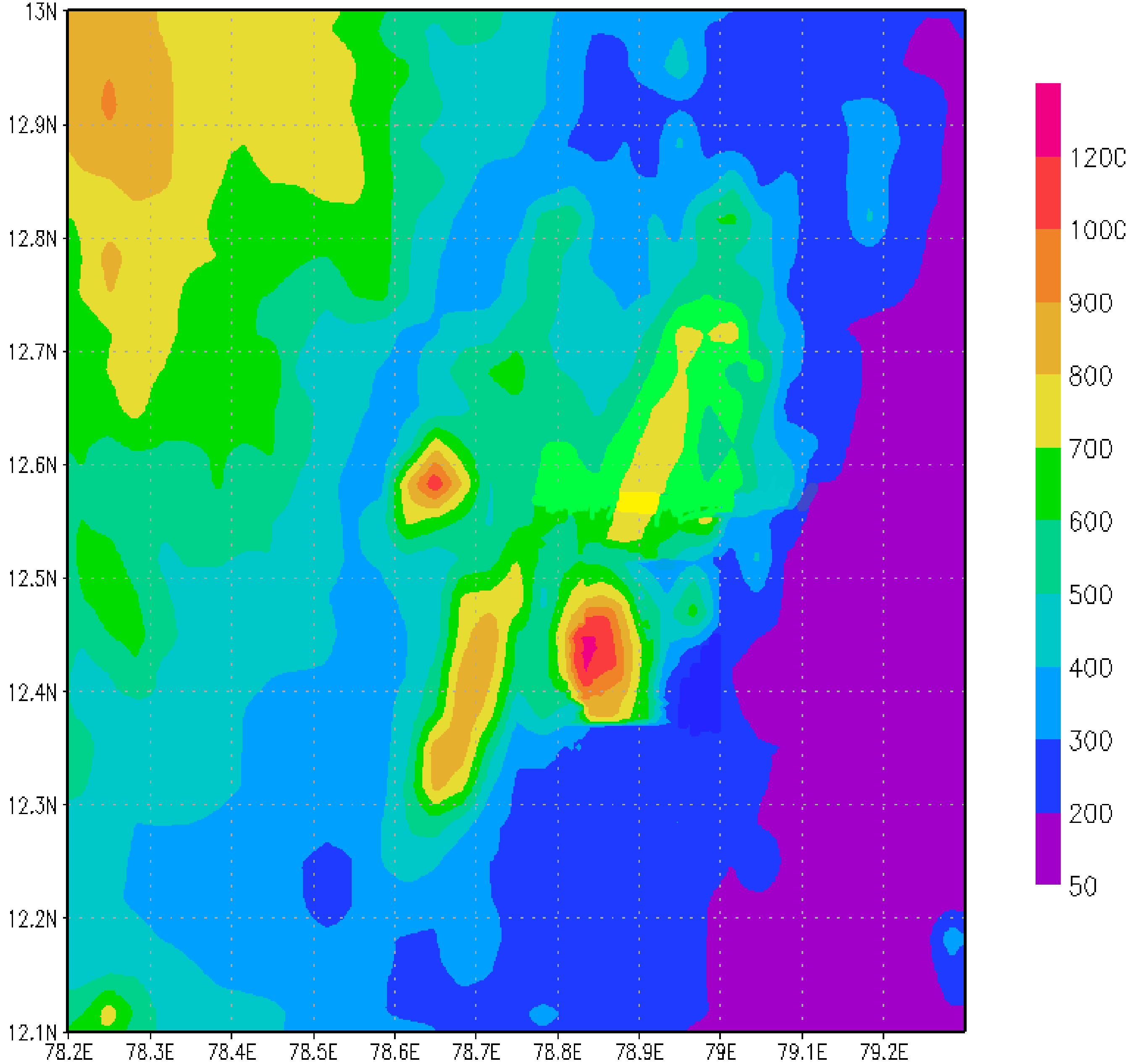
LARGER PERSPECTIVE OF HAWAII MOUNTAIN PLACED ON THE JAWADHU HILLS , TAMILNADU, NO ROTATION



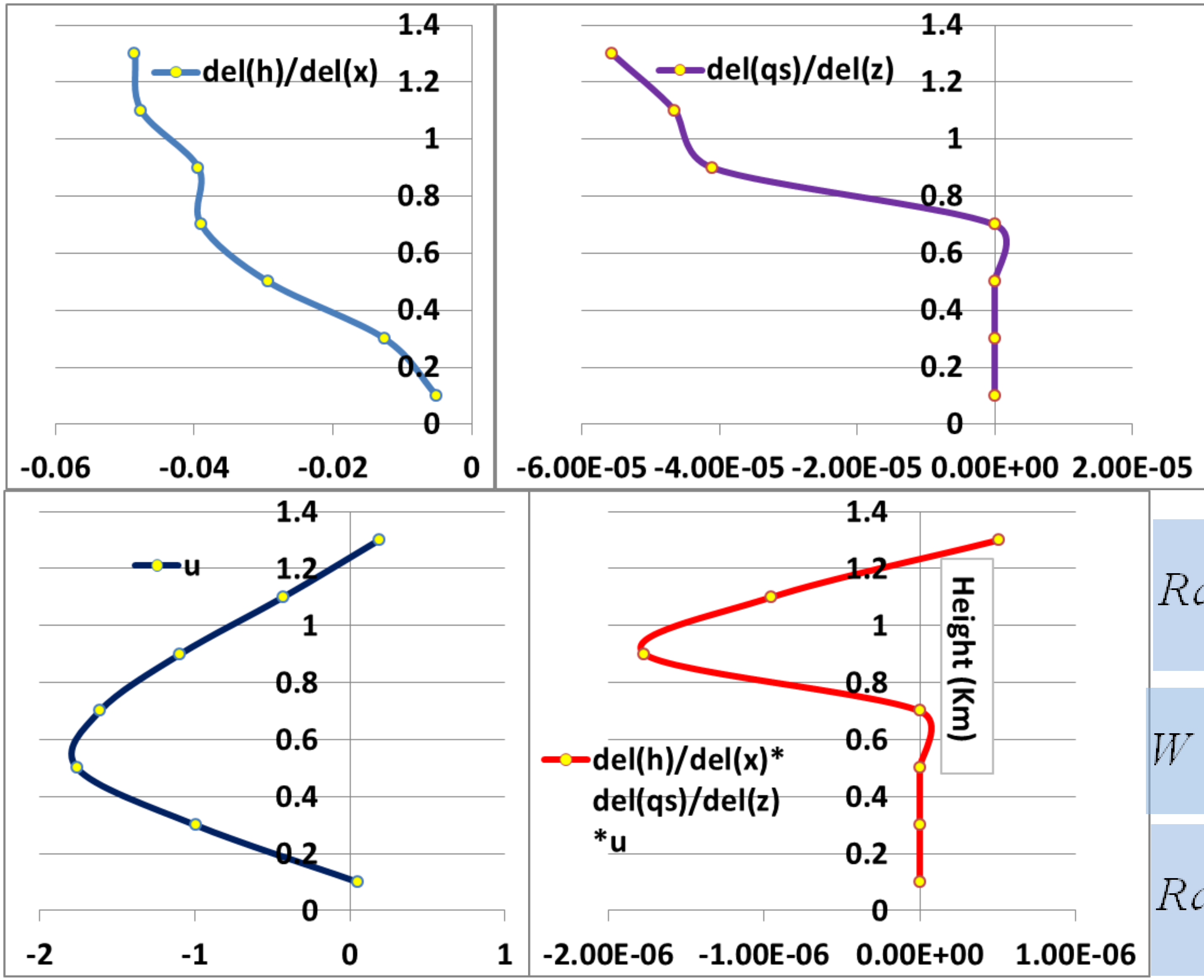
ORIGINAL OROGRAPHY AROUND JAWADHU HILLS , EASTERN GHATS, TAMILNADU



ROTATED HAWAIIAN MOUNTAIN PLACED ON THE JAWADHU HILLS, TAMILNADU



Orographic rain near JAWADHU with rotated Waialeale mountain

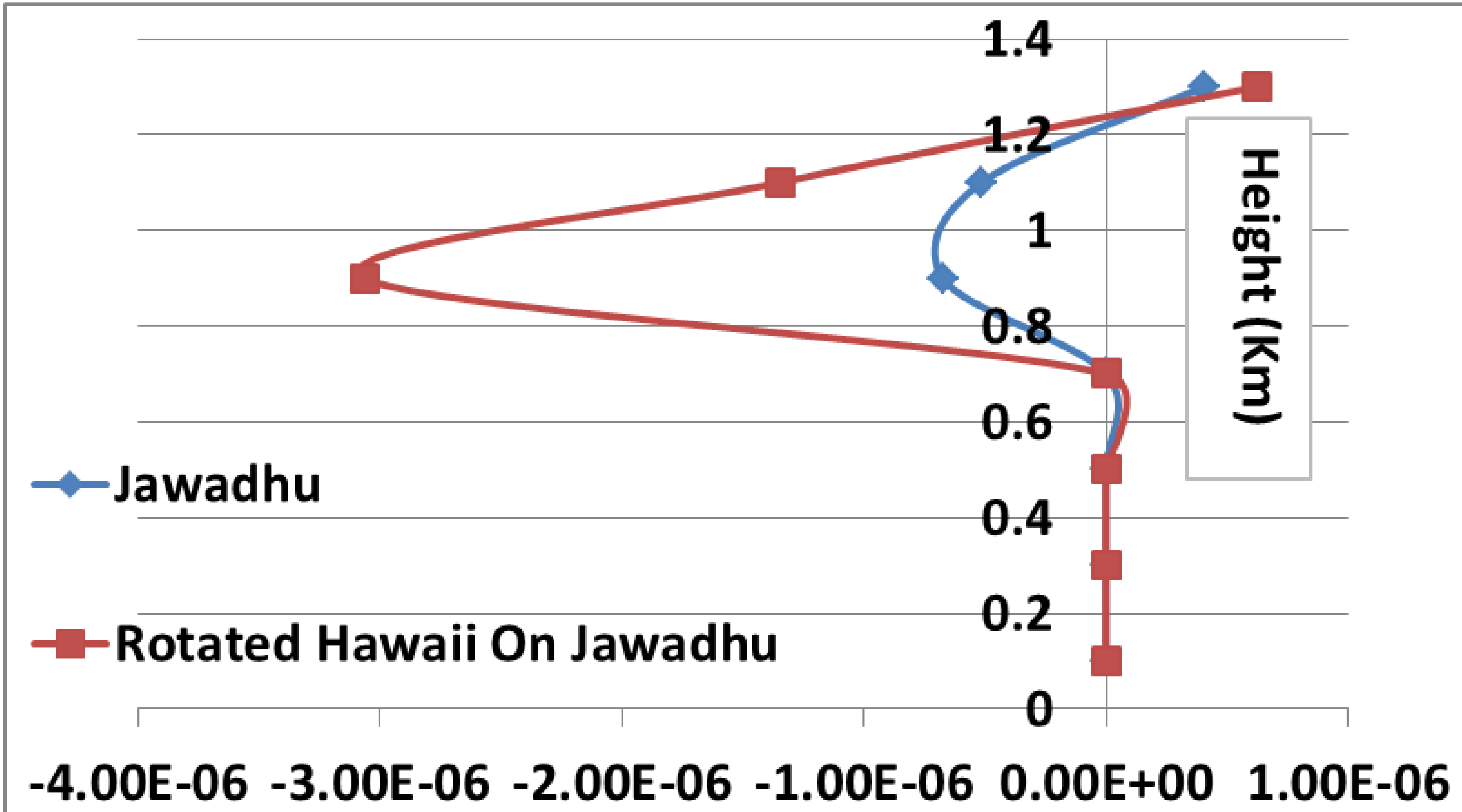


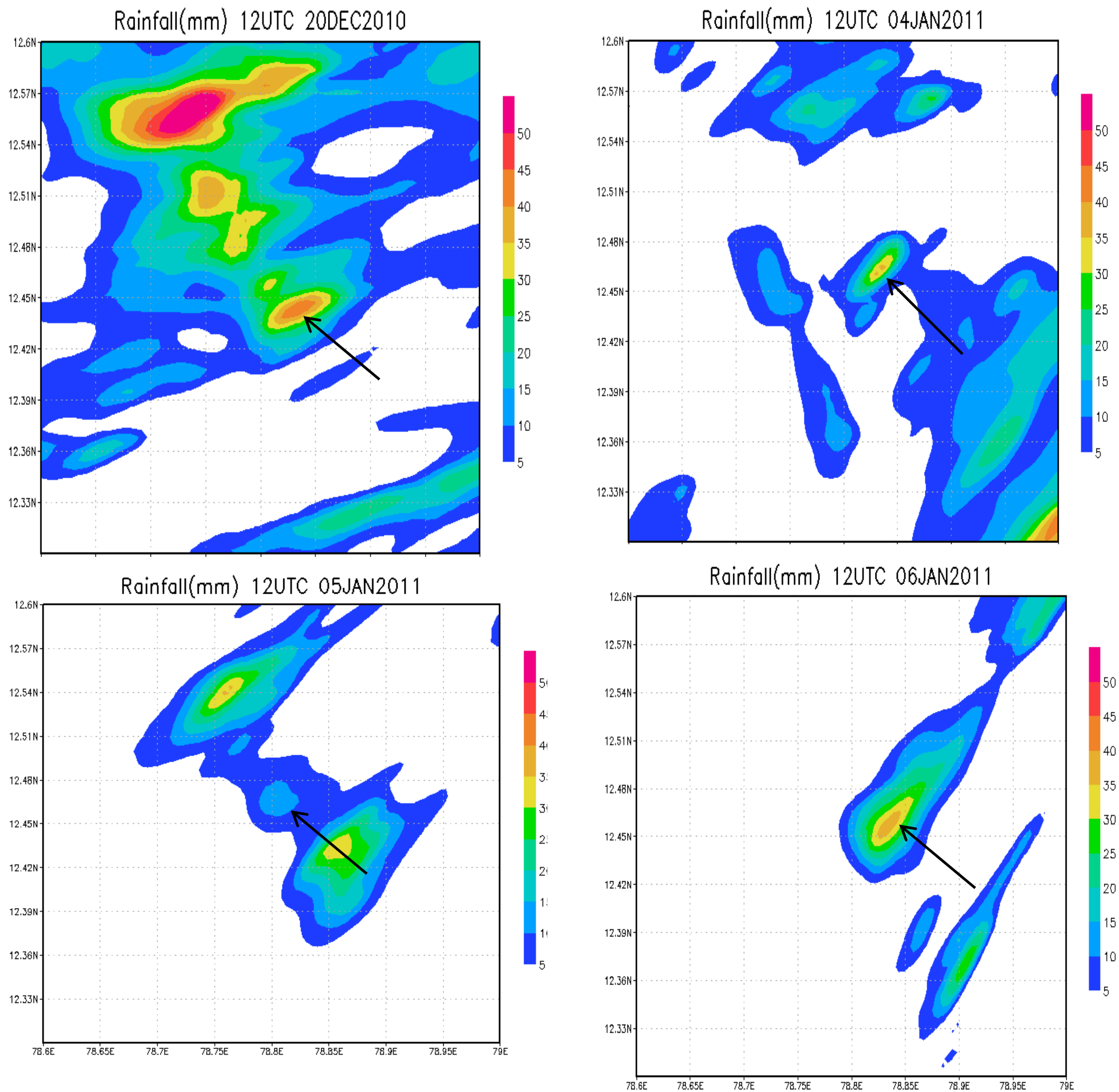
$$Rain \approx \int_0^{TOP} W \frac{\partial q_s}{\partial z} dz$$

$$W \approx U \frac{\partial h}{\partial x}$$

$$Rain \approx \int_0^{TOP} U \frac{\partial h}{\partial x} \frac{\partial q_s}{\partial z} dz$$

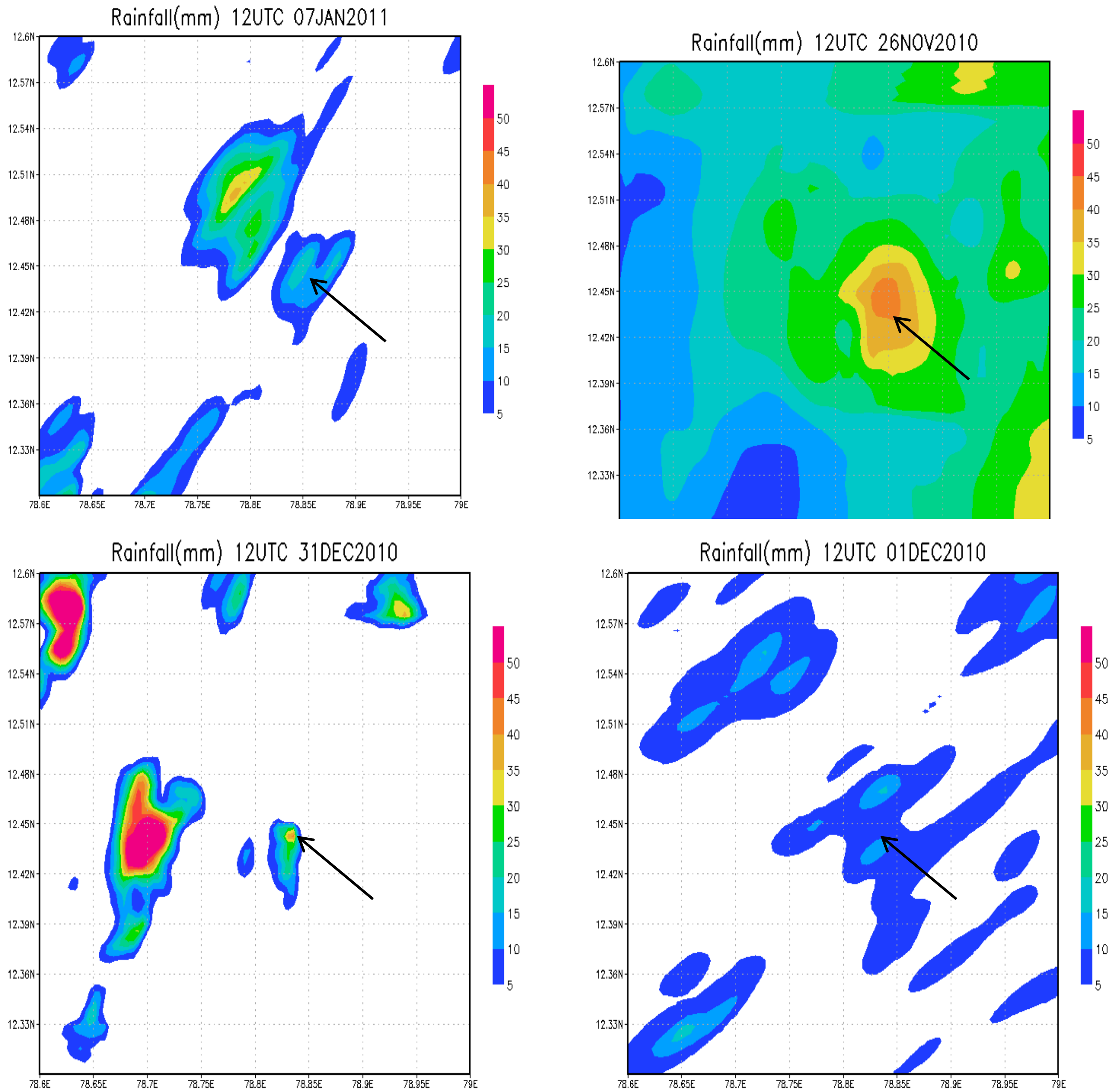
Del(h)/Del(x)*Del(qs)/Del(z)*u





A SEQUENCE OF DAY 1 FORECASTS FOR UNDISTURBED DAYS OVER THE REGION OF JAWADHU HILLS.

THIS MAKES USE OF THE ROTATED FRONT END OF THE WAIALEALE MOUNTAINS OVER THE JAWADHU HILLS .



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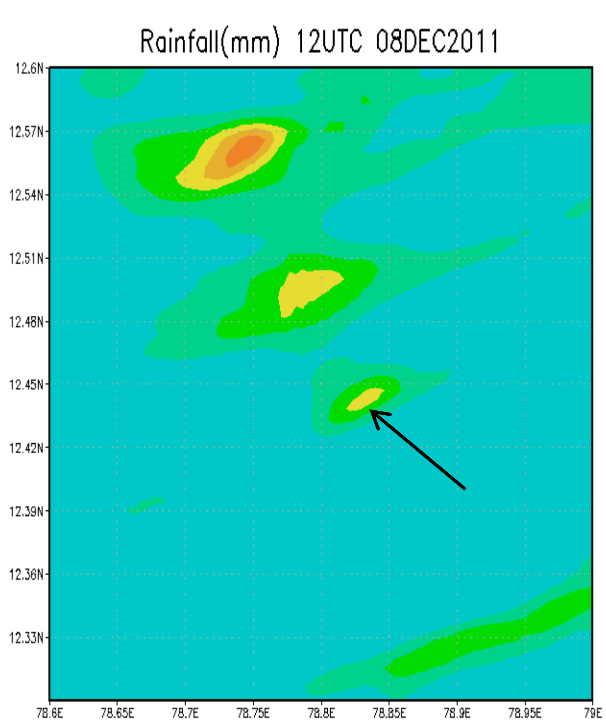
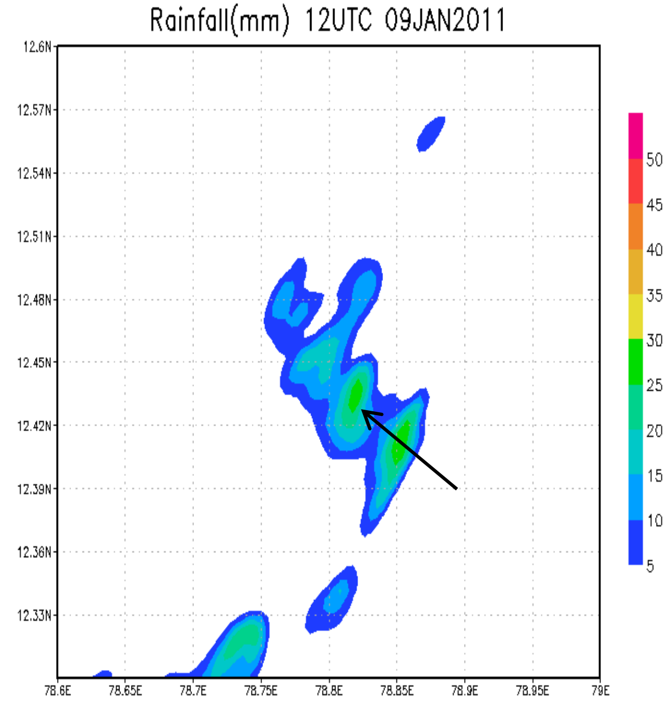
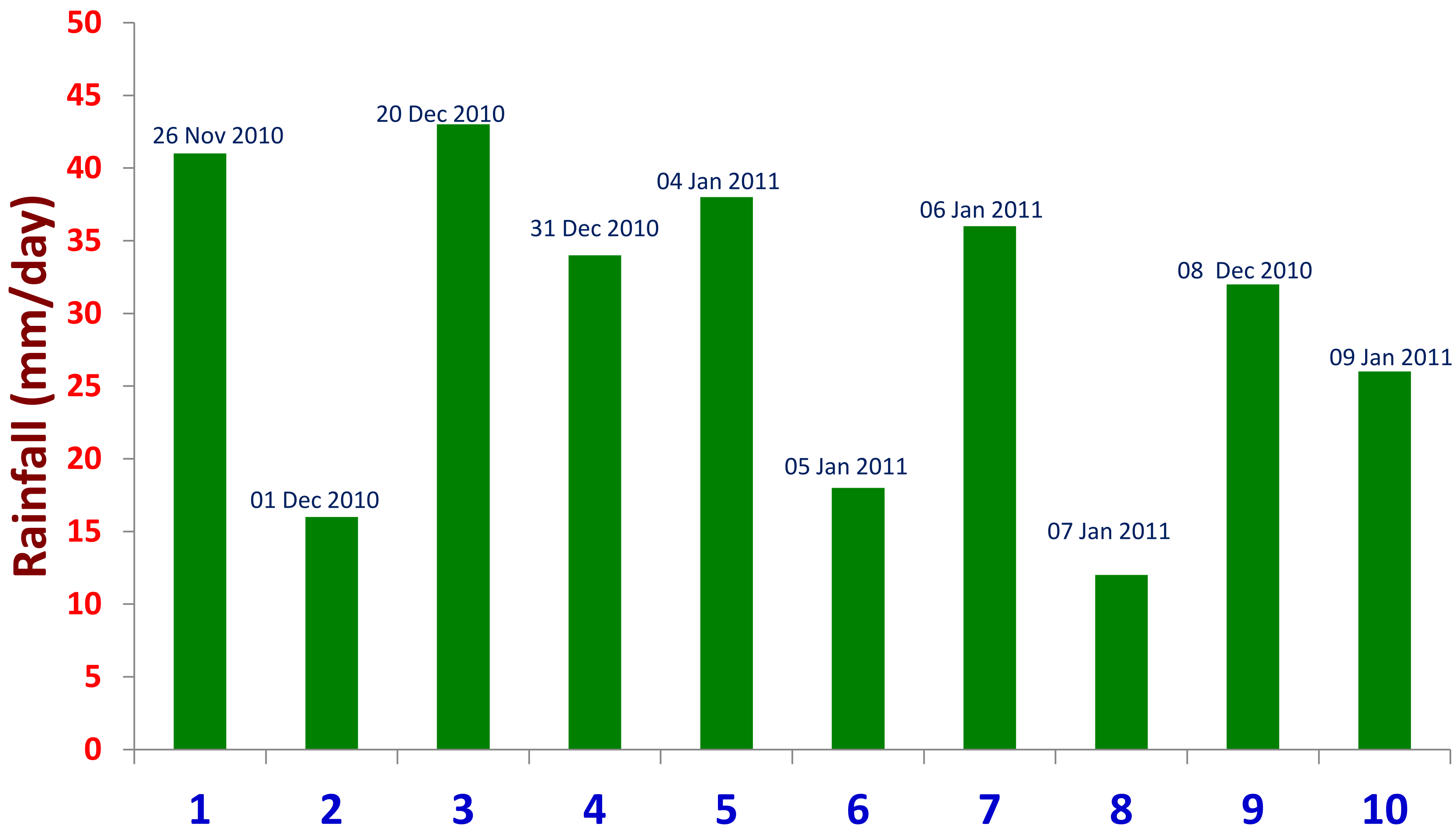




A SEQUENCE OF DAY 1 FORECASTS FOR UNDISTURBED DAYS OVER THE REGION OF JAWADHU HILLS.

THIS MAKES USE OF THE ROTATED FRONT END OF THE WAIALEALE MOUNTAINS OVER THE JAWADHU HILLS.

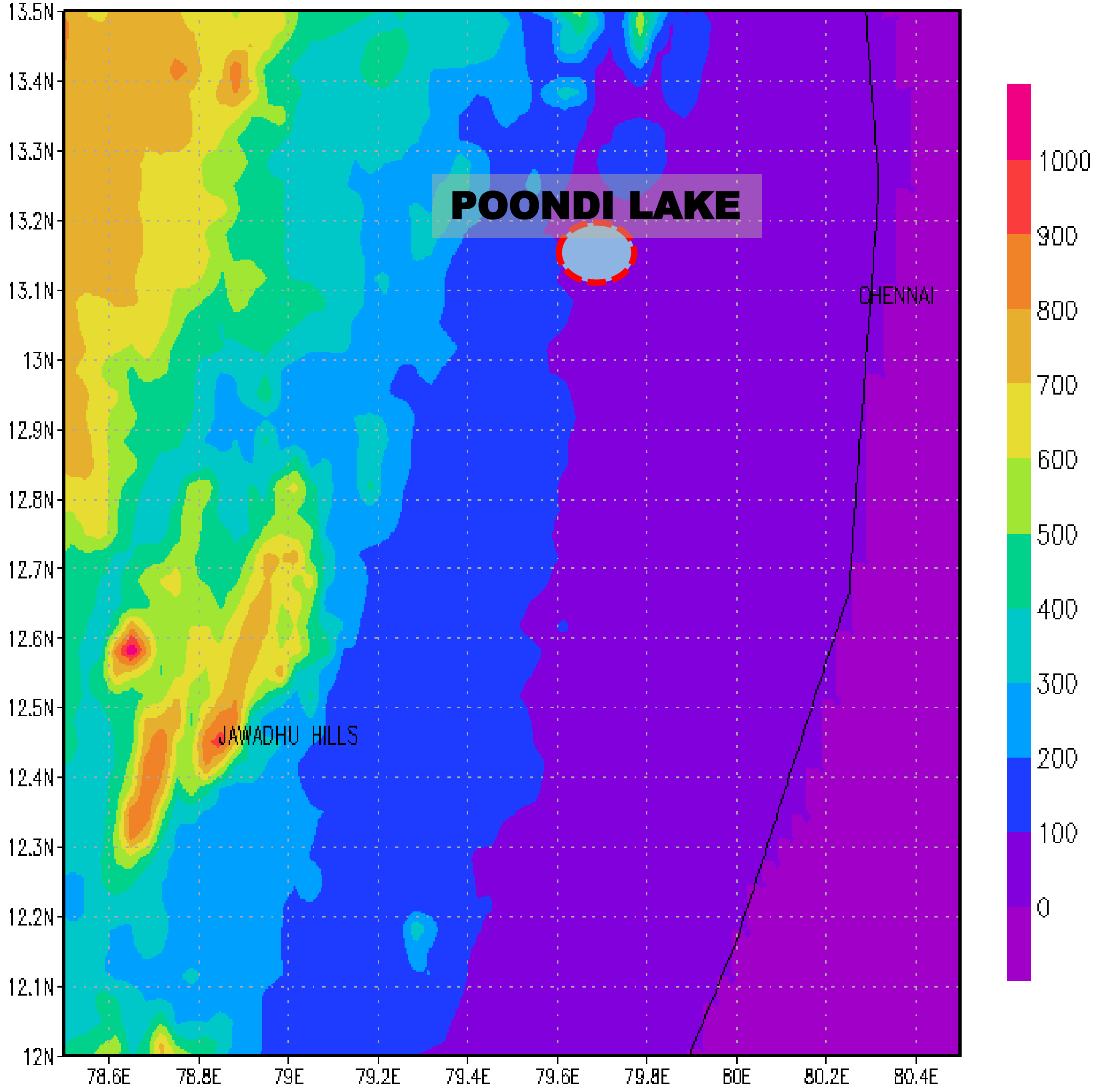
MODEL BASED RAINFALL(mm/day) IN THE SAME GEOGRAPHICAL LOCATION NEAR THE JAWADHU Hills FOR UNDISTURBED DAYS. THE OBSERVED RAINFALL ON THESE DAYS WAS NIL. THIS MAKES USE OF THE ROTATED FRONT END OF THE WAIALEALE MOUNTAINS OVER THE JAWADHU Hills



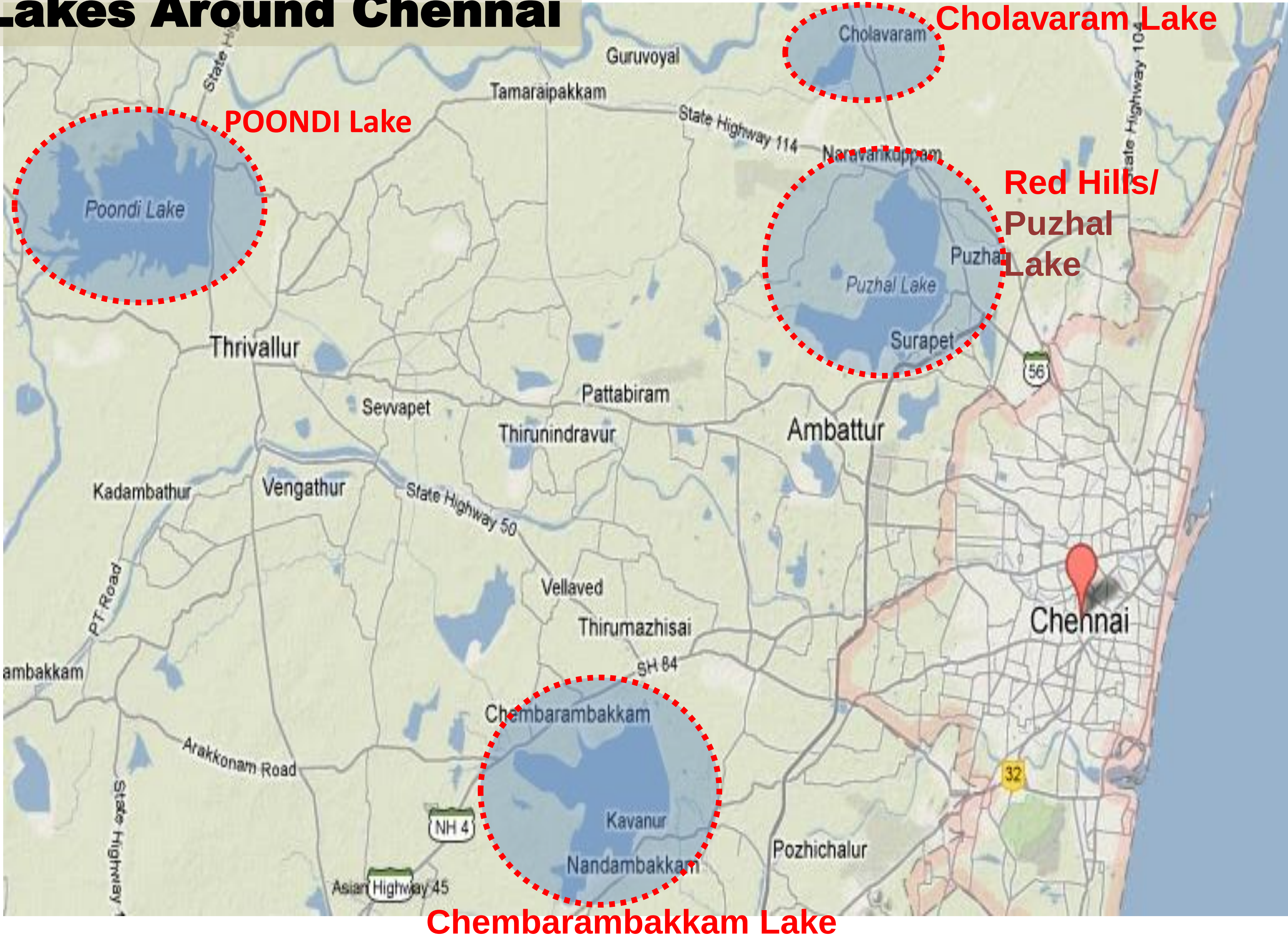
Simulations of rain between one to one and half inches per day was possible in 80% of the cases that we ran.


POONDI Lake
Red Hills/ Puzhal Lake
CHENNAI
130Km
JAWADHU Hills
Chittoor
Ammavarikuppam
Narasinga Rayani Pet
Thiruthani
Sholinghur
Paranji
Arakkonam
Thrivallur
Vellanur
Pattabiram
Ambattur
Vengathur
Thirumazhisai
Chembarambakkam
Nandambakkam
Adyar
Velachery
Sriperumbudur
Tambaram
Sholinganallur
Vandalur
Urappakkam
Uthandi
Navallur
Muttukadu
Kelambakkam
Thiruporur
Nemmeli
Pattipulam
Mahabalipuram
Kunnathur
Kalpakkam Township
Katpadi
Narasingapuram
Sathuvacheri
Vellore
Pallikonda
Wallajah
Vilapakkam RF
Sathur
Bagayam
Adukkamparai
Timiri
Kannamangalam RF
Kannamangalam
Kalavai
Vembi
Baluchetty Chatram
Marudham
Kanchipuram
Oragadam
Kattankulathur
Maraimalai Nagar
Walajabad
Kalur
Asoor
Chithathur
Chengalpattu
Ananthapuram
Nammiyambut
Arni
Painkinar
Cheyyar
State Highway 116
Mamandur
Nesal
Sengadu
Vilanallur
Uthiramerur
Irembedu
Jawadhu Polur RF
Veivasambanur
Polur
Vandavasi
Ulundai
Karunguzhi
Madurantakam
Kottai
Chetpet
Viralur
Kaveripakkam Lake
SH 6A

TOPOGRAPHY FOR THE PIPE



Lakes Around Chennai



Chennai has fresh water reservoirs/lakes (Those all lakes are located around 80E,13N) namely **Poondi, Sholavaram, Puzhal Lake (Red Hills), Chembarambakkam, Veeranam** to cater the daily needs of water for Chennai area. Some of them used to store water from Krishna river.

Chennai receives most of its water from these reservoirs,

1. **Poondi Lake** (**3,231 Mcft-million cubic feet**),

2. **Cholavaram Lake** (**881 Mcft, Ponneri taluka of Thiruvallur district, Rain-fed reservior**),

3. **Puzhal Lake/Red Hills Lake** (**3,300 Mcft;, Ponneri Taluk of Thiruvallur district, Rain-fed reservior**)

4. **Chembarambakkam Lake** (**3,645 Mcft; Kanchipuram district, 40 km from Chennai ; Rain-fed reservior**): The Adyar River originates from this lake.

HOW DOES THE NEW OROGRAPHIC RAIN COMPUTE FOR CHENNAI CITY'S WATER NEEDS

- As of 2012, Chennai Metrowater supplies about 830 million litres of water every day to residents and commercial establishments (Chennai Metro).

- Chennai has fresh water reservoirs/lakes namely ***Poondi, Sholavaram, Red Hills, Chembarambakkam, Veeranam*** to cater the daily needs of water for Chennai area.

- The average rainfall in Chennai is 1276 mm. Chennai receives about 985 million liters per day (mld) from various sources against the required amount of 1200 mld and the demand is expected to rise to 2100 mld by 2031. The newly constructed Minjur desalination plant adds another 100 mlds to the city's growing demand.

- Given an inch of rain per day over a two and half mile square (from the proposed orographic effect) , hypothetically if that water were to be harvested entirely, that would provide a number 411 million litters per day.

Calculations

1 mile = 63360 inches

Given one inch of rain/day

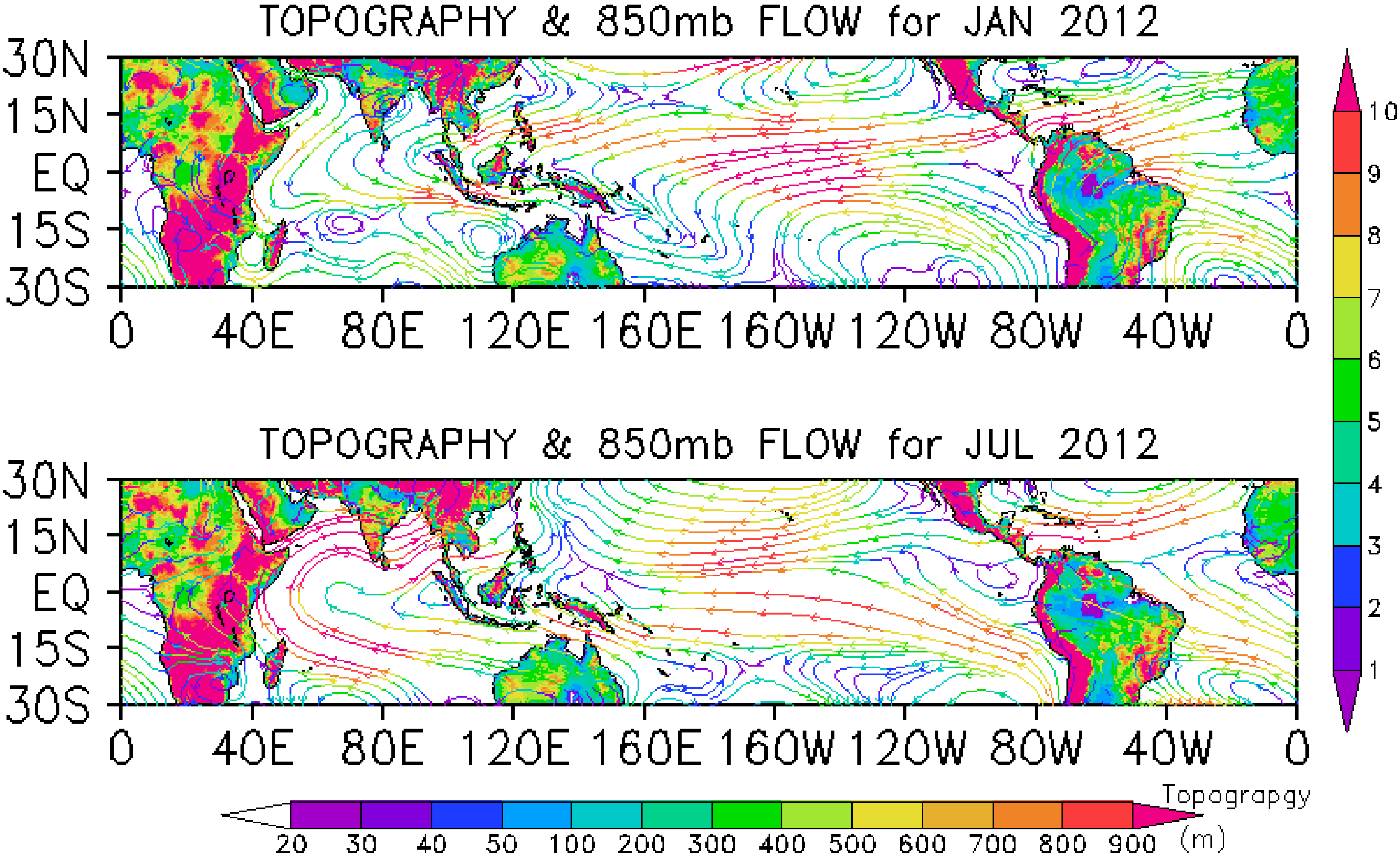
2.5 miles = 2.5 x 63360 inches

$(2.5 \text{ miles})^2 = (2.5 \times 63360)^2$ square inches

= 25090560000 square inches

1 litres = 61 cubic inches

Total no of liters/day from one inch of rain = 25090560000/61 = 411 millions litres/day


TOPOGRAPHY & 850mb FLOW for JAN 2012
TOPOGRAPHY & 850mb FLOW for JUL 2012
30N
15N
EQ
15S
30S
0
40E
80E
120E
160E
160W
120W
80W
40W
0
10
9
8
7
6
5
4
3
2
1
Topograpgy
(m)
20
30
40
50
100
200
300
400
500
600
700
800
900

SUMMARY REMARKS

- IT IS POSSIBLE TO PREDICT , THE DAY BY DAY RAINS, SOMEWHAT CACURATELY AT WAIALEALE (A MOUNTAIN THAT HOLDS A WORLDS RECORD FOR TOTAL ANNUAL RAINS) USING A CLOUD RESOLVING MODEL. THIS IS HERE ILLUSTRATED FROM A STRING OF DAY-1 FORECASTS. THE MODEL CARRIES A REALISTIC OROGRAPHY FOR THE WAIALEALE MOUNTAINS AT 500 METER RESOLUTION. THE MODEL PREDICTS A REASONABLE POPULATION OF MARINE STRATOCUMULUS, MERGERS INTO TOWERING CUMULUS, THE ENHANCED GROWTH OF BUOYANCY AS CLOUDS INTERACT WITH THE ASCENT OF UNDISTURBED TRADE WIND STRATOCUMULI OVER THIS OROGRAPHY.

- THE DISPOSITION OF SUPERSATURATION AND THE COALESCENCE PROCESS FOR WARM RAIN CONTRIBUTE TO THE HEAVY RAINS OVER THIS SPECIAL SLOPING TERRAIN.

- STREAMS OF STRATOCUMULS AND A SMALLER PROPORTION OF TOWERING CUMULUS ARE A PART OF THE SUBTROPICAL PACIFIC TRADE WIND BELT .

- THE MODEL SIMULATES A REASONABLE POPUALATION OF STRATOCUMULUS, TOWERING CUMULUS AND THE OROGRAPHIC RAINS.

...Continued

- THE MODEL RAINS IN THE VICINITY OF THE WAIALEALE SHOWS CONSISTENT RIANS OF THE ORDER OF AN INCH A DAY ON MOST UNDISTURBED PERIODS.

- THE SLOPE OF WAIALEALE , THE LOCATION OF THE LCL, THE VERTICAL GRADIENT OF SATURATION SPECIFIC HUMIDITY , THE TRADE WIND SPEEDS IMPACTING WAIALEALE ARE IMPORTANT FACTORS ALONG THE VERTICAL FOR THE DISPOSITION OF SUPERSATURATION RAINS.

- WE SHOW THAT SIMILAR WINDS, MARINE LAYER MOISTURE, INVERSION , PLETHORA OF STRATOCUMULUS AND OROGRAPHIC NEAR THE SUBTROPICAL COASTAL AREAS ARE SEEN IN SEVERAL OTHER PARTS OF THE WORLD. ONE SUCH CANDIDATE REGION IS THE SOUTH EAST COAST OF INDIA WITH THE NORTH EAST WINTER MONSOON FLOW AND THE EASTERN GHATS.

- ON UNDISTURBED DAYS THE RAINFALL ALONG THE SOUTHERN PARTS OF THE EASTERN GHATS IS VERY WEAK.

...Continued

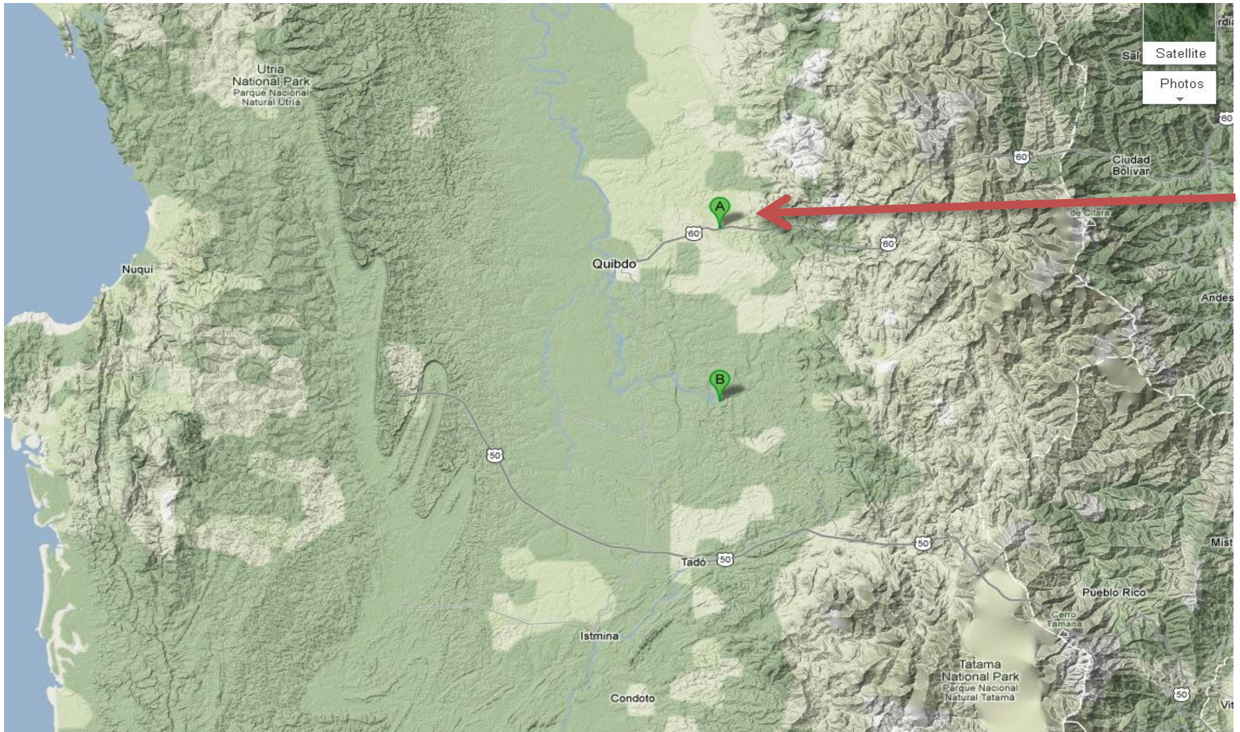
- **THIS STUDY SHOWS RESULTS FROM A MODELING STUDY WHERE THE FRONT FACE OF THE WAIALEALE MOUNTAINS (FACING THE WINDS) IS PLACED AS THE FRONT FACE OF THE JAWADHU HILLS, THAT FRONT FACE IS ROTATED TO BE PERPENDICULAR TO THE NORTH EAST WINDS OF THE WINTER MONSOON.**

- **THE MAJOR RESULT IS THAT ON UNDISTURBED DAYS WHEN NO RAINFALL IS OBSERVED NEAR THE JAWADHU HILLS, THE DEPLOYMENT OF A ROTATED FRONT END PRODUCES NEARLY AN INCH TO AN INCH AND A HALF OF RAIN EACH DATY.**

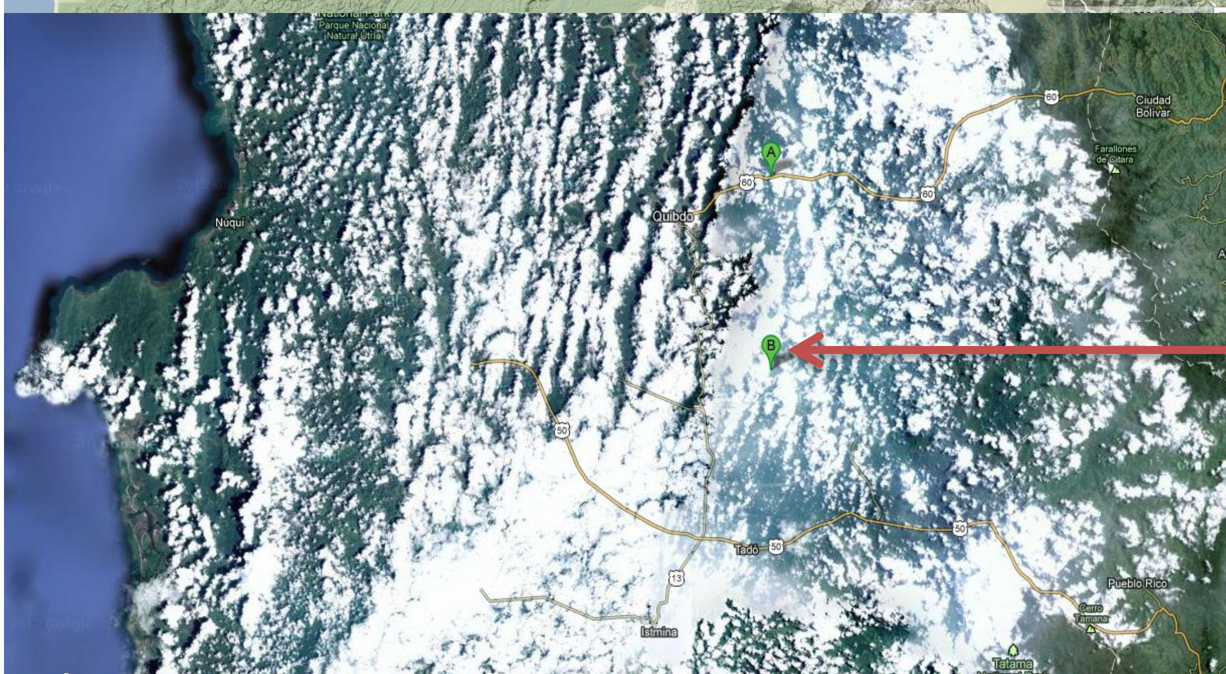
- **THE LAST PART OF THE TALK ADDRESSES POSSIBILITIES FOR RAIN HARVESTING FOR THE CHENNAI RESERVOIRS. A FEW GEO-ENGINEERING ISSUES, WITH THE OBJECTIVE OF CONTRIBUTING TO THE WATER SHORTAGE ISSUES OF CHENNAI REGION.**

FUTURE WORK WILL ADDRESS THE DESIGN OF A MINIMAL MODELING SYSTEM THAT CAN BE COST EFFECTIVE AND PRACTICAL FROM THE GEOENGINEERING PERSPECTIVE.

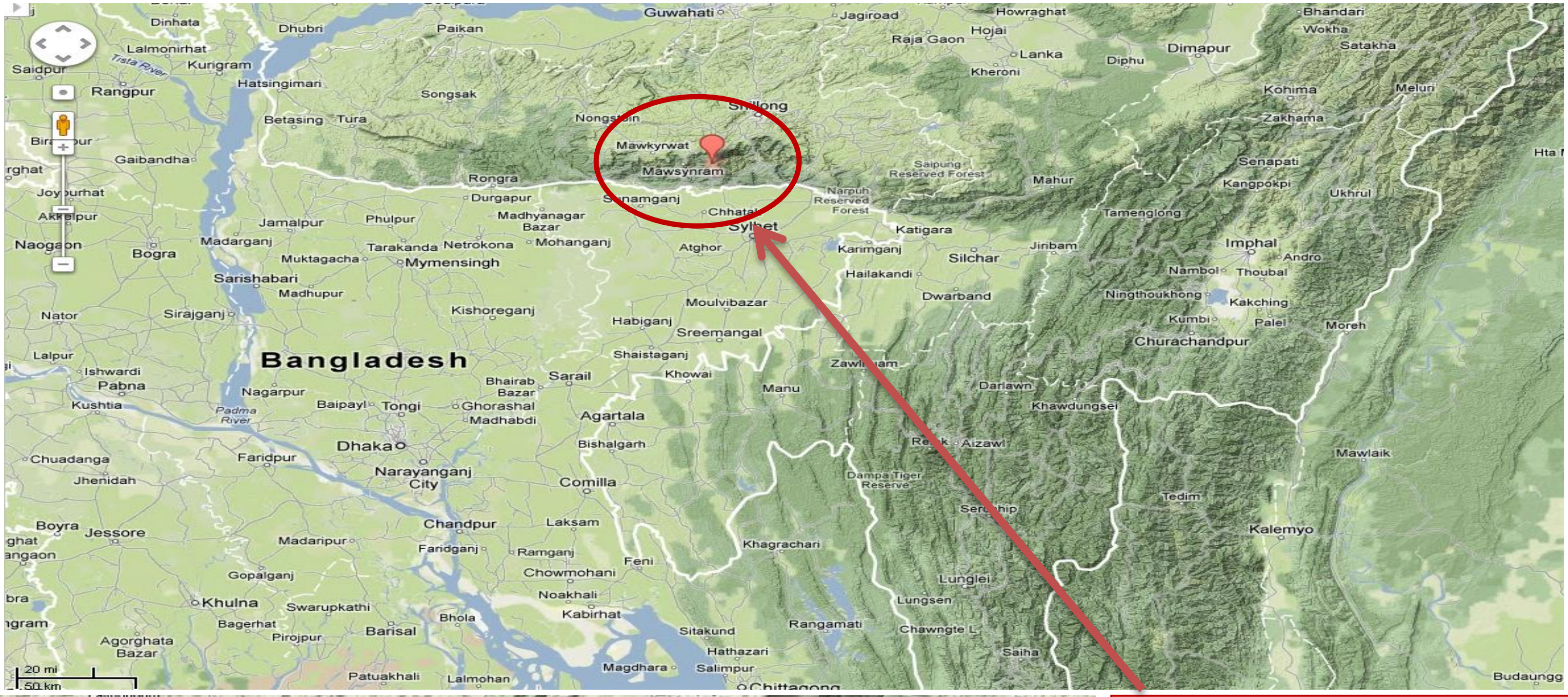

END & THANKS

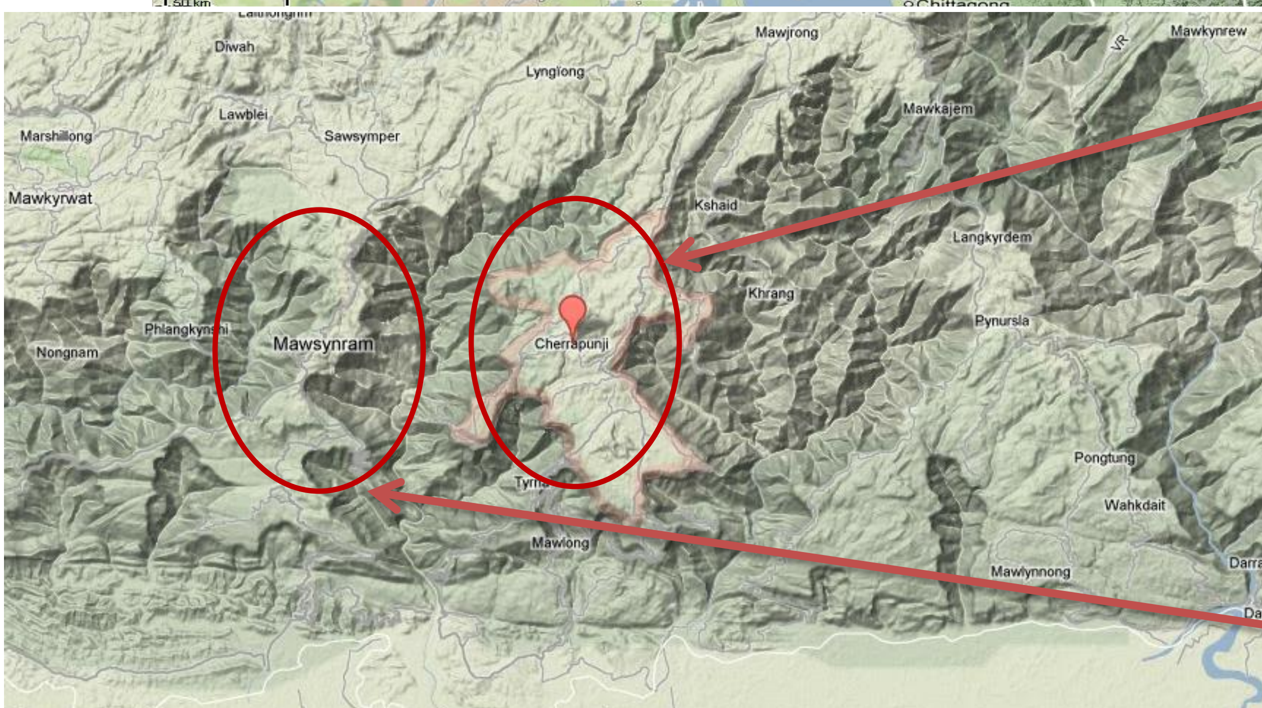


A. Tutunedo, Choco, Colombia, annual rainfall avg of 11394 mm (448 in)



B. LLoro, Colombia, annual rainfall avg of 13,300 mm (523.6 in)



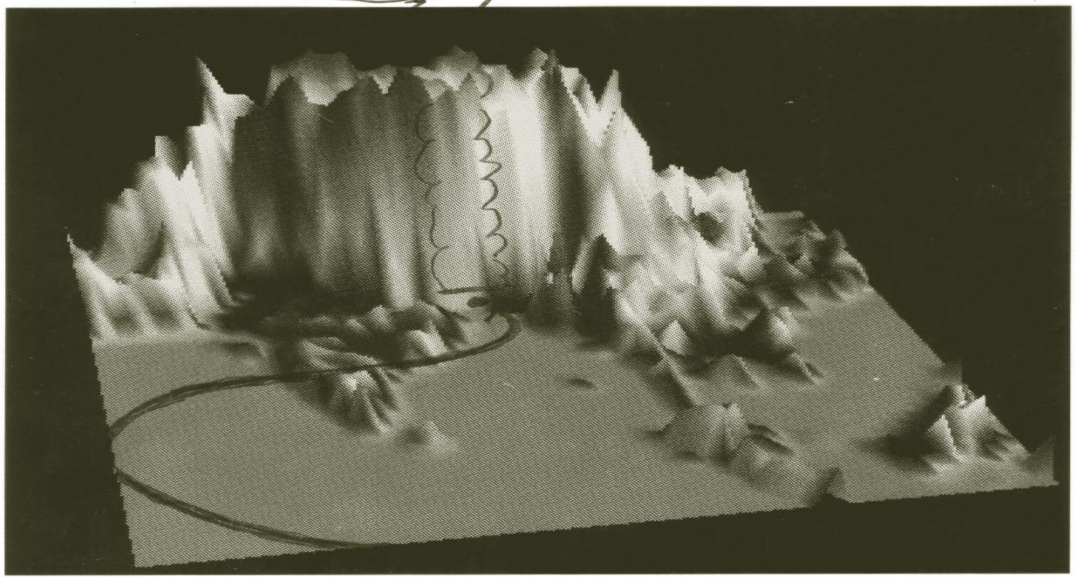


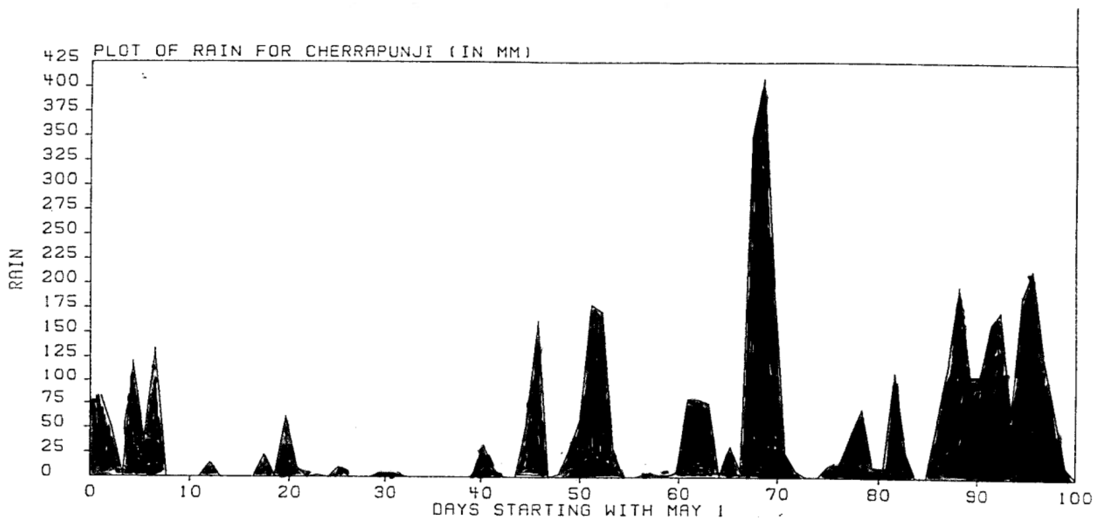
Cherrapunji, also in Meghalaya; yearly rainfall avg 11,430 mm (450 in)

Mawsynram, Meghalaya, India, averages 11,873 mm (467 in)

T255

3D Perspective of the Himalayas





May 1

FGGE Year 1979

A 3-D perspective of the terrain of the Himalayas. The location of Cherrapunji is marked with an X.

Cherrapunji, yearly rainfall avg 11,430 mm (450 in)

Daily rainfall amounts at Cherrapunji for the period 1 May – 10 August, 1979. Units of mm.