Large-scale coupling between the tropical greenhouse effect and latent heat flux via atmospheric dynamics

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Abstract. The clear-sky greenhouse effect (GE) is determined primarily by the amount and vertical distribution of water vapor in the atmospheric column. GE hampers surface radiative cooling and is maintained through surface evaporative cooling. This paper examines the intimate space-time relationships between the patterns of radiative heating of the atmosphere and surface evaporative cooling. We use data derived from satellite and in situ observations to show that tropical maritime GE is decoupled in space and time from latent heat flux (LHF), its source of water vapor. Large scale transport of atmospheric water vapor responsible for the observed relationships between GE and LHF is discussed. The spatial patterns of average GE and LHF are imbedded in the Walker and Hadley circulations and reinforce these circulations with strong evaporative cooling in the subtropical highs and greenhouse warming in the equatorial trough zones. Throughout tropical areas characterized by strong seasonality, the seasonal cycles of GE and LHF are out of phase. Much of the moisture that feeds GE in these off-equatorial regions is advected by the Hadley circulation from tropical moisture source regions of the opposite hemisphere. An out-of-phase relationship between GE and LHF also turns up on El Niño - Southern Oscillation timescales, most notably in the central tropical Pacific. The "super" greenhouse effect (SGE), a situation when GE absorption increases more than colocated surface longwave emission, is a seasonal feature of extensive tropical off-equatorial areas where it is maintained by moisture convergence and convection. On interannual timescales, the same dynamical processes appear to assert the SGE in the central equatorial Pacific. GE and LHF regimes are also described for the equatorial cold tongue and warm pool regions.

1. Introduction

Recently, the tropical greenhouse effect has been receiving much attention from climatologists because of questions raised about the workings of the so-called super greenhouse effect (SGE) and its role in climate. The SGE is an observed phenomenon whereby tropical surface temperature (and associated longwave emission) increases while colocated top-of-the-atmosphere clear-sky outgoing longwave radiation (OLR_{as}) decreases. Several studies focused on the physical and statistical properties of the clear-sky greenhouse trapping (GE), which is defined as the difference between longwave radiation emitted by the surface (ESLR) and OLR_{as} and examined its relationship with other climatic parameters. Raval and Ramanathan [1989] considered the spatial variation of monthly and annual averages of GE and SST and concluded that the positive relationship between GE and sea surface temperature (SST) in space is a result of a chain of positive dependence of GE on total water vapor content (W), which is dependent on saturation vapor pressure via the Clausius-Clapeyron relationship, which is dependent on atmospheric temperature, which is dependent on SST. Stephens and Greenwald [1991] followed up on this thought by showing that their greenhouse parameter (G = OLR_{as} / ESLR) is a nearly linear function of W and suggested that GE may also be sensitive to the vertical distribution of water vapor. Hallberg and Inamdar [1993] analyzed interseasonal shifts in the relationship between GE and SST, once more documenting their positive relationship in space regardless of season and pointing out the nonlinear enhancement of GE with SST at SSTs > 25°C. They suggested that dynamic processes along with local thermodynamics must play a role in bringing about this SGE. Inamdar and Ramanathan [1994] followed up on Hallberg and Inamdar's [1993] proposition that convective dynamics could play an important role in the determination of GE and examined the climatological response of GE to SST forcing in convective and nonconvective tropical regions. Using radiosonde data, they found that in convective regions the entire tropospheric column is moistened with increasing SST beyond what would be expected from the temperature dependence of saturation vapor pressure via the Clausius-Clapeyron relation (i.e., relative humidity increases) and that this moistening, together with a steepened temperature lapse rate in the lower troposphere at higher SSTs, is the cause of the SGE. They have also demonstrated the positive coupling between SST and GE on interannual timescales in the central tropical Pacific. Sinha [1995] examined local January-July variability in the normalized GE and obtained a rate of change with SST
that is 1.5 times larger than that obtained from spatially corre-
lating the aggregated data as in previous studies. He points out that this result indicates the importance of large-scale cir-
culations as well as SSTs in determining GE. Sinha found that in the tropics, the water vapor feedback accounts for about two thirds of the January-July change in GE, while the lapse rate feedback explains the rest.

When one considers that GE is mainly determined by water vapor, it becomes clear that large-scale atmospheric dynamics must indeed play a central role in the maintenance of GE. This is especially true above the equatorial warm pools. Over the western equatorial Pacific, where a strong positive relationship between SST and GE is well recognized [e.g., Inamdar and Ramanathan, 1994], evaporation actually decreases with SST on timescales of climatic importance [Comejo-Garrido and Stone, 1977; Zhang and McPhaden, 1995; Zhang et al., 1995]. Therefore the moisture that maintains GE and SIE at least above the western Pacific warm pool must be advected from remote source regions. Low-level convergence is thermodynamically enhanced over warm SIE regions on climatic space scales and timescales, and we expect to see strong non-local coupling between GE and LHF on these scales. Locally, this view is consistent with Ramanathan and Collins's [1991] premise for their cirrus cloud thermostat hypothesis that as SST increases in already warm oceans, evaporation cannot provide a negative feedback. However, this view also promotes consideration of the nonlocal nature of any such thermostat, emphasizing that greenhouse-induced surface warming is associated with remote evaporative cooling. The idea that local thermodynamics cannot be adequately understood separately from large-scale dynamics has been proposed by many workers [e.g., Wallace, 1992; Hartmann and Michelsen, 1993; Lau et al., 1994; Pierrehumbert 1995; Walliser, 1996a, b]. In this paper, we investigate the local and nonlocal space-time relationship between observed greenhouse trapping and latent heat flux over tropical-subtropical oceans and discuss the large-scale atmospheric dynamics that determine the observed relationship. In order to substantiate our conclusions about the dynamics involved, we also discuss local relationships between GE, LHF, ESLR, OLRe, surface wind, and low-level moisture convergence in four tropical regions representative of different climatic regimes.

In what follows, we investigate the relationship between GE and LHF in space and in time. Section 2 briefly describes the data. In section 3, we present spatial distributions of GE and LHF, discussing their climatological, seasonal, and interannual relationships. The nonlocal nature of the GE \( \leftrightarrow \) LHF coupling in time is also considered. In section 4, the observed spatial distribution of the SIE is presented, temporal variability of GE in several regions with different GE regimes, especially those characterized by a seasonal SIE, is considered; and sources of moisture for these regions and the large-scale teleconnections between GE and LHF are described. A summary of results is found in section 5.

2. Data

Atmospheric clear-sky greenhouse trapping is commonly defined as a difference between ESLR and OLRe (GE = ESLR - OLRe) and can be easily calculated from colocated observations of surface temperature \( (T_s) \) and OLRe. ESLR is given by \( \epsilon \sigma T_s^4 \), where \( \epsilon \) is the emissivity and \( \sigma \) is the Plank constant. The analysis is restricted to oceanic areas, mainly because while the ocean surface is nearly a black body in the infrared (\( \epsilon \approx 0.98 \)), it is difficult to estimate \( \epsilon \) over the nonhomogeneous land surfaces.

OLRe is one of the variables observed by the Earth Radiation Budget Experiment (ERBE). There have been some questions about the accuracy of these data, especially in convective regions [Hartmann et al., 1992; Briegleb, 1992], but recent studies indicate that the systematic error in these data is statistically insignificant [Collins and Inamdar, 1995]. Inamdar and Ramanathan [1994] raised the question of the applicability of OLRe to estimating GE, the water vapor greenhouse effect. In their study, they compared the ERBE OLRe observations to OLRe calculated using a radiative transfer model initialized with colocated radiosonde humidity profiles. Both approaches yielded remarkably similar results. One reason why OLRe agrees so well with OLRe resulting from water vapor absorption estimated by radiative transfer model calculations using all-weather humidity profiles may be that some effect of clouds on OLRe through their delay in influence on clear-sky humidity is implicitly present in the ERBE data.

LHF was computed by the Earth Space Research Group (ESRG) at the University of California at Santa Barbara using a parameterization given by Liu et al. [1979] and a combination of satellite-derived (SST and surface wind speed) and blended Comprehensive Ocean-Atmosphere Data Set (COADS) observed and satellite-derived input parameters (water vapor mixing ratio and air temperature). The input parameters and derivation of the blended LHF and its accuracy are described in detail by Jourdan and Gauthier [1995]. Our analysis is restricted to 40øN-40øS where LHF data are quite reliable because of relatively frequent sampling by ships of opportunity (COADS). One region where LHF may be systematically overestimated is the southeastern subtropical Pacific, where the blended analysis is weighted heavily toward the satellite-only derivation because of infrequent COADS sampling. The bias, however, is small in the context of our qualitative analysis.

The SST data used to compute ESLR and LHF are a standard satellite product called multi-channel sea surface temperature (MCSST) produced at the University of Miami, Rosenstiel School of Marine and Atmospheric Sciences. These data were obtained from the Physical Oceanography Distributed Active Archive Center (DAAC) at the Jet Propulsion Laboratory/California Institute of Technology. Surface wind data used in our analysis (not the same as used for derivation of LHF where only wind speed is required) are u and v components of the wind at 2 m produced with the Goddard Earth Observing System (GEOS) general circulation model (GCM) at the Data Assimilation Office of the Goddard Space Flight Center. Low-level moisture convergence (LLMC) data were calculated by Jones and Weare [1996] from European Centre for Medium-Range Weather Forecasting (ECMWF) wind and water vapor mixing ratio analyses, integrated from the surface to 700 mbar.

All fields used in this analysis are monthly averages, from July 1987 to February 1990. LHF data are missing in December 1987, while LLMC extends only to December 1989. The spatial resolution of the SST, OLRe, GE, LHF, and LLMC data is 2.5ø x 2.5ø, while that of the surface winds is 4ø x 5ø.
3. Spatial Distributions of GE and LHF and Their Temporal Relationship

We now examine in some detail the large-scale features of the GE and LHF distributions and the nature of the local temporal relationship between the two fields.

3.1. Mean Fields

The horizontal distribution of time-averaged GE for the period of July 1987 through February 1990 is displayed in Figure 1a. The similarity of this figure to the climatological horizontal distribution of SST, tropical convection, and W immediately suggests a coupling between these fields and GE. This is certainly not surprising in view of the demonstrated relationship between W, convection, and GE [Stephens and Greenwald, 1991; Inamdar and Ramanathan, 1994] and that between SST and convection [e.g., Fu et al., 1994]. The strongest climatological mean GE (as high as about 150 W/m²) is observed over the tropical western Pacific and Indian Oceans. These regions are characterized by year-round high SSTS and weak convergent surface winds. High GE is also observed along the Intertropical Convergence Zone (ITCZ), the southwestern and the western North Pacific convergence zones, and, to a lesser magnitude, their Atlantic counterparts. These regions generally experience strong seasonal variation in SST, surface winds, convection, and rainfall [Wang, 1994a; Gershunov and Michaelsen, 1996]. The weakest observed GE (as low as 80 W/m²) occurs in the subtropics along the west coasts of continents, most notably the west coasts of South and North America and southern Africa. These are regions of high along-shore winds, high pressure, and cold upwelled waters.

The highest mean values of LHF (as high as about 220 W/m²) are observed away from the equator in extensive belts characterized by warm SST and strong divergent surface winds (Figure 1b). Because the warmest SST occurs under calm, often convergent, winds and high winds limit SST by enhancing evaporational surface cooling, there is little spatial overlap between regions marked by the warmest SST (and the strongest GE) and the highest LHF. There is, however, some overlap between regions marked by moderately strong GE and LHF. These regions are the outskirts of convergence zones in the Pacific and Atlantic Oceans. The Pacific and Atlantic moisture source belts extend under the trade inversion, westward and equatorward of the subtropical west coasts of continents. Their western margins are wedged between the ITCZ and the western North Pacific and Atlantic convergence zones. This is where relatively high values of both GE and LHF are observed. Narrow, distinct bands of high LHF are located at subtropical latitudes along the east coasts of North America, Asia, Australia, and around India. A 15°-wide band of very high LHF (~200 W/m²) extends zonally from Australia to Madagascar. The equatorial regions do not generally undergo very high rates of evaporation. In the equatorial Indian Ocean, mean LHF is approximately uniformly 120 W/m² and decreases to around 80-100 W/m² in the vicinity of Indonesia. In the eastern central Pacific, LHF reaches an equatorial maximum mean of about 150-160 W/m² where the two off-equatorial moisture source belts nearly meet and decreases to a tropical minimum of about 50-60 W/m² in the eastern equatorial Pacific cold tongue. Zhang and McPhaden [1995] observe a similar meridional LHF distribution in the equatorial Pacific with moored buoy data. The Atlantic exhibits features similar to but weaker than their Pacific counterparts.

The large-scale features of the climatological GE and LHF distributions described above support the widely held notion that moisture cycling is an intrinsic and active component of the tropical general circulation. The Pacific sector provides an excellent example. Very high evaporation rates are observed in the tradewind regime westward and equatorward of the eastern Pacific subtropical highs. Evaporated moisture is concentrated below the persistent trade inversion in these areas [Hastenrath, 1991], while GE is relatively low. Converging trades deliver this moisture to the ITCZ and into the western Pacific warm pool region where it fuels deep convection and enhances GE. Persistent deep convection above the warm pool and along the ITCZ provides the vigorous uplift in the rising branches of the Walker and Hadley cells. Moisture cycling may also promote the Hadley and Walker circulations by intensifying temperature gradients through evaporational surface cooling in the subtropical highs and tradewind regime and greenhouse warming in convective regions. The observed climatological GE and LHF can be viewed both as a side effect of the general circulation and as a contributing factor.

A slight but noteworthy hemispheric imbalance in LHF and GE is evident and probably results mainly because more of the southern tropics and subtropics are covered by water than their northern counterparts and the related somewhat northerly climatological position of the ITCZ. While the southern tropics exhibit larger and higher-yield moisture source regions, the northern tropics are characterized by more extensive maritime regions of high GE, suggesting that on average, the southern tropics are a moisture source while the northern tropics are a moisture sink. The same is true for the two hemispheres in general. The 2-year (1988-1989) average maritime GE between 30°S and the equator is 124 W/m² and 133 W/m² between the equator and 30°N. Corresponding LHF values are 154 and 140 W/m², respectively. In this study, we can not assess the effect of continental convection on the tropical GE budget, but judging from marine areas alone, it would seem that the extra surface evaporative cooling in the southern hemisphere translates into a comparable atmospheric warming in the northern hemisphere by way of atmospheric moisture dynamics. This is consistent with the fact that average meridional winds at the equator are southerly and the average position of the ITCZ is slightly north of the equator.

3.2. Local Correlations of Time Series

We now consider the local temporal relationship between GE and LHF in an attempt to shed light on the contribution of locally evaporated moisture to the overlying GE and, conversely, on whether evaporative cooling is enhanced under a stronger GE, when radiative surface cooling is inefficient. Local temporal correlation between GE and LHF (Figure 1e) manifests an out-of-phase relationship throughout most of the tropics. Correlations exceeding 0.41 in absolute value are statistically significant at the 0.99 significance level. Given that the usual assumptions about data implicit in such significance tests probably do not hold for these time series (e.g., independence of the errors), these values are meant only as rough guidelines as to the true significance of the observed correlations. The strongest negative correlations occur in the exten-
sive off-equatorial moisture source regions. The intensity of the negative correlations does not follow the pattern of the LHF intensity in the same regions but reaches a maximum in the vicinity of the overlap between regions of high GE and LHF described above. Negative correlations weaken where the moisture source regions nearly converge in the western central Pacific and become weakly positive in the west Atlantic. These narrow bands of weak correlations, 6°-8°N, are the positions of the ITCZ during its annual maximum in the late boreal summer and early fall [Mitchell and Wallace, 1992]. The axis of the South Pacific Convergence Zone (SPCZ) is marked visibly by a narrow band of near-zero correlations. Below it, correlations decrease again east of Australia, a region of moderately high GE and LHF.

In general, regions of high mean LHF, especially where they encounter regions of high mean GE, tend to display the strongest negative correlations (~0.85). Regions of moderately high GE and/or LHF such as the off-equatorial tropical Indian Ocean, and the vicinity of central America, are characterized by weaker negative correlations (about -0.6). The east coast areas of high evaporation and moderately low GE exhibit relationally incoherent correlations (close to 0), and re-

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**Figure 1.** (a) Temporal mean of clear-sky greenhouse effect (GE). Contours are drawn at 20 W/m² intervals starting with 100 W/m². (b) Same for latent heat flux (LHF) with contours at 50 W/m² intervals starting with 50 W/m². (c) Local temporal correlation between GE and LHF for July 1987 to February 1990. Contours are at 0.5 intervals, with the zero contour in bold. Vectors on all panels represent temporally averaged surface winds. A vector of length ~4.5ø represents a speed of ~8 m/s.
regions of low LHF and low to medium GE show a positive relationship with correlations up to 0.6-0.7. This is most prominent in the cold tongues of the eastern equatorial tropical Pacific and Atlantic Oceans. Regions of the highest mean GE such as the equatorial Indian and western Pacific Oceans (these are also regions of medium-low LHF) exhibit a patchy pattern of mostly positive but low correlations. The highest positive correlations in this region of the most intense mean GE outline the band of the lowest mean LHF there. The mid-latitudes show uniformly large positive correlations between GE and LHF. It is somewhat surprising to see that except for the tropical Indian ocean and the maritime continent, where mean GE is at a global maximum, and areas where both GE and LHF are extremely low, most of the tropics are characterized by a coherent out-of-phase relationship between GE and LHF.

Mean surface winds (Figures 1a-1c) reveal the origins of the water vapor that feeds the strong year-round convection and GE. In the equatorial Indian, western Pacific, and Atlantic Oceans and around Central America, moisture is supplied in large part from the subtropical moisture source regions which are characterized by dry conditions, high pressure, and strong divergent winds and are located directly upwind of the prevailing trades. In the more seasonally varying convergence zones, the negative correlations between GE and LHF suggest that a strong out-of-phase seasonality in colocated values of both fields probably controls the nature of the local relationship. This also implies that much of the moisture feeding GE and convection is advected from remote regions.

3.3. Seasonality

The seasonal nature of the relationship between GE and LHF can be easily observed by comparing the maps of GE and LHF for the two extremes of the seasonal oscillation in the tropics: roughly August-September and February-March. Figure 2 presents these two pairs of seasonal fields along with corresponding seasonal mean surface winds. The extremes of the seasonal shift in GE are displayed in Figures 2a and 2c. The equatorial band of very high GE extending from the Indian Ocean well into the western equatorial Pacific is the only region that does not experience a large seasonality, while a thicker envelope (20°-25°) of high GE associated with monsoonal convection migrates annually north and south around the equator. The GE seasonality in localized west coast upwelling regions of extremely low GE is very weak and manifests itself in a small increase (<20%) in the GE next to the coast and a slightly larger increase away from the coast during late summer as wind speeds decrease and the well-defined boundary layer is moistened at the coasts, while convection associated with the seasonal convergence zones expands closer to the continent. All other tropical/subtropical regions experience large seasonal shifts in GE. Most notably, the seasonal convergence zones display a very large seasonality (~110~150 W/m²) over extensive regions in all oceans.

Large-scale seasonal shifts in GE associated with the convergence zones are accompanied by corresponding shifts in LHF (Figures 2b and 2d). These shifts occur precisely in the extensive off-equatorial moisture source regions. Year-round, these areas experience relatively high evaporation rates which are strongly modulated by the annual cycle. GE and LHF in these regions of high seasonal variability are out of phase with each other. Both the spatial extent and the intensity of high LHF are visibly increased during the winter, when surface winds and divergence are enhanced. In most of these areas, LHF is less than 200 W/m² in late summer-early fall and around 250 W/m² in the late winter-early spring. Although even during the seasonal LHF minima in these moisture sources, the moisture flux from these regions is very high, their opposite hemispheric counterparts contribute considerably more moisture for convection and GE in the seasonally and nonseasonally varying convergence regions. These seasonal shifts in GE and LHF with respect to the equator and related meridional winds represent the seasonal modulation of the Hadley circulation.

The underlying causes of strong negative correlation between GE and LHF observed in seasonal convergence zones and moisture source regions (Figure 1) can now be interpreted. On the seasonal plots (Figure 2), the wedge pattern made by moisture source regions and convergence zones is seen to migrate seasonally. When the convergence zones expand poleward and eastward into the summer hemisphere and surface winds become weaker and less divergent, the moisture source regions shrink in size and intensity. Even though SST is enhanced in the summer hemisphere, LHF is reduced because of weaker wind stress and higher surface-level relative humidity brought about by anomalous low-level convergence which accompanies convection. Much of the moisture used to feed the GE in the convergence zones is advected from the moisture sources in the opposite hemisphere, where surface wind divergence and LHF are at a seasonal maximum while convection and GE are at a minimum. The positive feedback loop resulting from the spatial decoupling of evaporational cooling and GE heating enhances the associated meridional temperature and pressure gradients and Hadley circulation intensity, probably adding to the effect of the ocean's delayed response to insolation heating, to cause convection and GE to peak a few months past the summer solstices. The zonal cells of the Pacific and Atlantic are driven mainly by processes varying on interannual timescales, but they are nevertheless seasonally modulated. In the seasonal GE and LHF maps, this seasonal modulation manifests itself in the inversely varying intensities of GE and LHF about the equator.

3.4. ENSO Effects

Our data span a time period during which a cool phase of ENSO prevailed but which also includes the tail end of the 1987 El Niño. In this section we attempt to illustrate ENSO effects on GE and LHF by contrasting August-September 1987 with the same 2-month period of the remaining 2 cool years. Figure 3a shows 1987 August-September averaged GE (and surface wind) minus 1988-1989 August-September averaged GE (and surface wind). Figure 3b shows the same information for LHF. Resulting maps represent the contrasts in GE and LHF, respectively, for the two extremes of the southern oscillation, during late summer-early boreal fall. In Figure 3a, observe the large increase in GE associated with the warm phase of ENSO concentrated in the anomalous convergence zone in the central equatorial Pacific (values above 20 W/m²) decreasing but remaining positive (~10 W/m²) all the way to the eastern boundary where GE increases again in the cold tongue to about 15-20 W/m². The result for the central equatorial Pacific corroborates results of Inamdar and Ramana-than [1994] in the same region, which is a region of enhanced convection during anomalous warming associated with El Niño. In contrast, note that LHF is reduced by 50% in the warm tongue of ENSO, about 100 W/m² below the 1987 level.
Figure 2. (a) August and September mean GE. Contours are at 20 W/m² intervals starting with 80 W/m². (b) Same for LHF, with contours at 50 W/m² intervals starting with 50 W/m². (c) February and March mean GE with contours at 20 W/m² intervals starting with 80 W/m². (d) Same for LHF, with contours at 50 W/m² intervals starting with 50 W/m². Vectors are seasonal averages of surface winds. A vector of length ~4.5° represents a speed of ~7 m/s.
Figure 3. (a) August-September 1987 mean GE minus August-September 1988-1989 mean GE. Contours are at 10 W/m$^2$ intervals with the zero contour in bold. (b) Same for LHF, with contours at 50 W/m$^2$ intervals. Similar differences in surface winds are denoted by vectors. A vector of length $\approx 4.5 \, \text{m/s}$ represents a difference in speed of $\approx 2.8 \, \text{m/s}$.

Nino [Deser and Wallace, 1990]. A slight increase in GE is also observed branching out into the southeastern Pacific moisture source. The rest of the Pacific Ocean, most notably the SPCZ, the maritime continent, and the subtropics, display a decrease in GE up to -10 W/m$^2$. The Atlantic displays a weaker decrease, while the Indian Ocean exhibits a slight average increase in GE. On the whole, the study area experiences a 0.8 W/m$^2$ average enhancement in GE. LHF is decreased during the warm phase of ENSO by 100-120 W/m$^2$ in a concentrated area in the central western equatorial Pacific, just west and slightly overlapping with the center of the increase in GE. LHF is also decreased (by 50-100 W/m$^2$) in the moisture source region of the southeastern Pacific, coincident with the GE increase there. The rest of the tropics and subtropics, including the Indian and Atlantic Oceans, experience a small increase in evaporation. This increase is most prominent in the SPCZ, where differences reach 50-70 W/m$^2$. On a tropical-subtropical average, LHF is enhanced in August and September of 1987 by 0.8 W/m$^2$ as compared with August and September of the 2 cold years. Surface wind speeds seem to play the same role as they do on seasonal timescales: Increased winds and divergence go hand in hand with lower GE and higher LHF. In the center of action, the central equatorial Pacific, the contrasts in GE and LHF for the opposite phases of ENSO appear to be much larger than the seasonal contrasts presented above. In other areas, notably the SPCZ, the magnitude of the interannual contrast is similar to the seasonal magnitude. The spatial patterns of these contrasts are due in large part to the weakening of the Walker cell and associated changes in ocean-atmosphere interactions during the warm phase of ENSO [e.g., Deser and Wallace, 1990; Druyan and Hastenrath, 1994]. It appears therefore that even on interannual timescales, most tropical-subtropical areas experience a negative relationship between GE and LHF and that basically similar dynamical processes (i.e., convection and convergence) are involved.

4. The SGE and Some Representative GE Regimes

In the previous section, the seasonal contrasts provided some information on the space-time dynamics of GE and evaporation in regions characterized by strong SST-driven (ocean modulated) seasonality in these fields. In this section we present the spatial distribution of the SGE and consider SGE and other characteristic GE regimes in more detail. Much of the discussion centers on seasonal effects, but ENSO-related variability is also briefly considered.

4.1. Super Greenhouse Effect (SGE)

The super greenhouse effect is a situation when GE absorption increases more than colocated surface longwave emission. SGE can be observed as an increase (decrease) in
surface temperature or associated longwave emission along with a colocated decrease (increase) in OLR<sub>ca</sub>. A negative local correlation between ESLR and OLR<sub>ca</sub> therefore would reveal the SGE on timescales represented by the data. Figure 4 presents local temporal correlations between ESLR and OLR<sub>ca</sub>. Using SST instead of ESLR (−SST) has no significant effect on the relationship, so the two terms can be used interchangeably. Poleward of about 20°-25° north and south, the correlations are around 0.8-0.9, indicating the positive dependence of OLR<sub>ca</sub> almost exclusively on SST outside of the tropics. Raval et al. [1994] find that SST explains over 80% of the temporal variability in OLR<sub>ca</sub> in the midlatitudes. Indeed, the seasonal variation in SST increases in amplitude with increasing latitude and exerts a controlling influence on OLR<sub>ca</sub> in and poleward of the dry subtropics [Raval et al., 1994]. In the tropics, however, Raval et al. observe that this level of dependence drops to about 20%. This number is representative of the tropics on average; however, Figure 4 shows a large spatial variation in the relationship.

The most interesting feature of the local relationship between tropical SST and OLR<sub>ca</sub> is the largely negative correlations, especially in the off-equatorial seasonal convergence belts where correlations easily reach -0.8. These are approximately regions classified by Wang [1994a] as marine monsoonal regimes, regions which experience large unimodal seasonality in convection and rainfall. Moisture source regions adjacent to (or wedged between) the convergence belt display weaker but also coherently negative correlations (-0.2 to -0.4). The temporal resolution and extent of our data emphasize seasonal variability, and so the regions of strong negative correlations are mainly regions of the seasonal SGE, that is, regions where surface longwave emission increases (decreases) while that at the top of the atmosphere decreases (increases) seasonally. The seasonality, coherence, and geographical-climatological location of the negative relationship between SST and OLR<sub>ca</sub> all suggest that large scale dynamics have a primary effect on the maintenance of this relationship and warrant a closer examination of some relevant thermal/radiative and dynamical variables in these regions.

Other regions display somewhat less coherent relationships, which are nevertheless consistent for similar climatic regimes and also warrant closer examination. Correlations are relatively incoherent (close to 0) around the equator, specifically along the climatological position of the ITCZ. In the vicinities of the equatorial warm pools, correlations tend to be spatially as well as relationally incoherent, exhibiting patchy patterns of weakly positive and negative correlations. In the cold tongues, the relationship between SST and OLR<sub>ca</sub> tends to be weakly positive.

As in the previous section, we illustrate the August-September part of the spatial pattern of interannual or ENSO variability in the variables determining GE by displaying differences between August-September average ESLR and OLR<sub>ca</sub> for 1987 and the same season average for 1988 and 1989 (Figure 5). The emerging patterns for ESLR and OLR<sub>ca</sub> are remarkably similar to those for GE and LHF (Figure 3), especially in the tropical Pacific, where the ENSO signal is the strongest. This is not surprising in view of the demonstrated dependence of GE on SST and the negative relationship of both OLR<sub>ca</sub> and LHF with convection and moisture convergence. There are, however, noteworthy differences. Whereas ESLR is anomalously enhanced during El Niño in the central and eastern Pacific (up to 18 W/m²), GE is enhanced much more in the central Pacific because the decrease in OLR<sub>ca</sub> there associated with the increase in convection apparently produces an interannual SGE in the central equatorial Pacific, while in the eastern Pacific the increase in OLR<sub>ca</sub> dampens the effect of increased SST on GE. Since during El Niño, convection and rainfall are most notably enhanced in the central equatorial Pacific [e.g., Deser and Wallace, 1990; Gershunov and Michaelsen, 1996], this, once again, now on interannual timescales, affirms the role of convection and large-scale dynamics in driving the SGE. The curious higher-latitude tropical and subtropical Pacific anomalous cooling during El Niño is discussed in detail by Chou [1994]. This cooling, occurring in nonconvective regions, leads to a decrease in GE.

4.2. Regional Investigations

We now take a closer look at the processes responsible for the behavior of GE in several characteristic regions representative of some distinct tropical climatic regimes. These areas are outlined by rectangles in Figure 4. They include two re-

Figure 4. Local temporal correlation between longwave radiation emitted by the surface (ESLR) and clear-sky outgoing longwave radiation (OLR<sub>ca</sub>) for July 1987 to February 1990. Contours are drawn at 0.5 intervals, with the zero contour in bold. Rectangles outline the North Pacific convergence zone (NPCZ), the eastern Pacific cold tongue, the southeastern Pacific moisture source, and the western equatorial Pacific warm pool regions considered in section 4.2.
Figure 5. (a) August-September 1987 mean ESLR minus August-September 1988-1989 mean ESLR. Contours are at 10 W/m² intervals with the zero contour in bold. (b) Same for OLRc, with contours at 5 W/m².
Figure 6. Time series of spatially averaged monthly values of (a) ESLR, (b) OLRcs, (c) GE, (d) surface wind speed, (e) low level moisture convergence, and (f) LHF in the northwestern tropical Pacific (140°-170°E, 7.5°-20°N).

Figure 7. Temporal correlation between mean GE in the NPCZ and LHF at each grid square (gray scale and contours are at 0.5 intervals with the zero contour in bold) and surface wind u and v components (vectors). A vector of length ~4.5° represents a correlation of ±1.
seasonal peak in insolation, convection and surface-level convergence are enhanced while wind speeds and LHF are reduced. However, more moisture is advected from remote regions, the atmospheric column is moistened through convection fed by surface moisture convergence far beyond any moistening due to the temperature dependence of saturation vapor pressure [Nnamdar and Ramathan, 1994; Sinha, 1995], and GE is accordingly elevated to the SGE status, materializing in a decrease in OLR\textsubscript{a}.

The southeastern Pacific (95\textdegree W-145\textdegree W, 10\textdegree S-20\textdegree S) moisture source region exhibits some evidence of the 1987 El Ni\~n\~o, manifested in an anomalously high seasonal minimum in the time series of ESLR, a prolonged maximum in OLR\textsubscript{a}, an anomalously high GE minimum, a somewhat low peak in surface winds, weak divergence, and the absence of the usual strong late boreal summer-early fall maximum in the LHF time series (Figures 8a-8h). The seasonal cycles in these variables behave in roughly the same way as those described for the NPCZ, except, of course, that they are approximately out of phase for corresponding variables. ESLR tends to be about 15 W/m\textsuperscript{2} lower on average than ESLR in the NPCZ, while OLR\textsubscript{a} is a few watts per square meter higher (but leads ESLR by a couple of months), resulting in a GE which is about 15 W/m\textsuperscript{2} less efficient. This is a region characterized all year by moisture divergence (compare Figure 8e with Figure 6e) which is closely related to surface wind speed and LHF (Figures 6d and 6e). Because the region, on the average, experiences year-round high values of GE (Figures 8a and 8c), while the troughs lag by a month (compare Figures 8f and 6c), while the troughs lag by a month (compare Figures 8f and 6c), while the troughs lag by a month (compare Figures 8f and 6c), while the troughs lag by a month (compare Figures 8f and 6c). This suggests that strong evaporation in the southeastern Pacific promotes convection and GE in the NPCZ, while weakened seasonal convection, convergence, and GE in the NPCZ have a suppressing influence on surface winds, divergence, and LHF in the eastern central South Pacific and foster warming, moisture accumulation, and enhanced GE there. Apparently, decreased moisture input from reduced LHF is more than balanced by decreased moisture divergence and a higher capacity of a warmer atmosphere to hold vapor. The result is reduced LHF and enhanced GE during the summer in moisture source regions.

The western equatorial Pacific warm pool (140\textdegree E-160\textdegree E, 2.5\textdegree S-5\textdegree N) is characterized by year-round high values of GE without a well-defined seasonal cycle (Figure 9c). There is, however, a hint of a semiannual cycle with a double maximum around October and May and ill-defined minima around January-February. The range of GE variability is only about 12 W/m\textsuperscript{2} around a mean of 150 W/m\textsuperscript{2}. GE time series reflects variability of ESLR (Figure 9a). This makes sense for an equatorial region where SST and convection are enhanced around the time of the equinoxes but are nevertheless high throughout the year. OLR\textsubscript{a} (Figure 9b) is largely decoupled from ESLR (cor \approx 0), agreeing quite well with results of Raval et al. [1995], who observe that OLR\textsubscript{a} is mostly unrelated to SST in most tropical regions, regions of warm SST. Nevertheless, OLR\textsubscript{a} exhibits minima around May and October and incoherent maxima, thus helping to define the semiannual cycle in GE. The range of variability of OLR\textsubscript{a} is only about 8 W/m\textsuperscript{2} around a mean of 285 W/m\textsuperscript{2}, the same as the range of ESLR around a mean of 434 W/m\textsuperscript{2}.

The time series of LHF (Figure 9d) does not exhibit any coherent seasonal or semiannual cycle throughout the entire time series. There is, however, hints of both, with the only clear maxima occurring in February and September 1988 and the two clear minima in June. The largest LHF peaks correspond to peaks (troughs) in surface wind speed (LLMC). Note that the region is characterized by year-round, weak seasonal, but mainly erratic moisture convergence (Figure 9e). The range of LHF variability is quite large: ~80 W/m\textsuperscript{2} around a mean of 135 W/m\textsuperscript{2}.

LHF variability in the western tropical Pacific, including any seasonal and semiannual variability, is likely modulated by processes occurring on interannual and intraseasonal timescales. Because during the warm phase of ENSO the warm pool expands and convection shifts eastward into the central tropical Pacific [Detter and Wallace, 1990], the western Pacific cools somewhat (observe the anomalous minimum in ESLR in August 1987; Figure 9a), winds become stronger, surface-level humidity probably falls as a result, and LHF is enhanced while GE is diminished slightly along with convection (see Figure 3).

The Madden-Julian Oscillation (MJO) has also been shown to be important in modulating convection and boundary layer moisture convergence [Madden and Julian, 1994; Jones and Weaver, 1996] in the equatorial warm pools and is expected to modulate GE and LHF accordingly on 30 to 60-day scales, too short to be adequately resolved here. A suggestion that the MJO may be important appears in the erratic behavior of the monthly time series of GE and LHF and other variables in Figure 9. Even though on intraseasonal timescales the SOE may manifest itself in the equatorial warm pools, from the point of view of monthly and interannual (at least ENSO-frequency) variability, GE in the warm pools cannot be formally termed SGE.

The eastern Pacific cold tongue (85\textdegree W-105\textdegree W, 2.5\textdegree S-2.5\textdegree N) displays a weakly positive relationship between LHF and GE (see Figure 1o); correlations are about 0.4. LHF is roughly in phase with GE, peaking in the boreal spring and dropping in the late summer-early fall but going through higher-than-seasonal frequency variability of similar to seasonal magnitude (Figure 10f). GE is characterized mainly by seasonal variability driven by the well-defined SST seasonality. A hint of ENSO-related variability is found in the anomalously warm late summer-early fall of 1987 (see also Figure 5a). OLR\textsubscript{a} does not exhibit a strong seasonality, yet shows consistent maxima in November, lacking any consistent minima. The range of variability in OLR\textsubscript{a} is only about one third that in ESLR, making the seasonal cycle of GE determined primarily by SST but prolonging the seasonal minimum slightly into late fall. The general appearance of the OLR\textsubscript{a} time series (Figure 10b) is similar to that of LHF with weak seasonality and substantial nonseasonal variation. Once again, given data constraints, we cannot explore the intraseasonal variability in the present study.

Wang [1994b] suggested that the minimum in LHF should occur during the October-November SST minimum and the
decline in surface winds (Figure 10d), thus favoring the warming of the cold tongue. We do not observe any distinct minima in LHF during boreal fall apart from the weak seasonality in LHF in phase with SST and GE. Given the low evaporation rates in the cold tongue, it is unlikely that LHF exerts a strong influence on SST in this region. More likely, LHF mainly responds to ocean forcing there. This is consistent with observations by Zhang and McPhaden [1995] that when tropical SST is low, LHF is more sensitive to SST fluctuations than to variability of surface wind speed.

Results displayed in Figure 3b suggest that this is also the case on ENSO timescales. Through SST, however, LHF is likely related to surface wind variability, even though we do not see this directly (cor \( \approx -0.1 \)), since SST is rather strongly related to wind speed (cor \( \approx -0.8 \)) which determines thermocline depth and upwelling rates [Wang, 1994b]. The well-defined seasonal cycles in SST, GE, surface wind, and LLMC behave as do those in southern tropical seasonal convergence zones, although the cause and effect relationships are different. However, in the equatorial cold tongues, LHF and OLR\(_{cs}\) seem to be largely nonseasonal and decoupled from SST, GE, surface wind, LLMC, and from each other.

5. Summary and Conclusions

We have observed that throughout most of the tropics, strong greenhouse warming is decoupled in space and time from evaporative cooling. The spatial decoupling of GE and LHF means that remote moisture source regions provide much of the water vapor used to feed GE and, consequently, the
system relies heavily on large-scale atmospheric dynamics. It is fair to say that this arrangement plays a role in influencing large-scale atmospheric circulations in which it is imbedded. For example, strong GE promotes atmospheric and surface warming in the western Pacific warm pool region, enhancing zonal temperature and pressure gradients. This promotes the Pacific trades enhancing subsidence, divergence, evaporation, and latent surface cooling in the eastern Pacific subtropical high regions. This, in turn, works to further enhance horizontal temperature and pressure gradients. The latent heat is more efficiently transported across the Pacific, where it feeds GE and convection over the warm pool. In this way, spatial distributions of GE and LHF are imbedded in the Walker and Hadley circulations and act to reinforce these circulations.

The local temporal decoupling of GE and LHF means that greenhouse heating is not usually countered by local evaporational cooling. On seasonal timescales, in tropical areas characterized by strong seasonality, the seasonal cycles of GE and LHF are exactly out of phase. However, greenhouse warming is seasonally countered by remote evaporational cooling. The seasonal cycle in insolation heating introduces asymmetry with respect to the equator by effectively partitioning the tropics into a moisture-source, cooler, nonconvective, subdued greenhouse (late winter-early spring) hemisphere and a moisture-sink or enhanced greenhouse, warm, and convective (late summer-early fall) hemisphere. The seasonal variability in the extent and intensity of the Hadley cells accomplishes this seesaw in GE and LHF. On interannual timescales, the ENSO

Figure 9. Same as Figure 6 but for the western equatorial Pacific warm pool (140°-160°E, 2.5°S-5°N).
signal is manifested in a large increase in GE and decrease in LHF centered in the central equatorial Pacific produced by the eastward migration of the western Pacific warm pool and the weakening of the Walker cell and associated meteorological changes.

Areas of seasonal moisture convergence-divergence or marine monsoon regions [Wang, 1994a] can be characterized as areas of the seasonal SGE. The regions marked by a strong GE and weak LHF, usually in the late summer-early fall, and strong LHF but weak GE in the late winter-early spring, are the regions which experience a well-defined seasonal SGE. These are also areas where low-level moisture convergence and surface winds are strongly related to SST, OLRs, GE, and LHF, indicating that large-scale dynamics related to moisture cycling are intimately connected to local thermodynamics. During the high GE season, SST, convection, and low-level moisture convergence are also at a seasonal high, and moisture is brought in from remote regions experiencing the opposite phase of the seasonal cycle characterized by high LHF, winds, and low-level moisture divergence. Areas located in the western off-equatorial Pacific and Atlantic can be called seasonal (summer) moisture sinks, while the areas to their east (particularly in the opposite (winter) hemisphere) are, relatively speaking, moisture sources. Moisture sinks are characterized by a better defined, stronger and more efficient seasonal SGE which is related to stronger average GE, warmer SST, weaker winds, and stronger moisture convergence and convection. Aside from the magnitudes and sea-

**Figure 10.** Same as Figure 6 but for the eastern Pacific equatorial cold tongue (85°-105°W, 2.5°S-2.5°N).
sonal amplitudes of these variables, they behave in very similar ways relative to each other in seasonal moisture sinks and sources. Our results reaffirm the important role of convection in enhancing the tropical GE suggested by previous studies [Inamdar and Ramanathan, 1994; Sinha, 1995]. Convection is also suggested to be important in driving the interannual SGE, especially in the central equatorial Pacific.

One weakness of the present work is the loose treatment of interannual variability. Another is the question of whether the SGE manifests itself regionally on intraseasonal timescales is left unexplored and deserves future consideration. The data at our disposal are not adequate to carefully explore variability on nonseasonal frequencies: Much longer time series are required for a careful examination of interannual variability, and higher-than-monthly frequency of observations is required to adequately resolve the variability on higher-than-seasonal frequencies, the manifestations of which appear in the monthly time series. Our results present observational but qualitative and somewhat speculative evidence of the active role of moisture cycling in determining GE and driving tropical atmospheric circulations on several spatiotemporal scales. Useful work can be done to estimate the quantitative effect of evaporation in conjunction with condensation and moisture dynamics on the tropical circulation systems and GE. Such work would benefit from the interest and participation of the numerical modeling climate community and would, in turn, greatly benefit the evolution of numerical climate models.

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