Process-Based Decomposition of the Global Surface Temperature Response to El Niño in Boreal Winter

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(Manuscript received 24 January 2012, in final form 14 February 2012)

ABSTRACT

This paper reports an attribution analysis that quantifies addible contributions to the observed temperature anomalies from radiative and nonradiative processes in terms of both amplitude and spatial pattern for the two most prominent surface temperature patterns in an El Niño winter. One is the El Niño SST pattern consisting of warming SST anomalies over the eastern equatorial Pacific basin surrounded by cooling SST anomalies in the western and subtropical Pacific, and the other is a tripole surface temperature anomaly characteristic of a positive Pacific–North American (PNA) teleconnection pattern. The decomposition of the observed temperature anomalies is achieved with the coupled atmosphere–surface climate feedback-responses analysis method (CFRAM), which is formulated utilizing energy balance in the atmosphere–surface columns and linearization of radiative energy perturbation.

Out of the mean amplitude of 0.78 K of the El Niño SST pattern, the oceanic dynamics and heat storage term alone contributes to 2.34 K. Water vapor feedback adds another 1.6 K whereas both cloud and atmospheric dynamical feedbacks are negative, reducing the mean amplitude by 2.02 and 1.07 K, respectively. Atmospheric dynamical feedback contributes more than 50% (0.73 K) of the mean amplitude (1.32 K) of the PNA surface temperature pattern. Water vapor and surface albedo feedbacks contribute 0.34 and 0.13 K, respectively. The surface processes, including oceanic dynamics in the North Pacific, heat storage anomalies, and surface sensible/latent heat flux anomalies of ocean and land also contribute positively to the PNA surface temperature pattern (about 0.14 K). Cloud and ozone feedback, although very weak, act to oppose the PNA surface temperature anomaly.

1. Introduction

El Niño–Southern Oscillation (ENSO), the most pronounced mode of air–sea interaction in the tropical Pacific, affects the weather and climate globally and constitutes the main source of interannual variability in the earth’s climate system (e.g., Bjerknes 1969; Philander 1990). Following early efforts of Walker and Bliss (1932), numerous investigations since the late 1960s have painted a vivid picture of the global temperature response to ENSO (e.g., Newell and Weare 1976; Angell 1981; Van Loon and Madden 1981; Pan and Oort 1983; Kiladis and van Loon 1988; Kiladis and Diaz 1989; Halpert and Ropelewski 1992; Larkin and Harrison 2005; Wang et al. 2007). Among the most robust, ENSO-related temperature signals are 1) the in-phase relationship between tropical tropospheric temperature and equatorial Pacific sea surface temperature (SST; Newell and Weare 1976), and 2) the above- (below-) normal temperature in the northern United States/southern Canada (the south-eastern United States) during an El Niño winter that fits to the Pacific–North American (PNA) teleconnection pattern (e.g., Wallace and Gutzler 1981). The nature of the observed temperature response, in other words, the relative contributions of various dynamical and thermodynamic processes to the total temperature anomalies, however, remains largely unexplained.

Lau et al. (1996) first demonstrated that basic structures of water vapor and cloud feedback to underlying...
SST anomalies during active ENSO phases are primarily determined by the basinwide atmospheric circulation response to the SST forcing. Following a similar approach and analyzing the top of atmosphere (TOA) radiation budget, Sun et al. (2003, 2006) conducted systematic evaluations of the strength of the atmospheric radiative and dynamical feedbacks to interannual SST anomalies in the equatorial Pacific cold tongue. They found that the tendency for coupled models to develop a significant SST bias in this region was mainly caused by a model underestimate of the atmospheric negative feedbacks (e.g., cloud albedo and atmospheric energy transport) to the underlying SST anomalies. A recent analysis by Zhang et al. (2011) suggests that warming over the northern United States in an El Niño winter likely results from increases in both the downward solar radiation (due to reductions in both cloud optical thickness and surface albedo) and downward longwave radiation (due to increase in precipitable water). The cooling over the southeastern United States was similarly attributed to reduced solar radiation reaching the surface caused by increased cloud optical thickness. By comparing El Niño and La Niña composites, Zhang et al. (2011) also qualitatively tied the local surface radiation budget to largescale motions in the free atmosphere and thus changes in water vapor convergence and precipitable water.

Despite the results discussed above, we still miss in the literature a comprehensive, quantitative, and global-extent account of the relative contributions of various forcing and feedback processes to surface temperature anomalies in an El Niño winter. The purpose of the present study is to accomplish this task through a process-based decomposition of the observed El Niño surface temperature anomalies utilizing the coupled atmosphere–surface climate feedback-responses analysis method (CFRAM). CFRAM was originally formulated as a new framework, complementing the traditional TOA approach, for evaluating climate feedbacks (Lu and Cai 2009; Cai and Lu 2010). The foundation of CFRAM is the total energy balance (convergence) of longwave (shortwave) radiation flux within individual layers. For all layers above the surface layer, operator $\mathcal{Q}^{\text{non-radiative}}$ is the sum of partial radiative energy flux convergence/divergence perturbations due to individual radiative feedback processes:

$$\Delta E/\partial t = \Delta S - \Delta R + \Delta \mathcal{Q}^{\text{non-radiative}},$$

where $R$ ($S$) is the vertical profile of the net divergence (convergence) of longwave (shortwave) radiation flux within individual layers. For all layers above the surface layer, $\mathcal{Q}^{\text{non-radiative}}$ corresponds to the loss of energy due to surface sensible and latent heat fluxes, as well as the net energy convergence in the entire ocean column if the surface is over ocean. The elements of $\partial E/\partial t$ are the energy storage terms. All terms in Eq. (1) have units of watts per square meter.

By neglecting the interactions among various radiative feedbacks, thus linearizing the radiative energy perturbation, we may express $\Delta S$ and $\Delta R$ as the sum of partial radiative energy flux convergence/divergence perturbations due to individual radiative feedback processes:

$$\Delta S = \Delta S^{(w)} + \Delta S^{(c)} + \Delta S^{(\alpha)} + \Delta S^{(O_3)} \quad \text{and}$$

$$\Delta R = \Delta R^{(w)} + \Delta R^{(c)} + \Delta R^{(O_3)} + \frac{\partial R}{\partial T} \Delta T. \quad (2)$$

In Eq. (2), superscripts $w$, $c$, $O_3$, and $\alpha$ stand for water vapor, cloud, ozone, and surface albedo, respectively. Elements of $\Delta T$ are the temperature differences in each layer between the WPS and the NPS, and $\partial R/\partial T$ is the Planck feedback matrix whose $j$th column corresponds to the vertical profile of the radiative energy flux divergence perturbation due to 1-K warming at the $j$th layer from its NPS temperature profile. We add here that in linearizing radiative energy perturbation, we no longer assume the temperature dependence of various feedbacks, which distinguishes CFRAM from other linearization expansions (e.g., Wetherald and Manabe 1988). Substituting Eq. (2) into Eq. (1), rearranging the terms and multiplying both sides of the resultant equation by $(\partial R/\partial T)^{-1}$, we obtain the following:

$$\Delta T = (\partial R/\partial T)^{-1} \left[ \Delta(S - R)^{(w)} + \Delta(S - R)^{(c)} + \Delta(S - R)^{(O_3)} + \Delta S^{(\alpha)} + \Delta Q^{(\text{atmosdyn})} + \Delta Q^{(\text{oceansyn+storage})} \right]. \quad (3)$$

### 2. Application of CFRAM for feedback analysis of ENSO variability

The foundation of CFRAM is the total energy balance within an atmosphere–surface column at a given horizontal grid point that consists of $M$ atmospheric layers and a surface layer [see Lu and Cai (2009) for more details]. Writing the total energy balance equation separately for a winter state representative of El Niño condition [i.e., a warm-phase state (WPS)] and for a winter state free of ENSO variability [i.e., a neutral-phase state (NPS)] then taking the difference $\Delta$ between the two, we obtain

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where \( \Delta Q_{\text{atmos}} \) is zero at the surface layer, and in the atmosphere layers \( \Delta Q_{\text{atmos}} = -\Delta S - R_{\text{atmos}} \) representing the vertical profile of the energy perturbation in the atmosphere associated with atmospheric motions (including turbulent, convective, and large-scale motions) and heat storage anomalies (which is expected to be very small); \( \Delta Q_{\text{ocean}} = -\Delta S - R_{\text{ocean}} \) is zero in all layers except at the surface layer where it corresponds to the energy perturbation at the surface due to oceanic circulations (if the surface is over ocean), heat storage anomalies, and surface turbulent sensible and latent heat flux anomalies. Based on the linear decomposition principle, Eq. (3) enables us to express the vertical profile of the temperature difference between WPS and NPS in the atmosphere–surface column at a given horizontal location as the sum of the vertical profiles of the partial temperature anomalies due to (from left to right) water vapor feedback, cloud feedback, ozone feedback, surface albedo feedback, atmospheric dynamical feedback, and the surface dynamical/heat storage term.

We adopt the Fu–Liou radiative transfer model (e.g., Fu and Liou 1992, 1993) in the evaluation of the radiative energy perturbation terms and the Planck feedback matrix in Eqs. (2) and (3). Variables required as input to the radiative transfer model, including solar energy fluxes at the top of the atmosphere, air/surface temperatures, specific humidity, ozone mixing ratio, cloud amount, cloud liquid/ice water content, and surface albedo, are all obtained from the European Centre for Medium-Range Weather Forecasts (ECMWF) Re-Analysis Interim (ERA-Interim; Uppala et al. 2008; Dee et al. 2011). ERA-Interim is the latest global atmospheric reanalysis covering the period from 1979 to the present and has a horizontal resolution of 1.5º latitude with 37 pressure levels in the vertical ranging from 1000 to 1 hPa. Composite 3D and 2D fields used in radiative transfer calculation representing the WPS and NPS are constructed with the winter [December–February (DJF)]-averaged data of the ERA-Interim. Based upon the DJF-averaged Niño-3.4 index, a total of seven warm-phase winters (index anomaly greater than one standard deviation) and nine neutral-phase winters (absolute value of the index anomaly less than half of the standard deviation) are identified for the period from 1979 to the present and used in constructing the composites. Finally, given concerns on the use of a time-mean thermodynamic state to calculate time-mean radiative energy perturbation (Kato et al. 2011; Taylor et al. 2011), we have thoroughly validated the use of composite WPS/NPS for radiative transfer calculation by comparing the TOA and surface radiation anomalies calculated “off-line” to those obtained directly from the ERA-Interim.

3. Results

The composite surface temperature difference between the WPS and NPS, representing a canonical El Niño pattern, is shown in Fig. 1a. Signals that are statistically significant at the 90% level include the following: 1) warming (cooling) SST anomalies on the order of \( \sim 2 \) K (\( \sim 1 \) K) in the equatorial central-eastern (equatorial western and subtropical) Pacific; 2) warming with local maxima exceeding 3 K over the contiguous northern United States, Canada, and Alaska; 3) cooling over the eastern North Pacific and southern United States, which, in conjunction with the warming over northern North America, forms a tripole temperature anomaly characteristic of a positive PNA pattern (e.g.,
Wallace and Gutzler (1981); and 4) warming over the tropical Indian Ocean and midlatitude South Pacific and cooling over midlatitude South Atlantic. Figure 1b displays the sum of CFRAM-derived partial temperature anomalies. The high degree of similarity between Figs. 1a and 1b in terms of both spatial pattern and numerical values demonstrates that the linearization of radiative energy perturbation in CFRAM calculation is a reasonable approximation to make.

Figure 2 shows the partial temperature anomalies due to the six thermodynamic and dynamical processes obtained through CFRAM. Along the equatorial Pacific basin, changes in oceanic circulation, turbulent heat fluxes, and heat storage are responsible for an area-averaged cooling of approximately 4.9 K in the west and a warming of approximately 5.2 K from the central to eastern Pacific basin, consistent with shallowing thermocline anomalies in the west, deepening thermocline anomalies, and suppressed upwelling in the east during El Niño (Fig. 2a). The warming in the Pacific cold tongue is further enhanced by a positive feedback of approximately 4 K from water vapor (Fig. 2b) and counteracted by a negative feedback of approximately 6 K from clouds (Fig. 2c). The enhancement of convection over the equatorial central to eastern Pacific and reduction in the western basin results in a negative atmospheric dynamical feedback to the SST anomalies (i.e., suppressing warming anomalies in the cold tongue and cooling anomalies in the...
The significant warming found over the tropical Indian Ocean in WPS (Fig. 1a) is largely related to water vapor feedback (Fig. 2b). The effect of oceanic dynamics (Fig. 2a) on SST in this region is largely compensated by cloud feedback (Fig. 2c). Cloud feedback is also the main contributor to the warming over the midlatitude South Pacific (Fig. 1a), while both atmospheric dynamical feedback and cloud feedback are responsible for surface cooling over the midlatitude South Atlantic. The magnitude of ozone feedback is very small at the surface (Fig. 2e). Albedo feedback is also generally weak except over northern North America (as discussed above) and Antarctica (Fig. 2f).

To quantify the relative contributions of individual processes to both the spatial pattern and mean amplitude of surface temperature anomalies at a given region, beyond the grid-by-grid attribution as done in Fig. 2, we calculate the pattern-amplitude projection (PAP) to the observed temperature anomalies over the area $A$ under consideration from one of the partial temperature anomalies $\Delta T_i$ according to Jiang and Deng (2011) and Cai and Tung (2012):

$$\text{PAP}_i = \frac{A^{-1} \int_A a^2 \Delta T_i \Delta T \cos \phi \, d\lambda \, d\phi}{\sqrt{A^{-1} \int_A a^2 (\Delta T)^2 \cos \phi \, d\lambda \, d\phi}}, \quad (4)$$

where $\phi$ and $\lambda$ are latitude and longitude, respectively; and $a$ is the mean radius of the earth. Because the sum of all $\Delta T_i$ converges to $\Delta T$ as indicated in Fig. 1b, we have that the sum of all of PAP$_i$ converges to the root-mean-square amplitude of the total temperature anomalies over $A$, namely, $\sqrt{A^{-1} \int_A a^2 (\Delta T)^2 \cos \phi \, d\lambda \, d\phi}$.

We have calculated PAPs for two regions indicated by the two boxes in Fig. 1b, where the two most prominent surface temperature patterns in a canonical El Niño winter are observed. The El Niño SST pattern, consisting of warming SST anomalies over the eastern equatorial Pacific basin surrounded by cooling SST anomalies in the west and subtropical Pacific, has a spatial mean amplitude of 0.78 K. The PAP results shown in Fig. 3a indicate that oceanic dynamics and heat storage term alone contributes 2.34 K to the mean amplitude of the El Niño SST pattern. Water vapor provides the strongest positive feedback to the El Niño SST pattern (+1.6 K). Anomalies in cloud field give the strongest negative feedback (−2.02 K) and atmospheric dynamics represents the
second largest negative feedback (−1.07 K). Albedo feedback is also weakly negative (−0.08 K) in this region. In the extratropics, the PNA surface temperature pattern has a spatial mean amplitude of 1.32 K. As seen from Fig. 3b, atmospheric dynamics becomes the main driver of the PNA surface temperature anomaly, contributing more than 50% (0.73 K) to its mean amplitude. In order of decreasing importance, water vapor, oceanic dynamics and heat storage, and surface albedo feedback all act to strengthen the PNA surface temperature pattern by 0.34, 0.14, and 0.13 K, respectively. Over the PNA region, the area where cloud feedback is negative (the southern portion of the region) is slightly larger than the area with positive cloud feedback (the northern portion of the region; Fig. 2c vs Fig. 1a), resulting in a weak negative contribution (−0.006 K) from the overall cloud feedback to the PNA surface temperature pattern. Ozone feedback is also weakly negative (−0.004 K) in this region.

4. Conclusions

This study utilizes a new framework of climate feedback analysis (CFRAM) to isolate contributions from individual radiative and nonradiative dynamical processes to the observed global surface temperature anomalies in a canonical El Niño winter. Using CFRAM-derived partial temperature anomalies in the calculation of pattern-amplitude projection, we conducted an attribution analysis for the two most prominent surface temperature patterns in an El Niño winter: the El Niño SST pattern and the PNA surface temperature pattern. It is found that over the tropical Pacific, water vapor provides the largest positive feedback to the underlying SST anomalies driven mainly by oceanic dynamics and heat storage anomalies. Cloud, followed by atmospheric dynamics, represents the most significant negative feedback over this region. In the extratropics, particularly over the PNA sector, atmospheric dynamics becomes the main driver of the tripole temperature anomaly characteristics of a positive PNA teleconnection pattern. Water vapor and surface albedo feedbacks provide strong positive contributions to the PNA surface temperature anomaly, while cloud and ozone feedback are weakly negative. It is demonstrated here that CFRAM is an efficient “offline” approach for evaluating observed and/or simulated thermodynamic and dynamic processes that are responsible temperature anomalies associated with dominant modes of low-frequency variability in the climate system. It is also important to recognize that the degree of accuracy of the results presented here is constrained by the ERA-Interim data used in the analysis. Biases in the data, particularly those related to clouds, will affect the partitioning of WPS energy perturbations between cloud change and atmospheric–oceanic dynamics in CFRAM. Similar analysis will be conducted in the future with other high-resolution reanalysis such as the National Aeronautics and Space Administration (NASA) Modern Era Retrospective-Analysis for Research and Applications (MERRA) to further understand the contribution of model cloud bias to the overall uncertainty of the results.

Acknowledgments. We thank two anonymous reviewers for their thoughtful comments and suggestions that led to an improved manuscript. The ERA-Interim data used in this study were provided by the European Centre for Medium-Range Weather Forecasts (ECMWF). The Georgia Tech authors (Deng and Park) and FSU author (Cai) were supported by DOE Office of Science Regional and Global Climate Modeling (RGCM) program under Grants DE-SC0005596 and DE-SC0004974, respectively. Cai was also supported by a grant from National Science Foundation (Grant ATM-0833001).

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