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Quantitative Assessment of the Integrated Response in Global Heat and Moisture Budgets to Changing Solar Irradiance

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Earlier, we found time sequences of basin- and global-average upper ocean temperature (that is, diabatic heat storage above the main pycnocline) for 40 years from 1955-1994 and of sea surface temperature for 95 years from 1900-1994 (White, Lean, Cayan, and Dettinger, 1997; White, Lean, and Cayan, 1998) associated with changes in the Sun's radiative forcing on decadal and interdecadal timescales, lagging by 10°-30° of phase and confined to the upper 60-120 m. Yet, the observed changes in upper ocean temperature (~0.1°K) were approximately twice those expected from the Stefan-Boltzmann black-body radiation law for the Earth's surface, with phase lags (0° to 30° of phase) much shorter than the 90° phase shift expected as well. Moreover, White *et al.* (1997, 1998) found the Earth's global decadal mode in covarying SST and SLP anomalies phase locked to the decadal signal in the Sun's irradiance. Yet, Allan (2000) found this decadal signal also characterized by patterns similar to those observed on biennial and interannual time scales; that is, the Troposphere Biennial Oscillation (TBO) and the El Niño and the Southern Oscillation (ENSO). This suggested that small changes in the Sun's total irradiance could excite this global decadal mode in the Earth's ocean-atmosphere-terrestrial system similar to those excited internally on biennial and interannual period scales.

This is a significant finding, proving that energy budget models (that is, models based on globally-averaged radiation balances) yield unrealistic responses. Thus, the true response must include positive and negative feedbacks in the Earth's ocean-atmosphere-terrestrial system as its internal mode (that is, the natural mode of the system) respond in damped resonance to quasi-periodic decadal changes in the Sun's irradiance. Moreover, these responses are not much different from those occurring internally on biennial and interannual period scales.

To begin testing this latter hypothesis, we conducted three studies during the last three years, two descriptive and one theoretical. First, we examined how the Earth's global-average upper ocean temperature on interannual period scales responds to internal perturbations associated with the ENSO (White *et al.*, 2001). We conducted a quantitative assessment of the global average response in the upper ocean heat budget using the National Centers for Environmental Prediction (NCEP) atmospheric reanalysis datasets (Kalnay *et al.*, 1996) and the Scripps Institution of Oceanography (SIO) oceanic reanalysis datasets (White, 1995). This quantitative heat budget study found global-average upper ocean temperature changes of ~0.1°K during ENSO occurring in response to changes in Earth's hydrologic budget (not its radiation budget). It found global-average temperature and moisture content in the troposphere in equilibrium with the underlying ocean, with the time rate of change of global-average temperature in the upper ocean driven by the anomalous exchange of moisture in response to changes in the global wind systems. This demonstrated that Earth's climate system (that is, feedbacks between ocean and atmosphere) could internally generate a global-average temperature response to ENSO.

Second, we demonstrated that the observed decadal mode in covarying SST and SLP anomalies in the Pacific Ocean evolved as predicted by the delayed action oscillator model used to simulate El Niño (Graham and White, 1988), attaining the longer period scale from slower Rossby waves excited farther away from the equator between 15° and 20° latitude (White, Tourre, and Barlow, 2001). This indicates that the Pacific decadal mode behaves very similar in its evolution as the ENSO on interannual period scales. Thus, the fact that the decadal mode is phase locked to changes in the Sun's irradiance

(White *et al.*, 1997, 1998) and the fact that ENSO is able to generate a global-average upper ocean temperature change of similar magnitude from internal mechanisms (White *et al.*, 2001), suggested that the global-average temperature changes on decadal period scales do not arise necessarily from the change in Sun's surface radiative forcing, per se, but as a consequence of the internal mechanisms which accompany the damped-resonant decadal response.

Third, we needed to understand how this Pacific decadal mode could be excited by the decadal signal in the Sun's irradiance. To accomplish this, we utilized a delayed action oscillator model for El Niño (Graham and White, 1988) to determine whether small changes in the Sun's irradiance on decadal period scales could indeed excite this decadal mode (Dettinger and White, 2001). In this model, ENSO is found associated with the dominant natural mode of the Pacific ocean-atmosphere system, excited by white noise in the system. But the decadal mode in this model is only weakly excited by white noise. Yet, when the weak but quasi-periodic surface radiative forcing is applied to the model heat budget on decadal period scales (yielding realistic temperature changes less than expected from white noise), the decadal mode is excited above that expected from white noise. This arises because the Pacific decadal mode is in near-resonance with the decadal signal in the Sun's irradiance. It's magnitude is larger than expected from white noise forcing because the latter is not quasi-periodic, with random phase destroying any chance for a near- resonant response.

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