The Abdus Salam International Centre for Theoretical Physics

2356-6

Targeted Training Activity: ENSO-Monsoon in the Current and Future Climate

30 July - 10 August, 2012

ATMOSPHERIC PROCESSES RELEVANT TO ENSO

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4. ATMOSPHERIC PROCESSES RELEVANT TO ENSO

a. SURFACE FLUXES

b. CONVECTIVE BOUNDARY LAYERS

c. THE GILL MODEL

d. A CONCEPTUAL MODEL OF THE MARITIME TROPICS

e. HEAT SOURCES-HOW CLOUDS HEAT

f. WHY HEAT SOURCES LIE OVER WARM SST

g. BOUNDARY LAYER FORCING OF SURFACE WINDS

h. HEAT SOURCE FORCING OF SURFACE WINDS

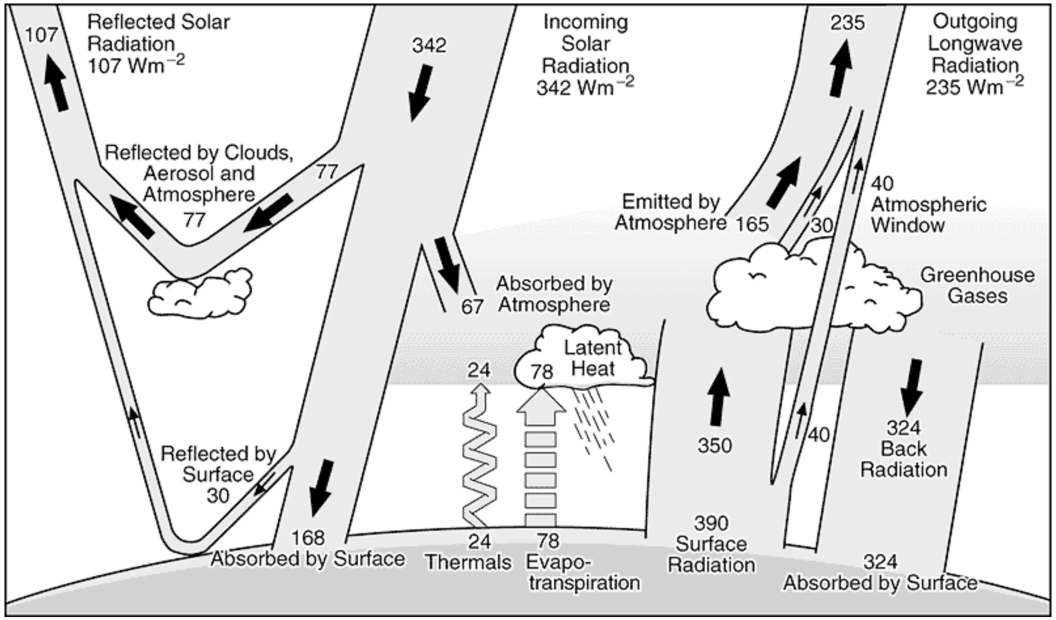
a. SURFACE FLUXES

- **INTERACTIONS BETWEEN THE ATMOSPHERE AND THE OCEAN TAKE PLACE THROUGH THE INTERCHANGE OF FLUXES AT THE SURFACE**

- **ULTIMATE SOURCE OF ALL FLUXES IS THE SOLAR CONSTANT**

F_{SOLAR}= 1367 W/m^2

[Amount of available solar flux at top of atmosphere = ¼ F_{SOLAR} =342W/m^2]



- **SURFACE BALANCE (ALL FLUXES POSITIVE UPWARD):**

$$-R_{NET} = LE + S + Q \qquad (1)$$

WHERE

$$R_{NET} = F_{SOLAR}(0) + F_{IR\ NET}(0) \qquad (2)$$

$$\text{Where } F_{IR\ NET}(0) = \varepsilon\sigma T_S^4 + F_{IR}^{\downarrow}(0)$$

LE = LATENT HEAT OF EVAPORATION INTO ATMOSPHERE

S = SENSIBLE HEAT INTO ATMOSPHERE

Q = SENSIBLE HEAT INTO OCEAN

- **AN INTERPRETATION OF (1) IS THAT THE NET RADIATION AT THE SURFACE THAT DOESN'T GO INTO EVAPORATING WATER OR SENSIBLE HEATING MUST GO INTO THE OCEAN**

- **ALL THE TERMS IN (1) AND (2) CAN BE PARAMETERIZED BY QUANTITIES MEASURED ON A SHIP** e.g.

$$F_{SOLAR}(0) \sim F_{BOOK}(0)\,(1-c_1 n)$$

where n is cloud fraction,

$$F_{IR\ NET}(0) \sim \varepsilon\sigma T_S^4\,(a-bq_a^{r})(1-c_2 n)$$

$$LE = \rho C_L L|v|(q_{sat}(0) - q_a)$$

where C_L is a drag coefficient, $q_{sat}(0)$ is the saturation vapor mixing ratio at the surface at temperature T_S, L is the latent heat of condensation, and q_a is the vapor mixing ration measured on ship,

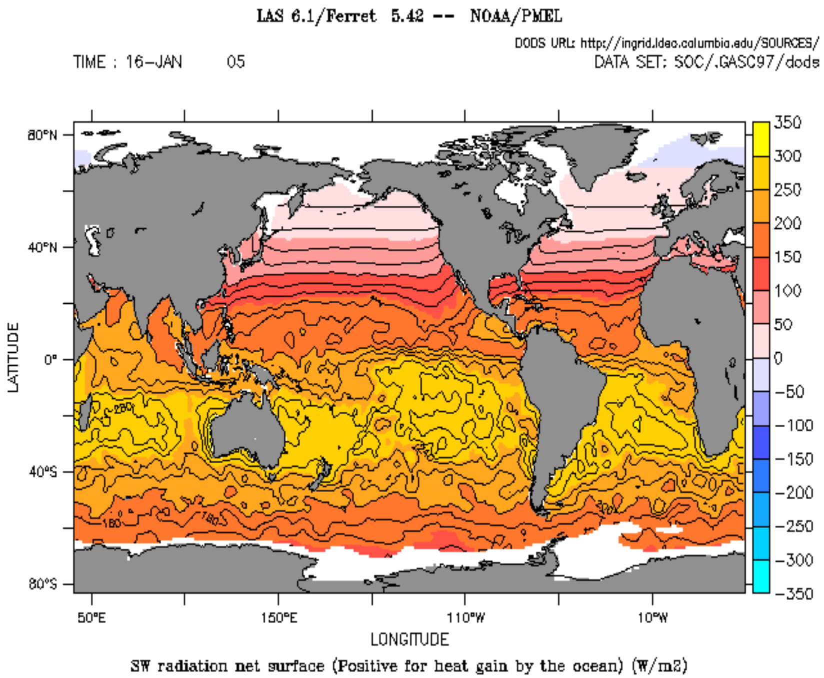
$$S = \rho C_S\,|v|(T_S - T_a),$$

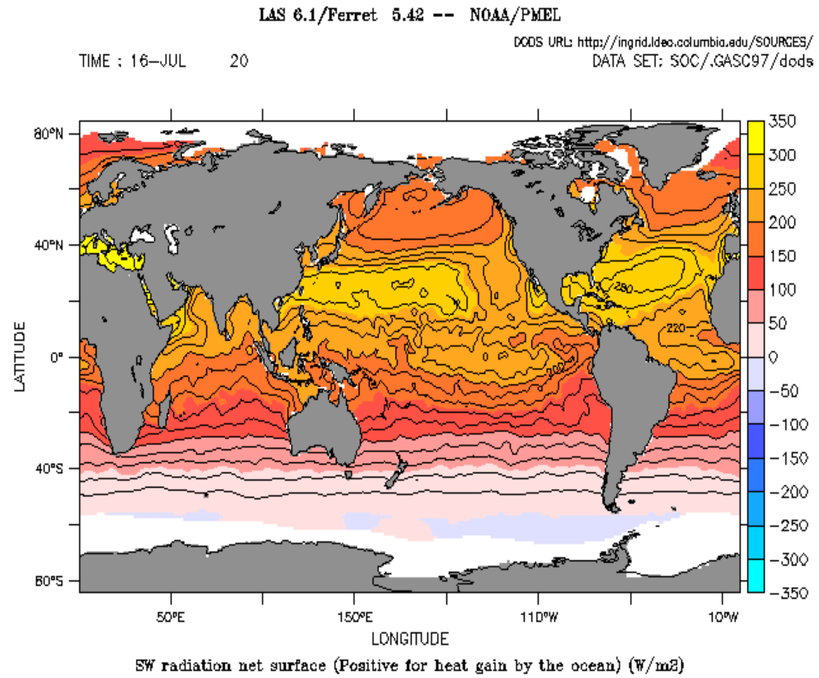
where C_S is a drag coefficient, and T_a is the temperature measured on ship (“anemometer level”).

- 29 W/m^2 EVAPORATES 1mm/day

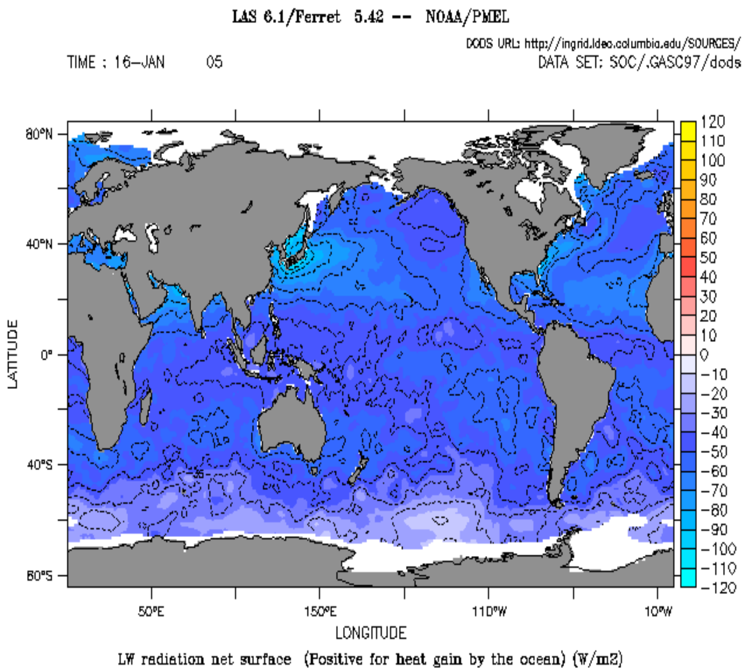
- **50 W/m^2 INTO A 50 m MIXED LAYER HEATS 1K IN 50 DAYS (OR 100 W/m^2 INTO 100m MIXED LAYER HEATS .6K/MONTH). 100 W/m^2 INTO THE ATMOSPHERE HEATS 1K/day.**

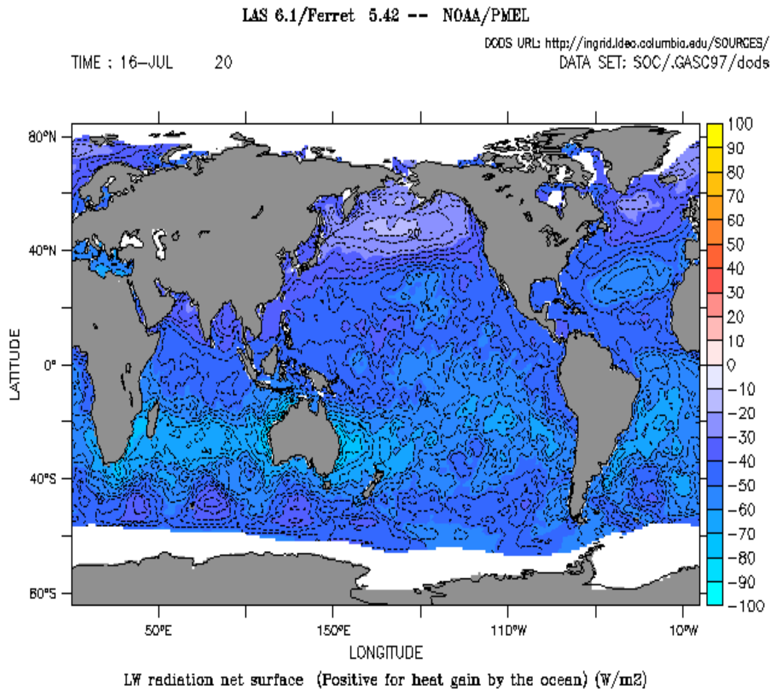
- **BELOW, WE WILL LOOK AT THE INDIVIDUAL COMPONENTS OF THE SURFACE HEAT BUDGET FROM THE SOUTHHAMPTON ATLAS: JOSEY ET AL, 1999.**



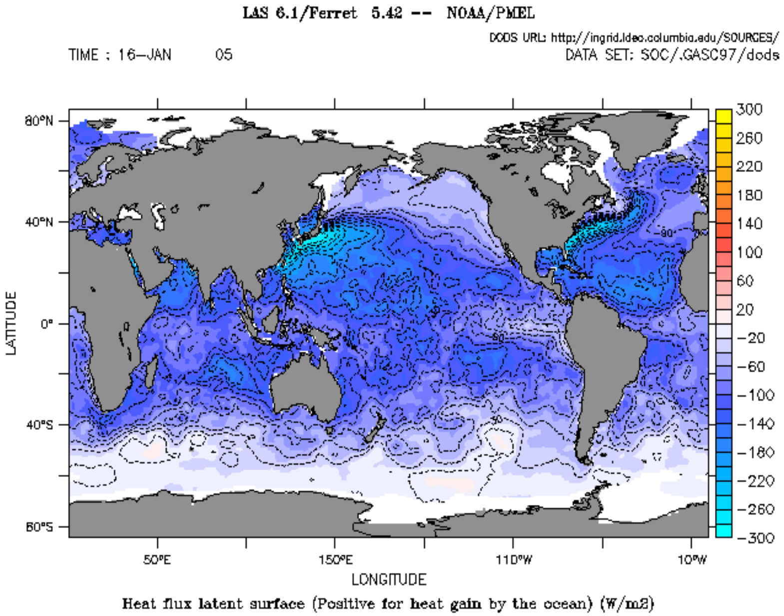


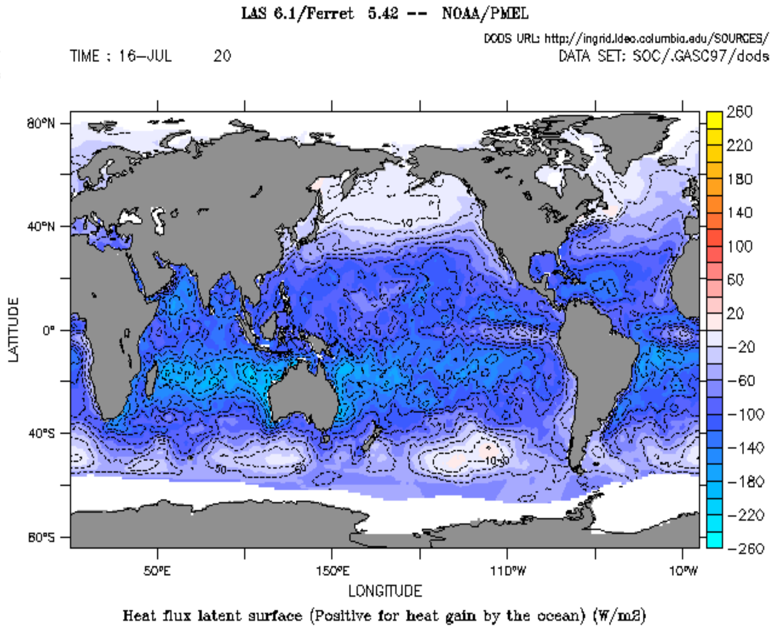
-1 × SW RADIATION AT THE SURFACE



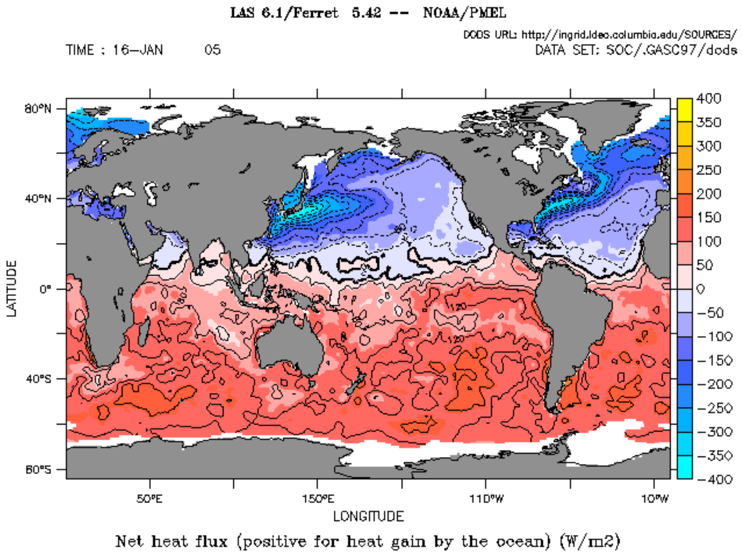


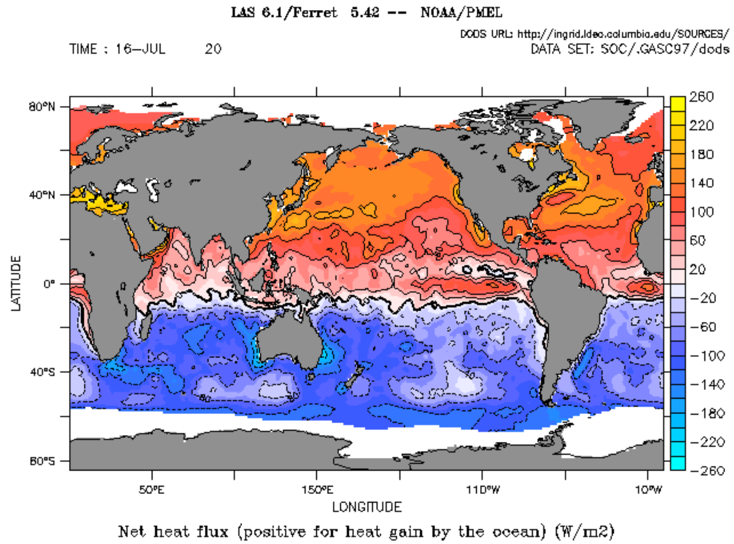
-1 × LW RADIATION AT THE SURFACE



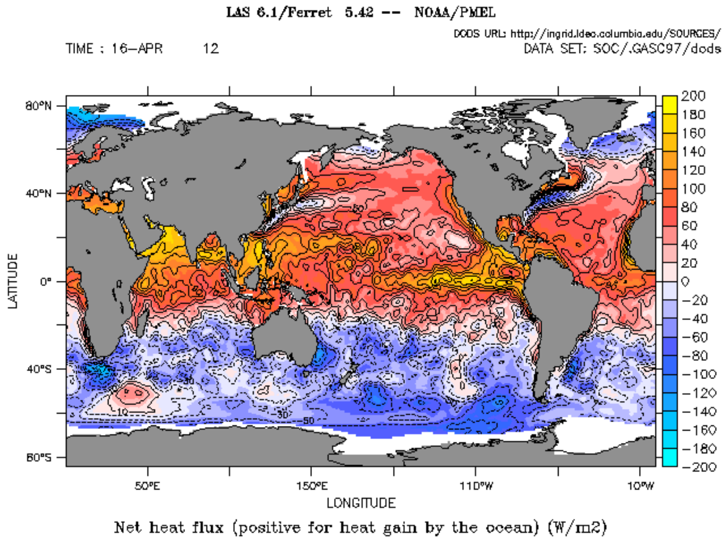


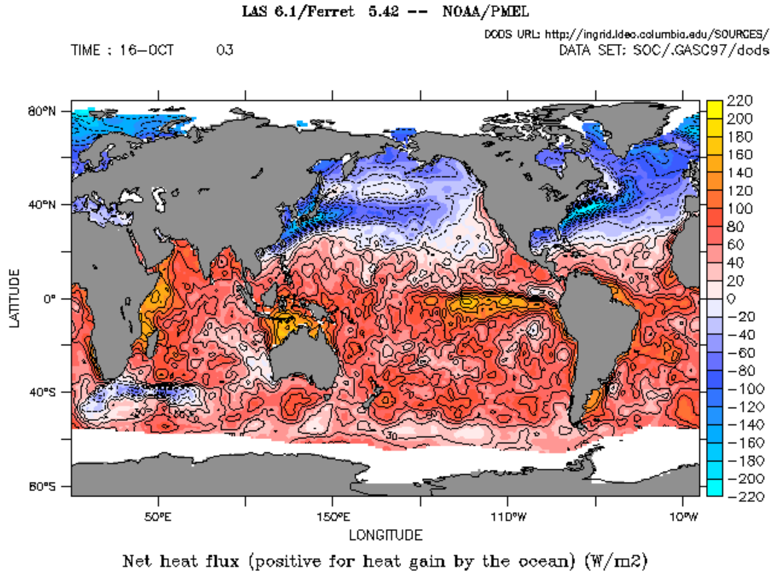
-1 × LATENT HEAT FLUX AT THE SURFACE



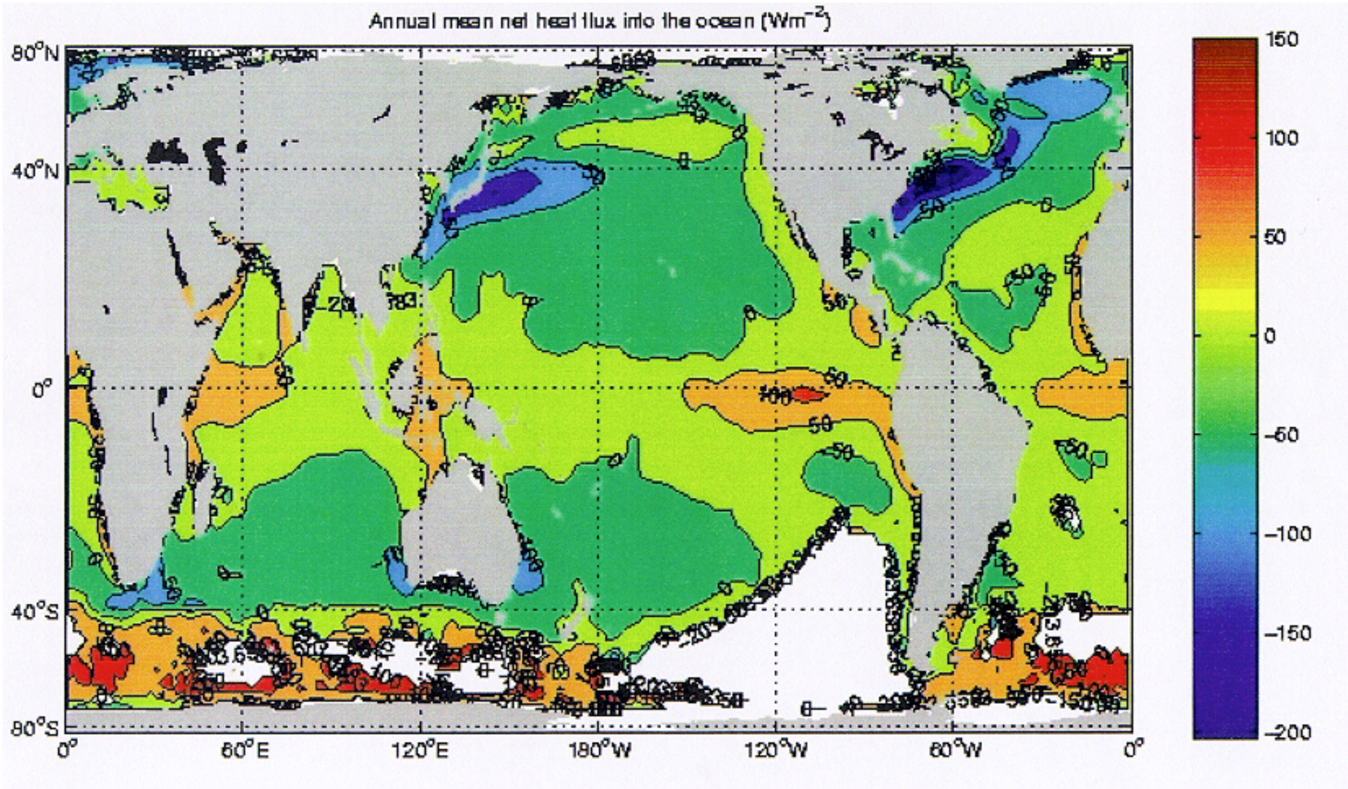


NET HEAT FLUX INTO OCEAN





NET HEAT FLUX INTO OCEAN



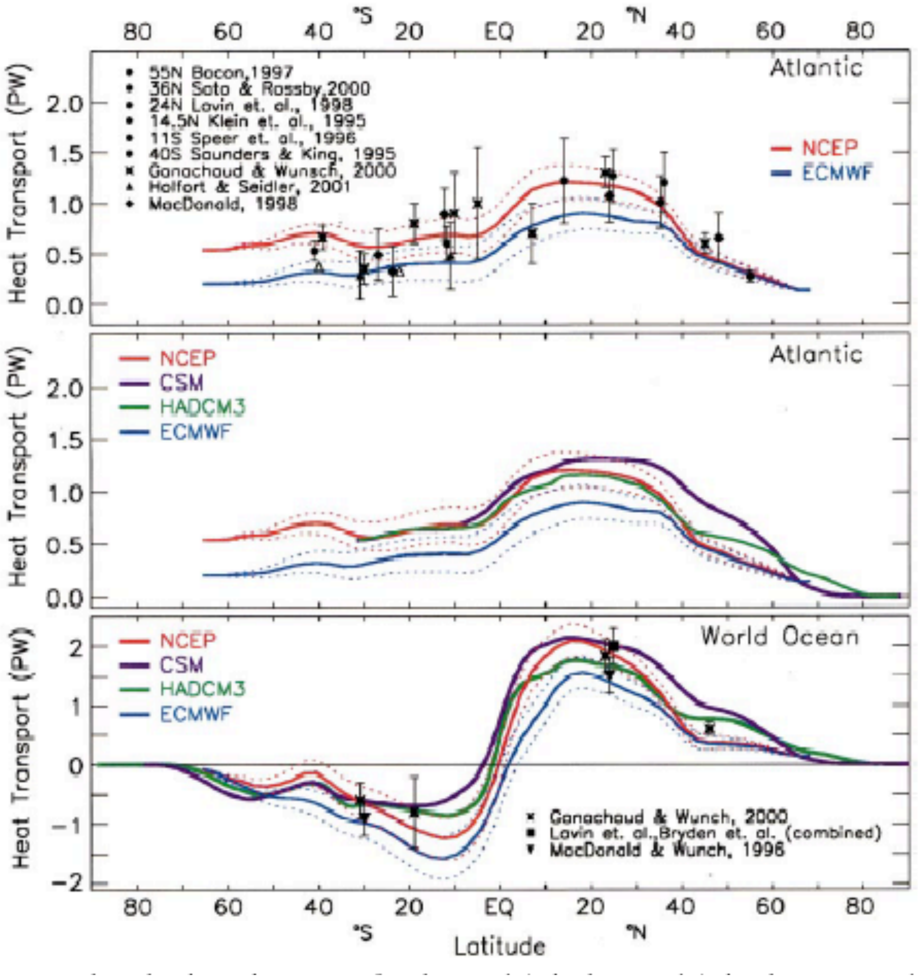
ANNUAL MEAN NET HEAT FLUX INTO THE OCEAN

- **NOTE THAT SUCH CHARTS ARE EXTREMELY INACCURATE—THE GLOBALLY INTEGRATED ANNUALLY AVERAGED HEAT FLUX INTO THE OCEAN IN THE SOC ATLAS IS 30 W/m^2**

- **ONCE THE HEAT GOES THROUGH THE SURFACE INTO THE OCEAN, IT CAN ONLY BE STORED OR DIVERGED AWAY:**

$$-Q = \text{STORAGE} + \nabla \cdot [\text{TRANSPORT}]$$

- **IF WE KNOW THE ANNUALLY AVERAGED FLUXES OVER THE ENTIRE OCEAN [STORAGE=0] AND HAVE A BOUNDARY CONDITION FOR TRANSPORT, WE KNOW THE MEAN TRANSPORT.**



Trenberth and Caron, 2001.

b. CONVECTIVE BOUNDARY LAYERS

1. INVERSIONS

IF WE MIX A STABLE PROFILE UP TO A HEIGHT H WITHOUT ADDING OR SUBTRACTING HEAT, AN INVERSION RESULTS.

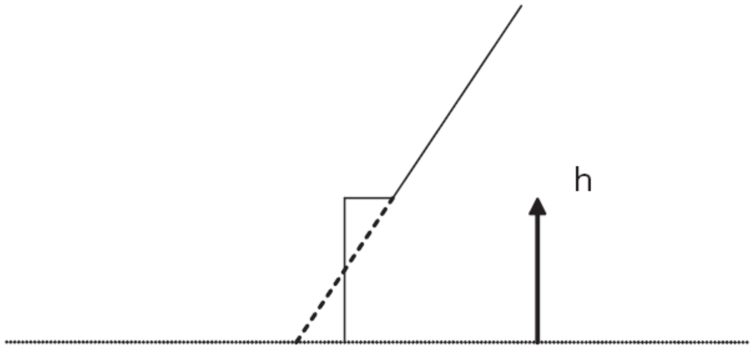


Figure 4.1. The effect of adiabatically mixing an initial, stable potential temperature profile to height h_a in the atmosphere.

THE PROFILE IS THE STABLE DRY STATIC ENERGY: $S=C_pT+GZ$. S IS CONSERVED IN DRY ADIABATIC ASCENT (LIKE THE POTENTIAL TEMPERATURE). NOTE THAT

$$\frac{ds}{dz} = c_p T + g$$

SO THAT THE STRENGTH OF THE INVERSION IS:

$$\Delta s = \Delta T = \frac{1}{2}\frac{ds}{dz}h$$

2. MIXING

WHAT CAUSES THE MIXING?

SINCE WATER VAPOR IS LIGHTER THAN AIR, MIXING IS CAUSED BY A COMBINATION OF HEAT FLUX FROM THE SURFACE PLUS EVAPORATION FROM THE SURFACE AND MECHANICAL MIXING DUE TO WIND STRESS τ.

THE WORK DONE BY MECHANICAL MIXING IS PROPORTIONAL TO $(\tau \bullet U)$ AND THE WORK DONE BY BUOYANT MIXING $\Theta'_V w'$ WHERE THE VIRTUAL TEMPERATURE IS:

$$T_v = T[1+.61q]$$

WHICH ALLOWS THE BUOYANCY OF MOIST PARCELS TO BE COMPARED. Q IS THE MOIST MIXING RATIO.

THE MONIN-OBUKHOV LENGTH MEASURES THE RATION OF MECHANICAL PRODUCTION OF TURBULENCE TO THE BUOYANT PRODUCTION OF TURBULENCE:

$$L = \frac{u_*^3}{k \frac{g}{\theta_v} (w' \theta'_v)}$$

WHERE

$$\tau = \rho u_*^2$$

WHEN THE BOUNDARY HEIGHT IS MUCH LARGER THAN L, THE BOUNDARY LAYER IS CONVECTIVELY DRIVEN. WHEN THE BOUNDARY LAYER HEIGHT IS SMALLER THAN L, THE BOUNDARY LAYER IS MECHANICALLY DRIVEN. FOR 6MM OF EVAPORATION AND A STRESS OF ONE DYNE, L~ 100M. SINCE THE MIXED LAYER HEIGHT IS ABOUT 600M, THE TROPICAL BOUNDARY LAYER IS CONVECTIVELY DRIVEN.

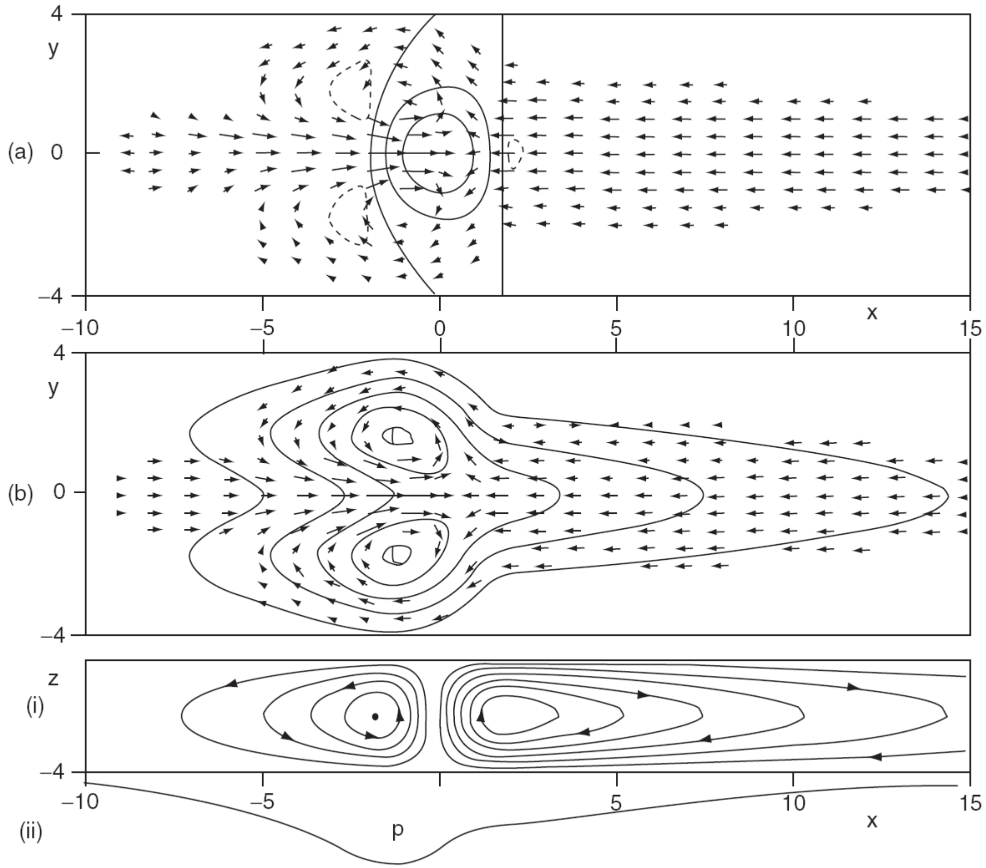
[THE OCEAN MIXED LAYER IS MECHANICALLY DRIVEN BY THE WIND STRESS.]

c. THE GILL MODEL

$$\varepsilon u - \beta y v = -\frac{\partial p}{\partial x},$$

$$\varepsilon v + \beta y u = -\frac{\partial p}{\partial y},$$

$$\varepsilon_T p + \frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} = -Q,$$



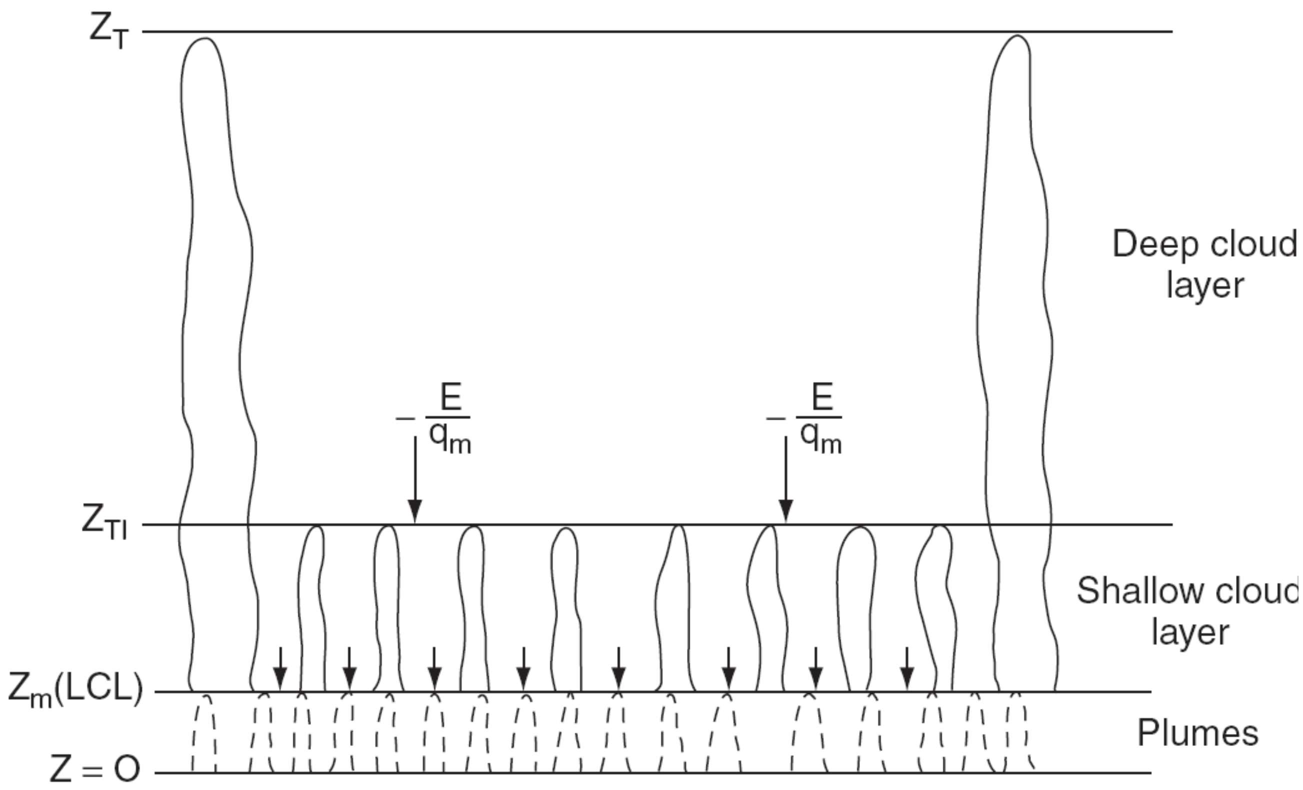
The vertical structure of the heating and of the vertical velocity is sin(πz/D); since (u, v)~ (dw/dz) the vertical structure of the u and v fields is cos(πz/D). D is depth of troposphere.

The Gill model produces a realistic-looking structure of the response of the atmosphere to tropical heating when the heating is located on the equator (ENSO-like) or off of the equator (monsoon-like).

However, the dynamics of the Gill model is unrealistic, as the frictional parameter has to be chosen to be much stronger than is thought to be reasonable (or than is used in state of the art CGCMs) to produce the realistic-looking structures. The agreement has to be regarded as coincidence, unless Raleigh friction is a good parameterization of the neglected nonlinear terms.

Because of its simplicity, the Gill model is a useful atmospheric component for modeling ENSO. Because of its incorrect dynamics, the Gill model will produce misleading conclusions with regard to ENSO mechanism and teleconnections within the tropical belt.

d. CONCEPTUAL MODEL OF THE MARITIME TROPICAL ATMOSPHERE



ASSUMPTIONS:

- **HORIZONTALLY HOMOGENEOUS**
- **NO CONVERGENCE OR DIVERGENCE SO P=E**
- **NO HEAT FLUX INTO OCEAN (LIKE WESTERN PACIFIC)**
- **ATMOSPHERE DRY ABOVE SHALLOW CLOUD LAYER**
- **FRACTIONAL AREA COVERED BY DEEP CLOUDS $\sigma_c \ll 1$**
- **MASS FLUX INTO DEEP CLOUDS IS M_C**

THEN THE WATER FLUX INTO THE DEEP ATMOSPHERE IS:

$$P = E = M_C q_M$$

THEREFORE

$$M_C = E/q_M$$

THE (DOWNWARD) MASS FLUX (ALMOST EVERYWHERE) IS THEREFORE:

$$\widetilde{M} = -\frac{E}{q_M}$$

SINCE

$$\widetilde{M} + M_C = 0$$

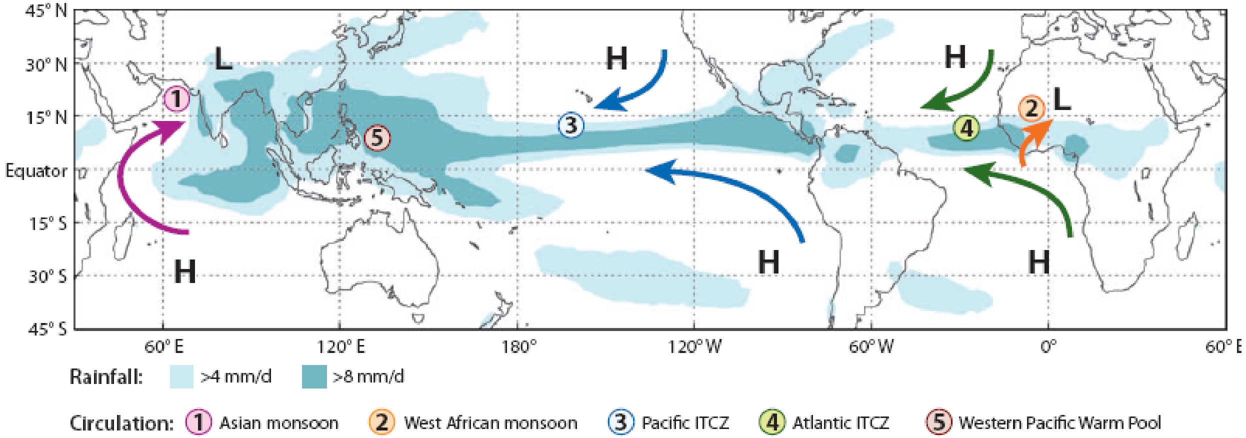
THE HEAT BALANCE OF THE ATMOSPHERE IS THEN:

$$LE = LP = -R$$

WHERE R IS THE NET RADIATIVE HEATING OF THE ATMOSPHERE (<0).

- **THE BASIC BALANCE IS THAT THE DOWNWARD MOTION BETWEEN THE DEEP CUMULONIMBUS CLOUDS BALANCES THE RADIATIVE COOLING OF THE ATMOSPHERE.**

e. HEAT SOURCES-HOW CLOUDS HEAT



LET:

$$Q_1 = \rho \frac{D\bar{s}}{Dt} = \rho \frac{\partial \bar{s}}{\partial t} + \rho \bar{\mathbf{u}} \cdot \nabla \bar{s} + \rho \bar{w} \frac{\partial \bar{s}}{\partial z}$$

AND

$$Q_2 = -\rho \frac{D\bar{q}}{Dt} = -\rho \left(\frac{\partial \bar{q}}{\partial t} + \bar{\mathbf{u}} \cdot \nabla \bar{q} + \bar{w} \frac{\partial \bar{q}}{\partial z} \right)$$

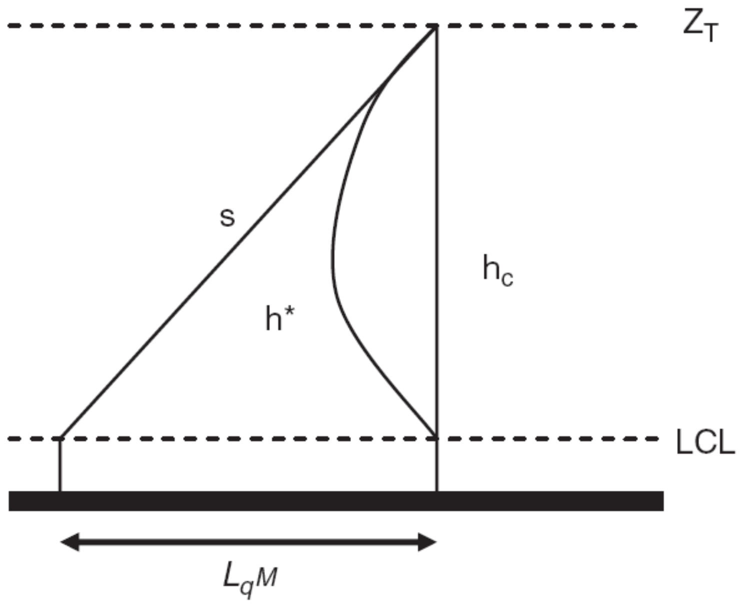
THE HEAT AND MOISTURE EQUATIONS, ASSUMING ALL THE RAINFALL FROM DEEP CUMULONIMBUS CLOUDS REACHES THE GROUND, IS:

$$Q_1 = M_c \frac{d\bar{s}}{dz} + Q_R$$

WHERE Q_R IS THE LOCAL RADIATIVE HEATING RATE AND Mc IS THE MASS FLUX IN THE CLOUDS.

$$Q_2 = - M_c \frac{d\bar{q}}{dz}$$

IN OUR SIMPLE MODEL OF THE ATMOSPHERE:



h = s + Lq is CONSERVED IN MOIST ADIABATIC ASCENT.
FROM THE DIAGRAM WE SEE $s(z_T)$ - $s_M = Lq_M$.

THE VERTICALLY INTEGRATED HEAT BUDGET OF THE SIMPLIFIED TROPICAL ATMOSPHERE IS:

$$\int_0^{z_T} Q_1\, dz = \int_0^{z_T} M_c \frac{d\overline{s}}{dz}\, dz + \int_0^{z_T} Q_R\, dz = 0$$

SO THAT

$$M_c(\overline{s}(z_T) - \overline{s}(0)) = -R$$

$$\frac{E}{q_M} L q_M = -R$$

OR, AS BEFORE

LE = -R AND E=P

NOW LET'S ALLOW SYNOPTIC CONVERGENCE AND DIVERGENCE:

$$\overline{\mathbf{M}} = \mathbf{M_c} + \widetilde{\mathbf{M}}$$

WHERE

$$\bar{M} = \overline{\rho w}$$

IS THE SYNOPTIC MASS FLUX.

NOW THE MOISTURE BUDGET IS:

$$P = E + \bar{M} q_M$$

BUT

$$P = M_c q_M$$

SO

$$\tilde{M} = -\frac{E}{q_M}$$

INDEPENDENT OF P.

WE SEE THAT NO MATTER HOW BIG THE CONVERGENCE, I.E. NO MATTER HOW BIG THE PRECIPITATION, THE DOWNWARD MOTION, ALMOST EVERYWHERE, DOESN'T CHANGE.

ASSUMPTIONS:

1. THE TROPICAL ATMOSPHERIC TEMPEATURE AND MOISTURE ARE HORIZONTALLY HOMOGENEOUS AND STEADY. NO MATTER HOW BIG THE PRECIPITATION AND NO MATTER HOW MUCH LATENT HEAT IS RELEASED, THE TEMPERATURE OF THE FREE ATMOSPHERE DOESN'T CHANGE. [BASED ON OBSERVATIONS].

IMPLICATIONS:

2. THE MODEL OF THE VERTICAL STRUCTURE IN OUR SIMPLIFIED MODEL IS STABLE—IT DOESN'T CHANGE WHEN P>E.

3. CONVERGENCE OF MOISTURE PRODUCES REGIONS OF DEEP CONVECTION WHICH DOESN'T CHANGE TEMPERATURE. INSTEAD, DEEP CONVECTION DRIVES CIRCULATIONS.

4. THE DEEP CLOUDS MAY BE CONSIDERED INSULATED PIPES.

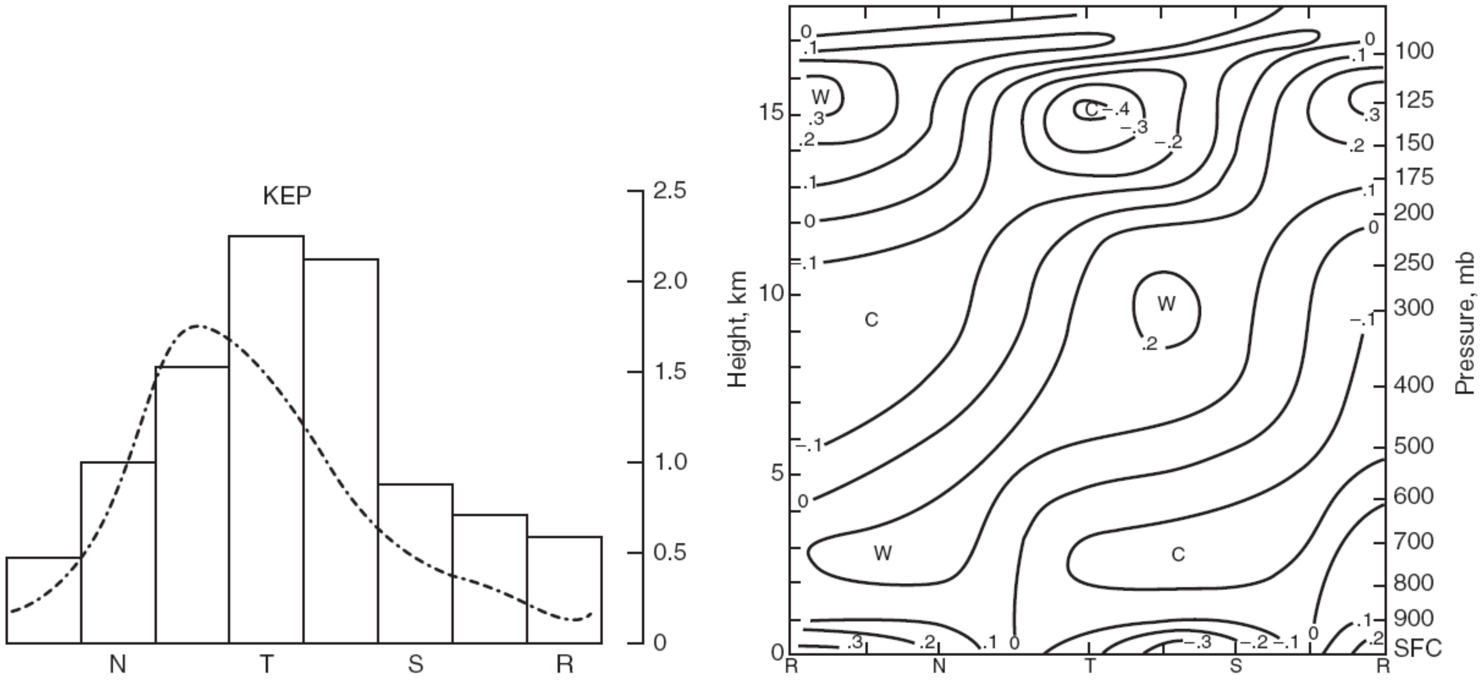


Figure 5.5. left panel: Precipitation (cm/d) in the various parts of the composite wave (the dot-dashed line gives an estimate based on the moisture budget). Right panel: Temperature structure (degrees K) through the wave. (From Reed and Recker, 1971.)

NOTE: 2 CM/DAY OF PRECIPITATION RELEASES 580 W/M^2 WHICH WOULD HEAT THE ATMOSPHERIC COLUMN BY 4.6^o/DAY.

f. WHY HEAT SOURCES LIE OVER WARM SST

BASIC REASON: WARM SST INDUCES LOW PRESSURE ABOVE THE WARM SST AND THIS LOW PRESSURE CAUSES CONVERGENCE OF MOISTURE THAT PRODUCES REGIONS OF PERSISTENT PRECIPITATION.

ALTHOUGH WE WON'T SHOW IT, PRESSURE IN A SHALLOW CLOUD BOUNDARY LAYER LIKE THE ONE WE HAVE BEEN TALKING ABOUT SATISFIES THE GILL EQUATIONS.

- **THERE ARE WESTERLY SURFACE WIND ANOMALIES TO THE WEST OF REGIONS OF PERSISTENT PRECIPITATION.**

- **ONLY FOR TEMPERATURES ABOVE ~28-29ºC WILL THE CLOUDS REACH THE TROPOPAUSE.**

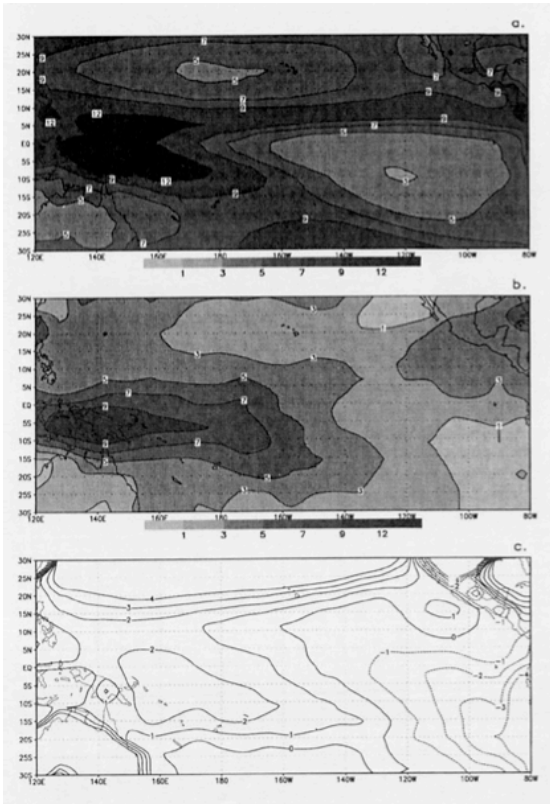
BUT WHAT ABOUT THE SURFACE WINDS FORCED DIRECTLY BY THE HEAT SOURCE?

h. HEAT SOURCE FORCING OF SURFACE WINDS

- **RECALL THAT THE GILL MODEL WAS FOR A HEAT SOURCE EXTENDING TO THE SURFACE AND HAVING THE VERTICAL STRUCTURE $\sin(\pi z/D)$ WHICH PRODUCES u, v~ $\cos(\pi z/D)$. BUT REAL HEAT SOURCES START AT CLOUDBASE ~600M AND THE VERTICAL STRUCTURE OF THE TROPICAL ATMOSPHERE IS NOT RESOLVED BY A TWO LEVEL MODEL.**

- **INSTEAD, THE PROBLEM TO BE SOLVED IS THAT OF STEADY FORCING IN AN ATMOSPHERE WITH A REALISTIC VERTICAL STRUCTURE, AND BY CONVECTIVE HEAT SOURCES WHICH START AT 600m, AND EXTEND TO THE TROPOPAUSE. THIS HAS BEEN DONE IN DEWITT (1994) AND DEWITT ET AL. (1996) USING A LINEARIZED STEADY PRIMITIVE EQUATION MODEL.**

- **IN THE TROPICAL PACIFIC:** **THE LARGE SCALE HEAT SOURCES ARE THE PREDOMINANT FORCING OF THE SURFACE WINDS, BUT CANNOT FORCE ENOUGH MOISTURE CONVERGENCE TO MAINTAIN THEMSELVES. CONVERGENCE FORCED BY SURFACE TEMPERATURE GRADIENTS IS ALSO IMPORTANT.**



OBSERVED PRECIPITATION

AGCM PRECIPITATION

EDDY SURFACE TEMPERATURE

- **VERTICALLY INTEGRATED MOISTURE FLUX CONVERGENCE IN THE PACIFIC (LINEAR DIAGNOSIS OF AGCM PERPETUAL JANUARY SIMULATION)**

VERTICALLY INTEGRATED MOISTURE FLUX CONVERGENCE

AGCM

LINEAR MODEL TOTAL

CONVECTIVE LATENT HEATING

SURFACE TEMPERATURE

OROGRAPHY

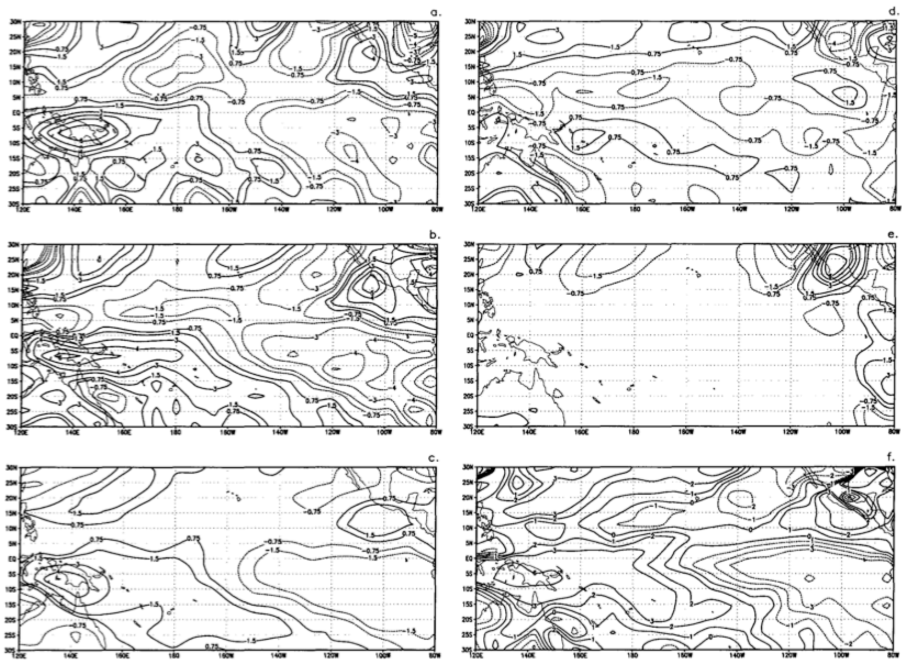


FIG. 3. Eddy vertically integrated moisture flux convergence of the time-mean flow (a)–(e): contours ± 0.75, 1.5, 3, 4, 5, 6 mm day^{-1}. (a) GCM. (b) Linear model forced by total forcing. (c) Linear model forced by convective latent heating. (d) Linear model forced by surface temperature forcing. (e) Linear model forced by orography. (f) GCM eddy moisture flux convergence from (a) combined with eddy evaporation and eddy moisture flux convergence by the Hadley cell: contours 0, ±1, 2, 3, 6 mm day^{-1}.

1 AUGUST 1996 DEWITT ET AL. 2255

- **SURFACE ZONAL WIND IN THE PACIFIC (LINEAR DIAGNOSIS OF AGCM PERPETUAL JANUARY SIMULATION)**

SURFACE ZONAL WIND

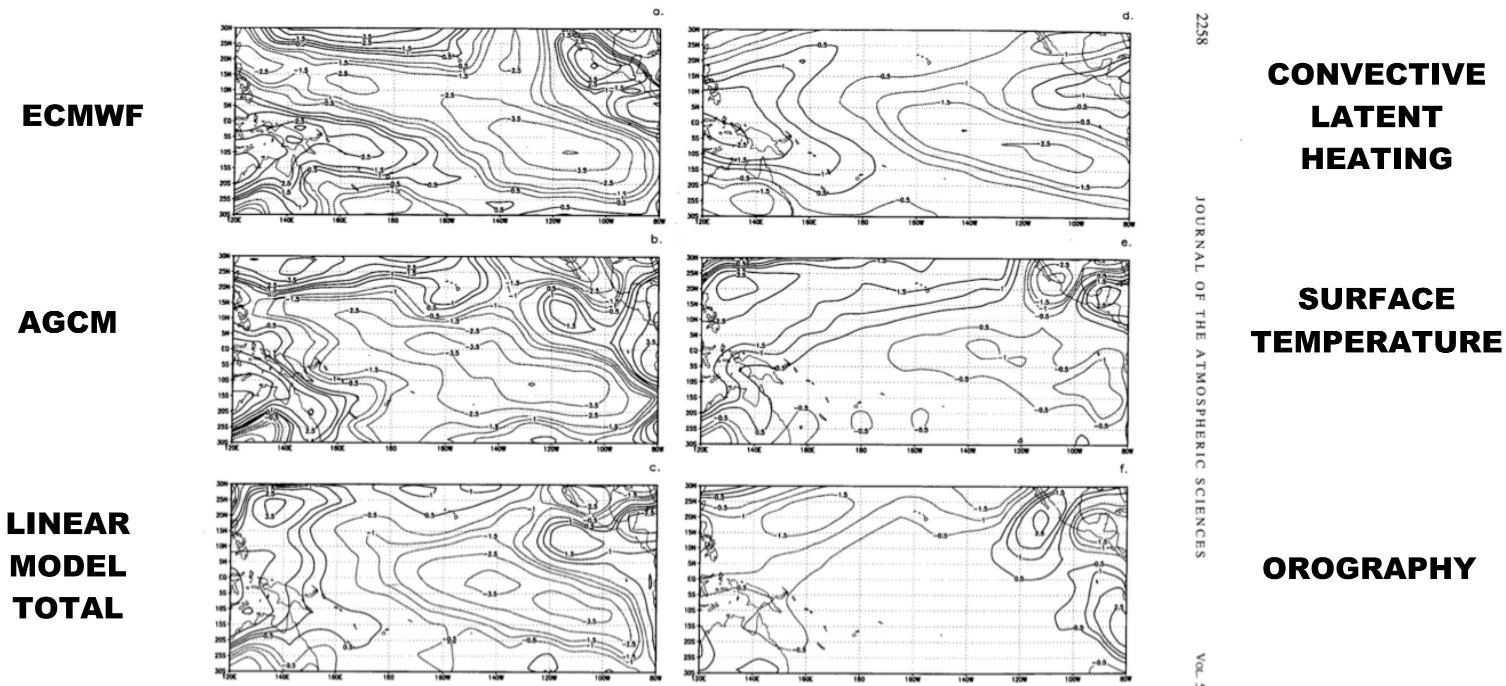


FIG. 5. Eddy zonal wind: contours ± 0.5, 1, 1.5, 2.5, 3.5, 5, 7 m s^{-1}. (a) ECMWF climatological (1980–1992) 1000 mb eddy zonal wind. (b) GCM lowest sigma level eddy zonal wind. (c) Linear model eddy zonal wind at lowest sigma level in response to total forcing. (d) Same as (c) but response to convective latent heating. (e) Same as (c) but response to surface temperature forcing. (f) Same as (c) but response to orographic forcing.

- **SURFACE MERIDIONAL WIND IN THE PACIFIC IN THE PACIFIC (LINEAR DIAGNOSIS OF AGCM PERPETUAL JANUARY SIMULATION)**

SURFACE MERIDIONAL WIND

ECMWF		**CONVECTIVE LATENT HEATING**
AGCM		**SURFACE TEMPERATURE**
LINEAR MODEL TOTAL		**OROGRAPHY**

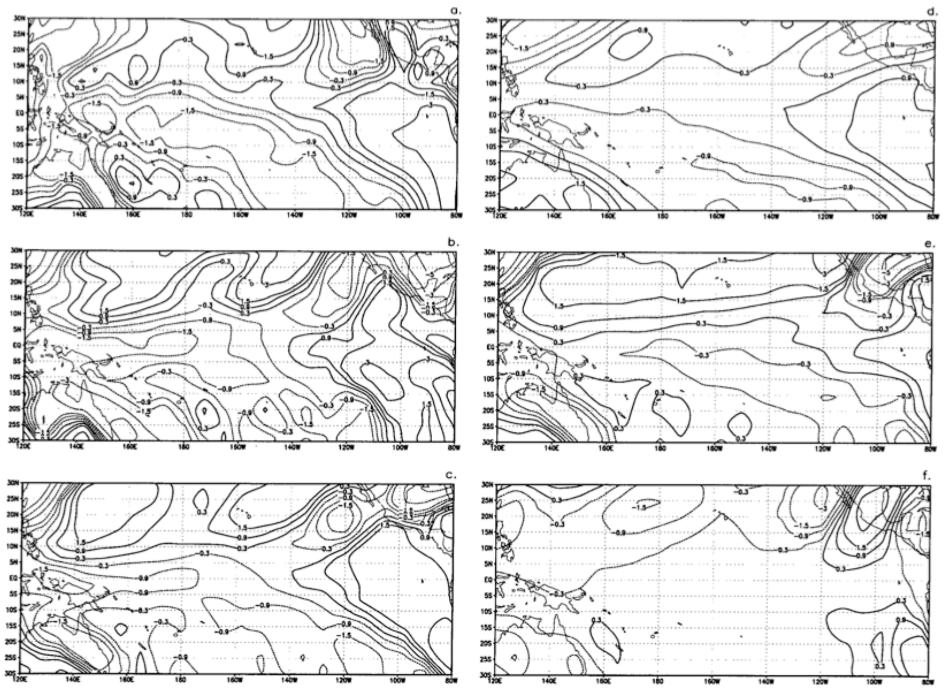
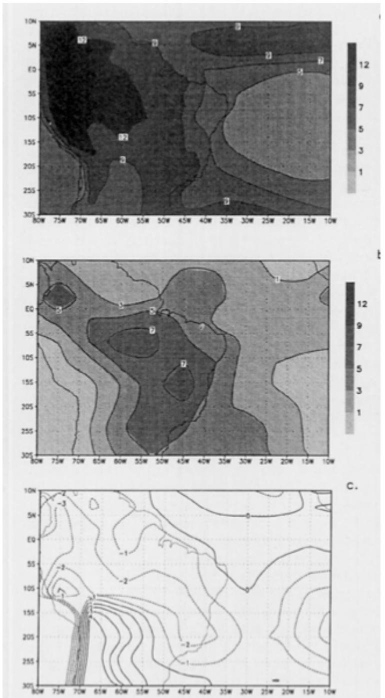


FIG. 4. Eddy meridional wind: contours ± 0.3, 0.9, 1.5, 3, 5, 7 m s^{-1}. (a) ECMWF climatological (1980–1992) 1000-mb eddy meridional wind. (b) GCM lowest sigma level eddy meridional wind. (c) Linear model eddy meridional wind at lowest sigma level in response to total forcing. (d) Same as (c) but response to convective latent heating. (e) Same as (c) but response to surface temperature forcing. (f) Same as (c) but response to orographic forcing.

- **OVER TROPICAL LAND AREAS:** **THE LARGE SCALE HEAT SOURCES ARE THE PREDOMINANT FORCING OF THE SURFACE WINDS, AND FORCE MORE THAN ENOUGH CONVERGENCE TO MAINTAIN THEMSELVES. CONVERGENCE FORCED BY SURFACE TEMPERATURE GRADIENTS IS A NEGATIVE FEEDBACK, AND REDUCES THE STRENGTH OF THE HEATING. THE SAME EFFECT WILL OCCUR OVER OCEAN REGIONS WHERE THE SST IS FORCED BY ATMOSPHERIC NOISE.**



OBSERVED PRECIPITATION

AGCM PRECIPITATION

EDDY SURFACE TEMPERATURE

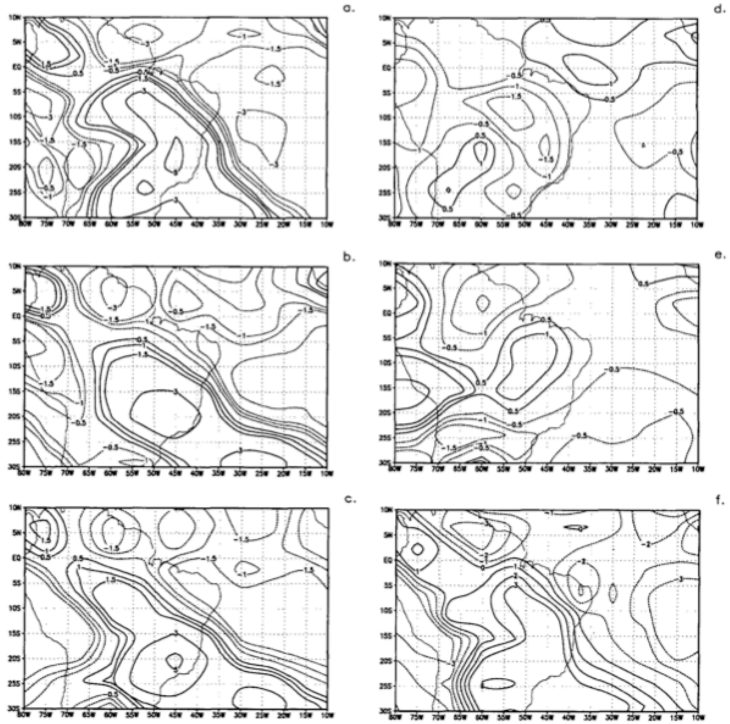
- **VERTICALLY INTEGRATED MOISTURE FLUX CONVERGENCE OVER SOUTH AMERICA (LINEAR DIAGNOSIS OF AGCM PERPETUAL JANUARY SIMULATION)**

VERTICALLY INTEGRATED MOISTURE FLUX CONVERGENCE

AGCM

LINEAR MODEL TOTAL

CONVECTIVE LATENT HEATING

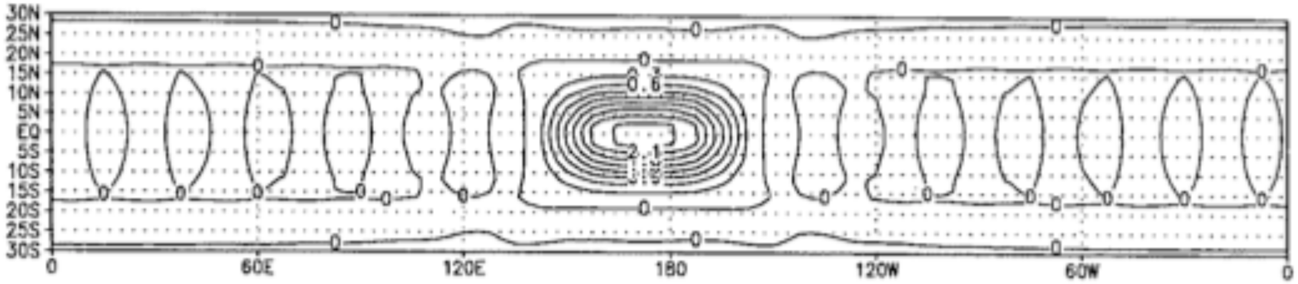


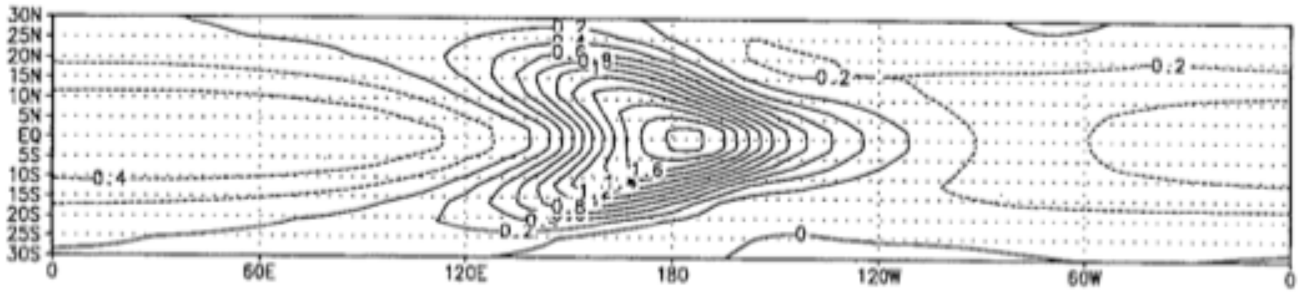
SURFACE TEMPERATURE

OROGRAPHY

FIG. 7. Eddy vertically integrated moisture flux convergence of the time mean flow (a)–(e): contours ± 0.5, 1, 1.5, 3, 5 mm day^{-1}. (a) GCM. (b) Linear model forced by total forcing. (c) Linear model forced by convective latent heating. (d) Linear model forced by surface temperature forcing. (e) Linear model forced by orography. (f) GCM eddy moisture flux convergence from (a) combined with eddy evaporation and eddy moisture flux convergence by the Hadley cell. Contours 0, ±1, 2, 3, 6 mm day^{-1}.

- **THE VERTICAL STRUCTURE OF THE HEATING IS IMPORTANT. IN PARTICULAR. LOW AND MID-LEVEL HEATING CONTRIBUTE TO MAINTAINING THE LOW LEVEL MOISTURE CONVERGENCE AND SURFACE WINDS (VERTICAL CROSS SECTIONS AT 2°S).**





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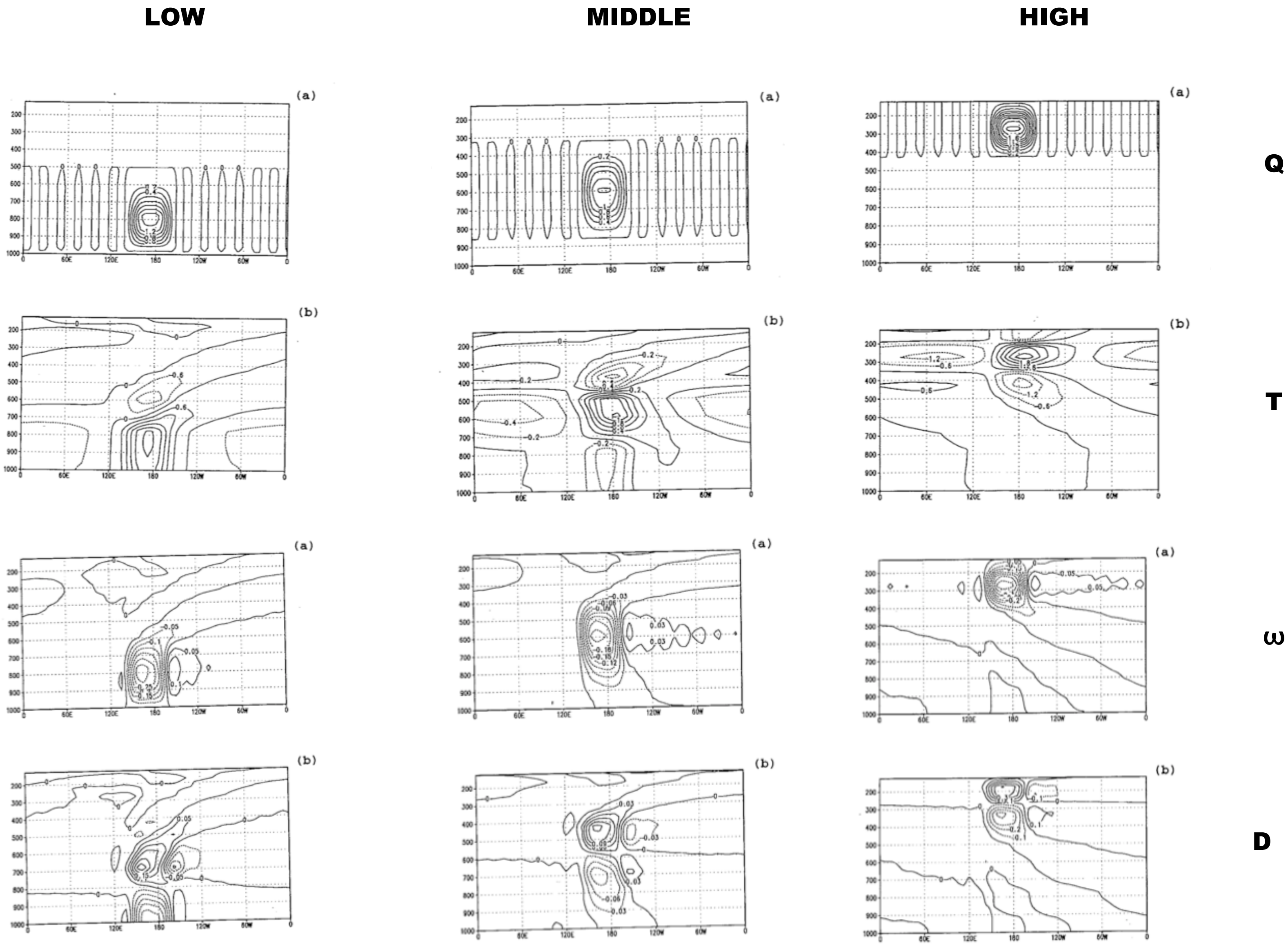
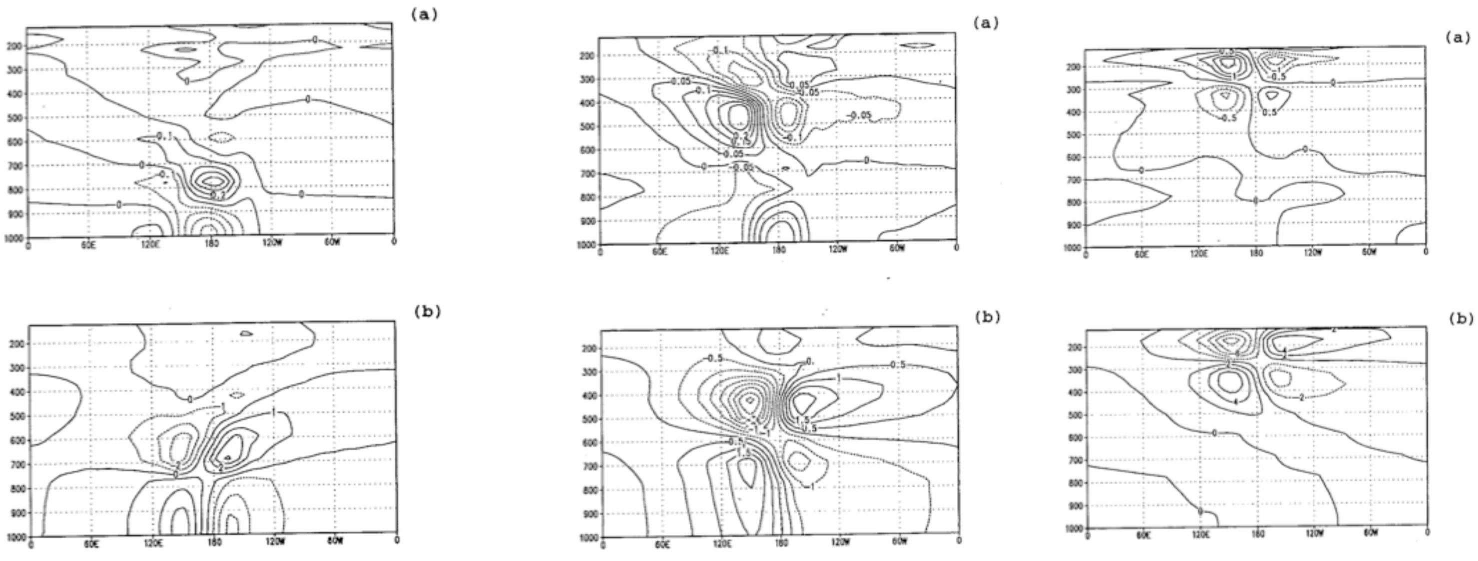


Cross sections at 2°S

LOW MIDDLE HIGH



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- **MYTH: STEADY CONVECTIVE HEATING STRUCTURES CANNOT MAINTAIN THEMSELVES WITHOUT SURFACE TEMPERATURE FORCING**

- **REALITY: CONVECTIVE HEATING NEEDS AN ANCHOR (LIKE BUBBLE SOURCES IN A POT OF BOILING WATER)**

- **EXAMPLE: KIRTMAN AND SCHNEIDER (2000) SHOWED THAT A TROPICAL ITCZ SPONTANEOUSLY FORMS ON A FEATURELESS EARTH WITH SOLAR FORCING AND SST TAKEN TO BE CONSTANT EVERYWHERE (OR JUST UNIFORM SOLAR FORCING + MIXED LAYER OCEAN).**
    - **WITH NO ROTATION, HEATING IS THE SAME EVERYWHERE AND THE CLIMATE IS RADIATIVE-CONVECTIVE EQUILIBRIUM WITH NO LARGE SCALE MOTION.**
    - **WITH ROTATION, A ZONALLY UNIFORM ITCZ FORMS**

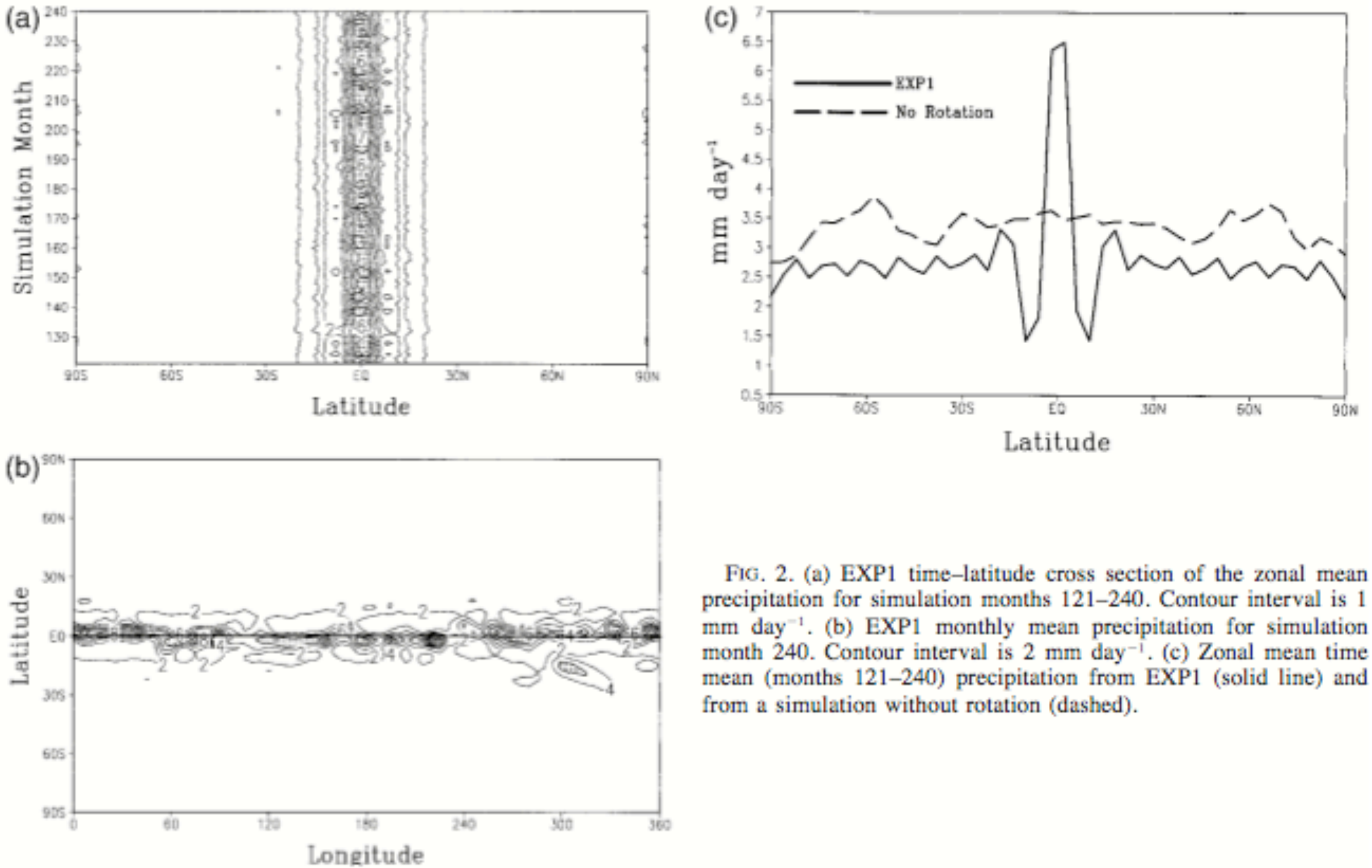

FIG. 2. (a) EXP1 time–latitude cross section of the zonal mean precipitation for simulation months 121–240. Contour interval is 1 mm day^{-1}. (b) EXP1 monthly mean precipitation for simulation month 240. Contour interval is 2 mm day^{-1}. (c) Zonal mean time mean (months 121–240) precipitation from EXP1 (solid line) and from a simulation without rotation (dashed).