

Response of the Atmosphere to SST anomalies

Class Notes, ATM560

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1 The Heating

1.1 Heating of the PBL

In most areas of the tropics, SST anomalies cause anomalies in the turbulent heat flux Q_s that are distributed in a boundary layer that is capped by a strong temperature inversion.

Turbulent heating causes the boundary layer to thicken and hence it drives a low level convergence in the PBL. The turbulent heating Q_h can be written

$$Q_h \sim C_D |U| (SST - T_a) + \text{vapor flux}, \quad (1)$$

where fluxes of vapor can also create pressure gradients in the PBL. The PBL flow advects moisture from afar.

In the steady state, the net increase in vapor flux must be balanced by precipitation P :

$$P = \mathcal{H} \left\{ E - \int_{P_s - \Delta P}^{P_s} \nabla \cdot q \tilde{u} dp \right\}, \quad (2)$$

where q is the mixing ratio (in kg vapor / kg dry air), $\tilde{u}$ is the horizontal flow in the PBL, E is the evaporation rate ($[E] = kg\ m^{-2}s^{-1}$), ΔP is the pressure difference between the top of the PBL and the surface, and $\mathcal{H}$ is the Heavyside function:

$$\mathcal{H} \equiv \begin{cases} 1 & x \geq 0 \\ 0 & x < 0 \end{cases}. \quad (3)$$

The evaporation rate E is parameterized as

$$E = C_D |U| \rho_o (q_s(SST) - q(T_a)), \quad (4)$$

where ρ_o is the density of the air near the surface, Q_s is the saturation vapor mixing ratio at the SST and q is the mixing ratio of the air in contact with the ocean surface.

2 Heating of the free troposphere

A net convergence of moisture in the PBL must, in the steady state, be balanced by precipitation. Condensation releases heat to the atmosphere *above* the PBL. This heats the free troposphere with heating $Q_c = L P$, expanding the air and generating pressure gradients aloft.

So SST anomalies force flow in the PBL via turbulent fluxes and they create anomalous moisture convergences that create precipitation aloft. In turn, the precipitation aloft *may* affect the flow in the PBL and hence further modifies the precipitation.

Hence, we have a situation where turbulent heat fluxes Q_h drive flows in the PBL *and* precipitation aloft that heats the free tropopause Q_c . Both affect the winds in the PBL. In the end, however, the circulation associated with the total heating

$$Q = Q_h + Q_c \tag{5}$$

must be consistent with the precipitation P given in eqn 2.

3 The dirty history of the steady response of the tropical atmosphere to SST anomalies

We will now examine two simple views for the response of the tropical atmosphere to SST anomalies. The first is that of Gill (1980) and assumes all the important circulation is driven by condensation in deep convection Q_c . Specifically Gill treated the troposphere as a continuously stratified fluid and assumed the surface and the tropopause act as lids. In this framework, there is no PBL and the troposphere has an infinite set of vertical normal modes. Gill further assumed that the heating projected well onto the first vertical normal mode, which has a shallow water speed of $C_1 \approx 60m/s$. Hence, Gill's solution satisfies Matsuno's (1966) equations (Kelvin, Rossby, MRG, etc. waves) with a vertical structure is set by the first vertical mode.

The second paradigm is from Lindzen and Nigam (1987) who took a completely different approach. They assumed that SST anomalies drive turbulent heat fluxes Q_h that are confined to the PBL and that these heat flux anomalies are entirely responsible for the PBL flow. In their view, the PBL circulations are slave to the SST gradients, and the flow fields that result drive precipitation anomalies above the PBL that have *no* the no impact on the surface circulation. In their mind, the precipitation changes were simply a consequence of the PBL changes and affected only the flow above the PBL.

Of course, the actual answer is a blend of both. This became clear from the work of Chiang et al (1991), who employed a linear model of the tropical atmosphere that was best fit to observation to determine the relative contributions of elevated convective heating and PBL turbulent heating to the surface winds that result from changing SST. We look at each of these models in more detail below.

3.1 The Gill/Matsuno model of the free troposphere response to diabatic heating

Gill (1980) assumed no PBL and that the diabatic heating driven by the SST is entirely expressed by the convective heating Q_c distributed throughout the troposphere. He took only idealized cases of Q_c . Zebiak (1986) formulated a heating for the Gill model.

3.1.1 Zebiak's (1986) Convective Heating of the Gill/Matsuno Model

Zebiak adopted the Gill/Matsuno model and derived an expression for the condensational heating Q_c in terms of the SST. Specifically, Zebiak assumed that SST anomalies drive evaporation anomalies E and that this vapor immediately condenses to heat the entire troposphere. The subsequent circulation changes near the surface cause anomalies in moisture convergence, which changes the precipitation rate and thus further affects the heating.

Zebiak assumed evaporation E of is a function of SST:

$$E = \text{function}(\text{SST}) . \quad (6)$$

and that the vapor immediately condensed and thus provided a heating LE , where L is the latent heat of fusion. The convective heating LE then drives a circulation that gives rise to surface flow that affects the moisture convergence and hence feedbacks on the convective heating. Zebiak (1986) wrote:

$$L * P = \int_{P_T}^{P_s} Q dp = \int_{P_T}^{P_s} Q_c dp, \quad (7)$$

where

$$P = E + \beta \mathcal{H} \left\{ - \int_{P_T}^{P_s} \nabla \cdot \vec{u} dp \right\} \quad (8)$$

and β is a tuning constant. In equation 3.1.1, the integral is done over the bottom half of the troposphere, and the heating is assumed to project fully onto the first vertical mode. Note that equation 3.1.1 is not physically consistent (c.f., 2).

3.2 Problems with Gill/Matsuno Model

- You need large friction ($1/(1-2)\text{day}^{-1}$) compared to that observed ($1/(5-15)\text{day}^{-1}$).
- Theory shows that *Convective* heating must extend to the surface to generate surface winds (and surface convergence) (Wu et al 1999), but the observed convective heating starts above the PBL.
- The tropopause isn't a lid. In fact, because there is no lid the atmosphere has *no* internal normal modes (Wu et al 1999). Note, however, that Geisler and Stevens

(1982) argued that the density jump at the tropopause did a good job acting as a lid if you are interested in the equilibrated (or the low-frequency) response to heating, so this isn't that big of an issue.

- The Gill/Matsuno model requires large thermal relaxation time ($1/(1 - 2)\text{day}^{-1}$) for realistic solutions compared to that observed ($1/(15 - 30)\text{day}^{-1}$).
- The Gill/Matsuno model forced by observed Q_e does not reproduce the low level circulation that is observed. That is, it is not consistent with the heating that was used to drive the circulation.

4 An alternative model: The PBL response to heating

Lindzen and Nigam (1987) assumed the opposite model to that of Gill/Matsuno/Gill. They assumed the PBL wind response is entirely due to the PBL response to turbulent heat fluxes and is independent of changes in the heating due to changes in precipitation. In the LN model, Eq. (2) is used only to *diagnose* how the changes in surface heating drive changes in precipitation, but the latter is assumed to heat the atmosphere *above* the PBL and to *not* affect the surface flow.

LN were able to show that turbulent heat flux anomalies $Q_h = Q_s + Q_e = Q_s + LE$ associated with SST anomalies that account for the observed surface *meridional* winds and the observed surface convergence. Battisti et al (1990) extended the LN model to show that the surface wind anomalies driven by the turbulent heat fluxes, in concert with the observed surface evaporation anomalies, provided a good diagnostic for the precipitation anomalies (using equation 2. That is, the PBL formulation can also account for the convective heating anomalies during ENSO (although because the latter anomalies force the atmosphere above the PBL, the condensation heating anomalies associated with the precipitation anomalies do not affect the surface winds).

5 Reconciling the LN (PBL) and Gill/Matsuno/Zebiak (free troposphere) views of the response of the atmosphere to SST anomalies

Chiang et al (2001) constructed a linear model of the tropical atmosphere that includes both a PBL (enhanced mixing in near surface troposphere) and a free troposphere. They took the observed precipitation and SST anomalies (20 years) in the tropical Pacific and Atlantic and did a best fit of the response of the model wind anomalies to the observed wind anomalies, using a wide range of realistic values for eight key parameters (e.g., the height of the base of the convective heating, the amount of mixing in the PBL, surface drag coefficient, vertical viscosity, etc).

They found, consistent with LN and Battisti et al, that the near surface meridional winds and the convergence anomalies in the PBL are due to turbulent heat flux forcing of the PBL (the convergence, in turn is consistent with what is required to explain the precipitation anomalies that are observed. The condensational heating anomalies associated with the precipitation anomalies, in turn, can change the surface zonal flow if the momentum mixing in the lower troposphere above the PBL is sufficiently large. In fact, they found that the elevated heating is responsible for most of the *zonal* winds near the surface which are important for driving the ocean. The surface convergence associated with the convectively (condensationally) driven zonal winds is small, however, and so it has little feedback on the surface moisture convergence.

In the end, the Chiang results show the parameter values used in the Zebiak equation for the heating is reasonable, but the correct *interpretation* of the equation is very different from given in Zebiak.