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# Synoptic and mesoscale controls on the isotopic composition of precipitation in the western United States

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**Abstract** We present a new event-scale catalog of stable isotopic measurements from 5 years of storm events at 4 sites in southern California, which is used to understand the storm to storm controls on the isotopic composition of precipitation and validate the event-scale performance of an isotope-enabled GCM simulation (*IsoGSM*) (Yoshimura et al. 2008). These analyses are motivated to improve the interpretation of proxy records from this region and provide guidance in testing the skill of GCMs in reproducing the hydrological variability in the western US. We find that approximately 40% of event-scale isotopic variability

arises from the percentage of precipitation that is convective and the near surface relative humidity in the days prior to the storms landfall. The additional isotopic variability arises from the fact that storms arriving from different source regions advect moisture of distinct isotopic compositions. We show using both field correlation and Lagrangian trajectory analysis that the advection of subtropical and tropical moisture is important in producing the most isotopically enriched precipitation. The isotopic catalog is then used along with satellite-derived  $\delta D$  retrievals of atmospheric moisture to benchmark the performance of the *IsoGSM* model for the western US. The model is able to successfully replicate the observed isotopic variability suggesting that it is closely reproducing the moisture transport and storm track dynamics that drive the large storm-to-storm isotopic range. Notably, we find that an increase in moisture flux from the central tropical Pacific leads to a convergence of isotopically enriched water vapor in the subtropics and consequently an increase in  $\delta^{18}O$  of precipitation at sites along the entire west coast. Changes in poleward moisture flux from the central Tropical Pacific have important implications for both the global hydrological cycle and regional precipitation amounts and we suggest such changes can be captured through instrumental and proxy-reconstruction of the spatiotemporal isotopic patterns in the precipitation along the west coast of the US.

**Electronic supplementary material** The online version of this article (doi:10.1007/s00382-011-1262-3) contains supplementary material, which is available to authorized users.

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## 1 Introduction

The isotopic composition of precipitation at a given site reflects a summation of remote and local processes that can

affect contributions of moisture from different source locations, rainout along the storm trajectory and conditions that prevail during and after condensation (Dansgaard 1964). Thus, isotopic records capture an integrated record of synoptic and mesoscale atmospheric processes. In tropical and high latitude settings, the complex multivariate signal can often be reduced to a simple univariate linear regression model leading to climate reconstructions from archived precipitation that largely reflect a single climate variable (i.e. temperature in the high latitudes and aridity in the low latitudes). In the polar regions for example, the oxygen and hydrogen isotopic composition of precipitation tracks latitudinal variations in the moisture source, which varies with hemispheric temperatures and consequently allows for reconstructions of broadly regional or even global temperatures from high latitude ice cores (Noone 2008; Jouzel et al. 1987; White et al. 1997). The robustness of high latitude ice core temperature reconstructions is not simply a product of a direct physical relationship between local conditions and the isotopic composition of precipitation but rather arises because the atmospheric overturning circulation, which drives the isotopic variability, is tightly linked with hemispheric temperatures (Hendricks et al. 2000; Kavanaugh and Cuffey 2003). On the contrary, in tropical settings, the inverse relationship between the isotopic composition of precipitation and precipitation amount arises not directly from large scale circulation patterns but more from post-condensational processes (exchange and evaporation) operating on the scale of convective systems (Risi et al. 2008a).

In mid-latitude and subtropical locations the multi-scale influences on the isotopic composition of precipitation do not lend themselves to univariate regression analysis (Alley and Cuffey 2001; Fricke and O'Neil 1999; Sturm et al. 2010). This has consequently led to difficulties in calibrating isotopic records from these regions and therefore a lack of quantitative paleoclimate information that would be a valuable asset in understanding the regional climate variability beyond the instrumental period. Therefore, partitioning the controls on isotopic variability would provide opportunities to develop new records and quantitatively reinterpret existing ones. In this paper we consider this problem with an analysis of the stable isotopic composition of precipitation from southern California by merging results from an isotope-enabled GCM simulation with an extensive catalog of stable isotope measurements from individual storm events.

### 1.1 Background

In the most comprehensive study of the isotopic composition of precipitation from southern California, Friedman et al. (1992) suggested that storm trajectories were likely the leading cause of isotopic variability in precipitation for

this region. These conclusions were based largely on conjecture (by the authors own admission) because the analysis utilized 6-month integrated precipitation samples and thus lacked sufficient resolution to properly explore direct relationships between individual storm trajectories and the isotopic composition of precipitation. Benson and Klieforth (1989) working in the Yucca Mountain region of Nevada and Friedman et al. (2002) working in Utah and Nevada both presented event-scale isotopic values to address the shortcomings of seasonal and monthly sampling. Consistent between these studies was the finding that there is a range of storm to storm variations that is on the order of 20‰ for  $\delta^{18}\text{O}$  and 180‰ for  $\delta\text{D}$ . The wide range of isotopic variability was attributed to two primary factors; trajectory and the depth of atmospheric convection. Friedman et al. (2002) addressed the latter effect (depth of convection), showing that storms associated with high vertical wind shear generated isotopically more-depleted rainfall. Their data loosely fit a Rayleigh curve where the heavier isotopologues of water are preferentially distilled from the vapor phase as the air cools adiabatically upon ascent to higher altitudes. Recently, Coplen et al. (2008) provided a more rigorous test of this idea by making isotope measurements of precipitation collected every 15 min during a single storm that struck the coast of California. The authors observe systematic and synchronous changes in the altitude at which condensation occurs and the isotopic composition of the precipitate. Therefore the within storm variations were argued to reflect changes in condensation temperature.

The findings of Coplen et al. (2008), suggest that each storm is a discrete closed system that has been initialized with a different integrated water vapor (IWV) content. What is neglected in their analysis is a consideration that the moisture advected within the storm likely evolves over time, which influences both the isotopic composition of the original condensate and subsequently the exchange between the falling condensate and the vapor it interacts with during descent. Yoshimura et al. (2010) show with an analysis of the same precipitation event discussed in Coplen et al. (2008), that changes in the isotopic composition of moisture and not temperature are the likely source of isotopic changes within the storm.

The present study is in many ways a continuation of the discussion brought up by the two aforementioned studies by providing a catalog of storms large enough to more thoroughly address whether or not the most important influence on isotopic variability between storms is attributable to differences in the isotopic composition of the moisture source. There have been other event-scale studies for the western US including those by Benson and Klieforth (1989) and Friedman et al. (2002), which have considered this question but these studies were conducted in the Great Basin, which Ingraham and Taylor (1991) have argued

represents a quasi-closed isotopic system. In a closed-basin system, changes in the isotopic composition of water vapor that occur over the Pacific, which arise from variations in sea surface temperatures or from atmospheric circulation changes would have only a secondary influence on the isotope hydrology. This is because significant rainout and mixing with recycled evapotranspired water quickly overwhelm the signature of the initial moisture source (Ingraham and Taylor 1991; Eltahir and Bras 1996). The catalog presented in this study minimizes the role of continental moisture sources by presenting data from locations that are more directly influenced by moisture advected from the Pacific, which allows us to examine how changes in vapor source are manifest in the isotopic composition of precipitation that falls along the west coast of the US. The isotopic composition of IWV at a given location can be estimated using a Lagrangian perspective by solving for a probabilistic geographic region for the moisture source using trajectory analysis (Sjostrom and Welker 2009). The isotopic composition of the moisture originating from from this region can then be estimated if values for sea surface temperature, humidity and surface winds are known and an assumption is made that evaporation takes place in isotopic equilibrium with the sea surface and the vapor diffuses through a saturated boundary layer (Pfahl and Wernli 2008; Craig and Gordon 1965; Wright et al. 2001; Yamanaka et al. 2002). The initial isotopic composition of vapor would be modified following a Rayleigh model, as the vapor both loses and gains water through processes of mixing and rainout (Hendricks et al. 2000; Pfahl and Wernli 2008). Recently satellite and ground-based estimates of the isotopic composition of water vapor have validated the fundamental aspects of this well-accepted model (Frankenberg et al. 2009; Worden et al. 2007; Schneider et al. 2010). Given the inherent spatial and temporal complexities associated with the evolution of the vapor source, isotope-enabled General Circulation Models (GCMs) provide a tool to interpret the cause of isotopic variability that accounts for large scale mixing thus minimizing the reliance on the problematic assumption of a single moisture source region for a precipitation event (Henderson-Sellers et al. 2006; Hoffmann et al. 2000).

The efficacy of a GCM model simulation to capture the distribution of stable water isotopologues throughout the atmosphere depends greatly on its ability to accurately depict the isotopic fractionations that occur during phase changes and then to capture how the water vapor moves through the atmosphere, both vertically and horizontally. The former task has been well constrained and validated with numerous model-empirical inter-comparisons (Hoffmann et al. 2000; Noone and Simmonds 2002; Risi et al. 2010). Yoshimura et al. (2008) were able to improve the representation of atmospheric circulation by predicting

small-scale atmospheric processes with an Atmospheric General Circulation Model while synoptic-scale patterns were fixed to the NCEP Reanalysis II dataset, which has independently been shown to reproduce the synoptic scale patterns that produce the preponderance of precipitation over the western US.

## 1.2 Outline

We present 240 event-scale stable isotope measurements ( $\delta^{18}\text{O}$  and  $\delta\text{D}$ ) for precipitated water that arose from 96 individual storm events that struck southern California between 2001 and 2005. In Sect. 2 of the paper we discuss the analytical and numerical methods employed. In Sect. 3 we present the new isotopic catalog and discuss the correlation between storm to storm isotopic variations and both local and synoptic-scale climate fields. In Sect. 4 we use the isotopic data as well as data from other sources to benchmark the skill of *IsoGSM* for the study region. In Sect. 5 the validated model results are used to further explore how changes in the distribution of water isotopologues over the Pacific basin influence the isotopic composition of precipitation events and in Sect. 6 the results are discussed in light of their significance to retrospective (paleoclimate) studies that derive isotopic values of precipitation from archives such as tree cellulose, groundwater or speleothems. Throughout this study we limit the discussion principally to winter season storms, as we currently have limited data from the summer months. In addition, we focus discussion and results primarily on  $\delta^{18}\text{O}$  as opposed to either  $\delta\text{D}$  or *deuterium-excess* ( $\delta\text{D}-8*\delta^{18}\text{O}$ ), both of which were measured and are available as part of a supplement to the text. This is a deliberate choice, which reflects the fact that the primary existing and emerging stable water isotope proxy records from this region are based on  $\delta^{18}\text{O}$  and it is therefore more pressing at this time to understand the controls on this variable.

## 2 Methods

### 2.1 Analytical methods

Precipitation samples used in the study were provided from the National Atmospheric Deposition Program (NADP) archives. Previous work has shown that the collection and archiving protocol used by the NADP minimizes post-landfall evaporation and thus the samples are suitable for stable isotopic analysis (Harvey 2001; Harvey and Welker 2000; Vachon et al. 2007, 2010; Sjostrom and Welker 2009; Welker 2000). The samples were collected from 2001 to 2005 at four sites in the western US encompassing an area of approximately 500 km<sup>2</sup> (Fig. 1; Table 1). The

water samples were analyzed by continuous flow IRMS using a Thermofinnigan TC/EA and Delta Plus XP mass spectrometer. The 0.5  $\mu\text{l}$  water samples were injected into He carrier gas and carried in vapor form to the TC/EA reduction furnace where the water undergoes a pyrolysis reaction at 1400°C ( $\text{H}_2\text{O} + \text{C} \Rightarrow \text{H}_2 + \text{CO}$ ). The reaction products are separated by a GC column and analyzed directly. Data are corrected using 5 in-house and certified standards. The precision is  $\pm 0.2\text{‰}$  for  $\delta^{18}\text{O}$  and  $\pm 2\text{‰}$  for  $\delta\text{D}$ . The methods closely follow those described in detail by Sharp et al. (2001).

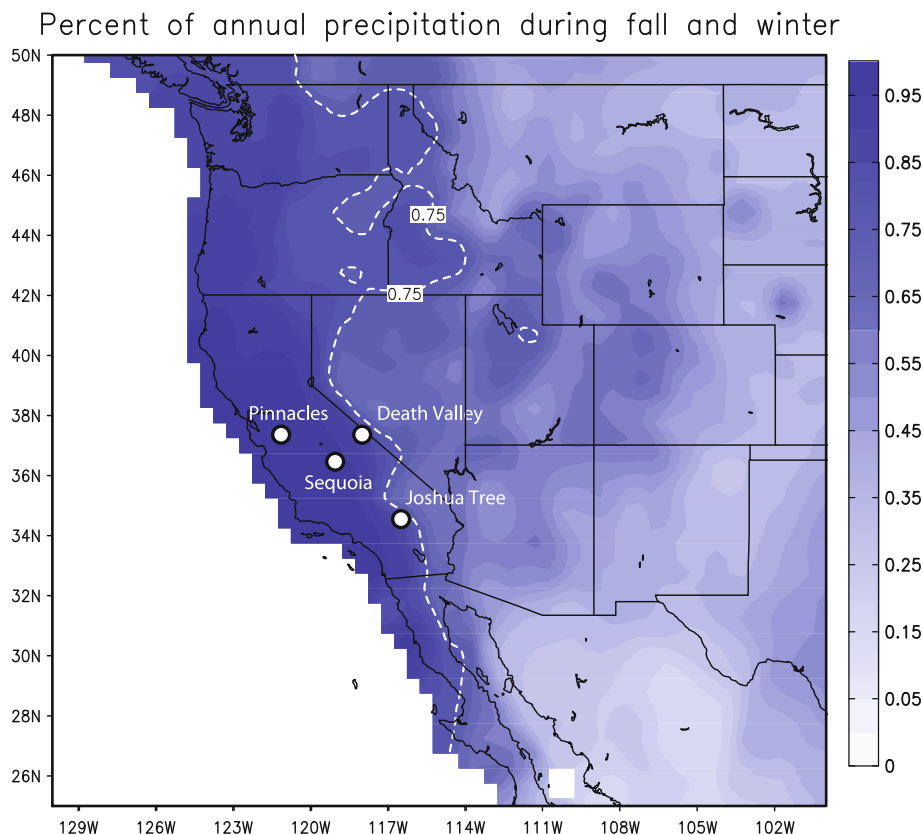
## 2.2 Data analysis

Local controls on the isotopic composition of precipitation events are derived using linear correlation analysis with local climate fields taken from the National Atmospheric Deposition Program's meteorological stations adjacent to each site (precipitation amount), and North American Regional Reanalysis (temperature, convective precipitation rate, relative humidity, potential evaporation and vertical velocity) (Compo et al. 2006). We compute the correlation coefficient between the isotopic composition of precipitation events and global climate fields from the Reanalysis II dataset (latent heat flux, wind fields and moisture fluxes) (Kanamitsu et al. 2002). Following the methods of

Sjostrom and Welker (2009), we perform Lagrangian trajectory analysis to assess probable moisture source regions using the single particle trajectory model, *Hysplit* (Draxler and Rolph 2003). For each precipitation event, an ensemble of 27 back trajectories is initiated with slight deviations of the starting altitude and location to account for the sensitivity of the analysis to initial conditions. We model longitude, latitude and vertical height for air parcels at 6-h time steps for the 72-h period prior to landfall. NCEP-II Reanalysis field are used to force the model. Along each of the trajectories, the change in specific humidity is calculated for each time step to assess where moisture is being added and lost from the air mass. Using changes in specific humidity we generate probable moisture sources for the air mass that made landfall during the precipitation event.

The source of isotopic variability is also interpreted using the *IsoGSM* model outputs from Yoshimura et al. (2008), which provide the isotopic composition for surface waters and atmospheric vapor at 6-h resolution on a  $2.5 \times 2.5^\circ$  global grid from 1979 to 2008. The model yields the isotopic composition of vapor, which has not been systematically measured in this region. The model simulation was generated by fitting isotope tracers into the Experimental Climate Prediction Center's *Global Spectral Model* with prescribed SSTs. The magnitude of isotopic fractionation during all phase changes are taken from

**Fig. 1** Site map showing location of the 4 collection sites used in this study. *Colored shading* is used to denote the fraction of annual precipitation that falls during Fall and Winter months (NDJFM). Precipitation data is from the Climate Prediction Center  $0.25 \times 0.25^\circ$  Daily US Unified Precipitation dataset. The *dotted contour* shows the location where 75% of the precipitation is from Fall and Winter precipitation



**Table 1** List of general isotopic and meteorological characteristics for each site used in this study

Site	# of samples	Altitude (m)	longitude	latitude	NDJFM temp (C)	AMJJASO temp (C)	NDJFM rainfall (mm/month)	AMJJASO rainfall (mm/month)	Average $\delta^{18}\text{O}$	90%	10%	$\delta^{18}\text{O}$ - $\delta\text{D}$ Slope
Sequoia NP	90	1,902	-118.8	36.6	4.8	16.7	142.3	30.7	-11.63	-16.1	-7.2	7.5
Joshua Tree NP	49	1,239	-116.4	34.1	15.1	28.1	10.8	3.5	-10.84	-15.5	-7.4	7.8
Death Valley NP	25	125	-117.0	36.6	14.3	31.3	7.1	2.9	-11.97	-15.8	-3.6	6.7
Pinnacles	80	317	-121.2	36.5	10.8	18.5	66.0	8.4	-7.7	-10.1	-2.3	7.7

Majoube (1971), Merlivat (1978) and Cappa et al. (2003). The model uses a Relaxed Arakawa-Shubert deep convection scheme and evaporation from falling hydrometeors is calculated following Stewart (1975). The simulation was run both in a free mode (only SSTs prescribed) and also nudged to wind and temperature fields from the Reanalysis II Model (Kanamitsu et al. 2002) at a spatial scale of 1,000 km. The nudging procedure follows Yoshimura and Kanamitsu (2008) and is critical for this analysis because it allows for direct comparison between model outputs and historical isotopic observations on event timescales, analogous to previous model validations using monthly-integrated Global Network of Isotopes in Precipitation samples or ice cores (Yoshimura et al. 2008; Schneider and Noone 2007; Lee et al. 2007). We test the influence of the nudging procedure through a comparison between the isotope hydrology produced by the “free” and nudged simulations. While we are primarily concerned with the isotopic fields from the model, we also analyze precipitation rate estimates from the model against satellite-derived precipitation rates as an integrity check that the model provides an accurate representation of the hydrology of the western US. Additional details of the methodology used to generate the model outputs can be found in the original publication (Yoshimura et al. 2008) and additional experiments using a similar numerical approach can be found in Risi et al. (2010).

The performance of the model is validated using an ordinary least-squares regression analysis between the isotopic composition of paired observed and modeled precipitation events. The residual between each modeled and observed event is used to assess the presence of any systematic biases in the model. Additional validations of the isotopic vapor fields from the model were conducted by comparison with satellite-derived (Worden et al. 2007; Frankenberg et al. 2009) and plane measurements (Ehlt 1971) of the  $\delta\text{D}$  of atmospheric vapor. These additional data allow for preliminary benchmarking of the vapor fields, which is not directly feasible from precipitation

fields alone. With respect to all model-observation comparisons presented in this study, we recognize that the spatial resolutions are not directly comparable without downscaling to adjust for the coarse grid of the model. However, as we primarily rely on the model outputs to yield information on large scale moisture transport, this simplification is warranted.

### 3 Results

#### 3.1 Isotopic characteristics

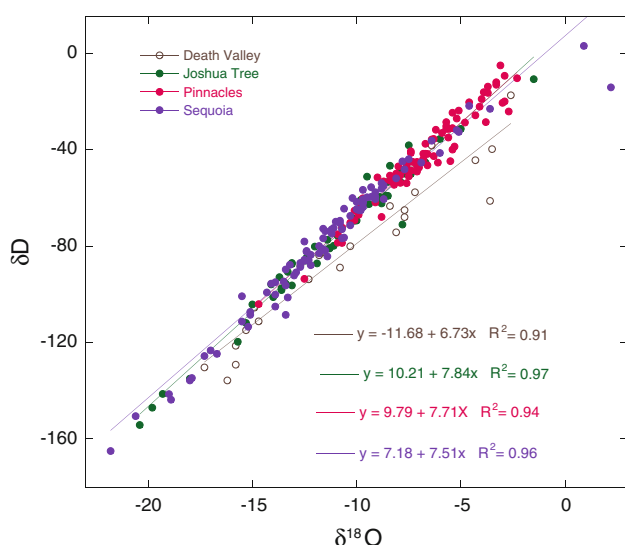
A complete list of isotopic ( $\delta^{18}\text{O}$  and  $\delta\text{D}$ ) measurements along with sampling date, altitude and location is provided in Supplementary Table 1. Although this data represents the only substantial dataset from this region on these timescales, it can be compared to other existing lower resolution studies from the region (i.e. Friedman et al. 1992) to confirm previously reported regional isotope characteristics. The local meteoric water line (LMWL) for each of the sites is presented in Fig. 2. We use the linear regression between these two fields to assess whether samples have experienced substantial evaporation, indicative potentially of evaporation from the sample collector (Harvey 2001). A persistently shallow slope or individual data that fall well below the mean LMWL represent potentially problematic samples (Clark and Fritz 1997). The LMWL at each of the sites is comparable to that of previous studies from the western US (Benson and Klieforth 1989; Friedman et al. 2002; Ingraham and Taylor 1991; Smith et al. 1992) and the slopes are not statistically different between the Sequoia (SEKI), Pinnacles (Pinn) and Joshua Tree (JT) sites. Although we cannot entirely rule out bias associated with evaporation from the precipitation collector at these sites, we infer based on the consistency between the LMWL calculated for these samples and that reported from previous studies that the influence is likely minimal and therefore did not significantly influence the



integrity of samples from the SEKI, PINN or JT sites. However, the slope of the LMWL is notably smaller at Death Valley (DV), which is not unexpected given the extreme aridity at this site. It is not apparent from this analysis alone whether this result indicates substantial rainfall evaporation or whether samples from this site have been adulterated during the collection or archiving procedure.

As noted previously by numerous authors including Friedman et al. (1992) and Feng et al. (2009), there is the presence of a seasonal  $\delta^{18}\text{O}$  cycle with enriched values during the warmer months and depleted values during the cooler months (Fig. 3). However, given the near absence of observations during the arid summer season, we cannot directly assess the amplitude and/or timing of the seasonal cycle. In Fig. 3 we bin the individual data by month and plot the isotopic distribution of events during the course of the year. The data show that the isotopic range of individual events during each of the rainy season months (NDJFM) spans 12–15‰. This observation highlights that sub-seasonal processes operating on time scales of days to weeks produce profound influences on the isotopic composition of precipitation. It is an understanding of these processes that motivate the subsequent analyses in this study. Also shown for comparison in the right panels of Fig. 3, is the seasonal cycle for deuterium-excess, which is poorly defined.

We calculate the isotopic lapse rate of precipitation, which reflects rainout distillation during air mass ascent and the temperature influence on fractionation during condensation. To make this calculation, we use the isotopic difference between synchronous storm events striking the Pinnacles and Sequoia site, which are near to each other



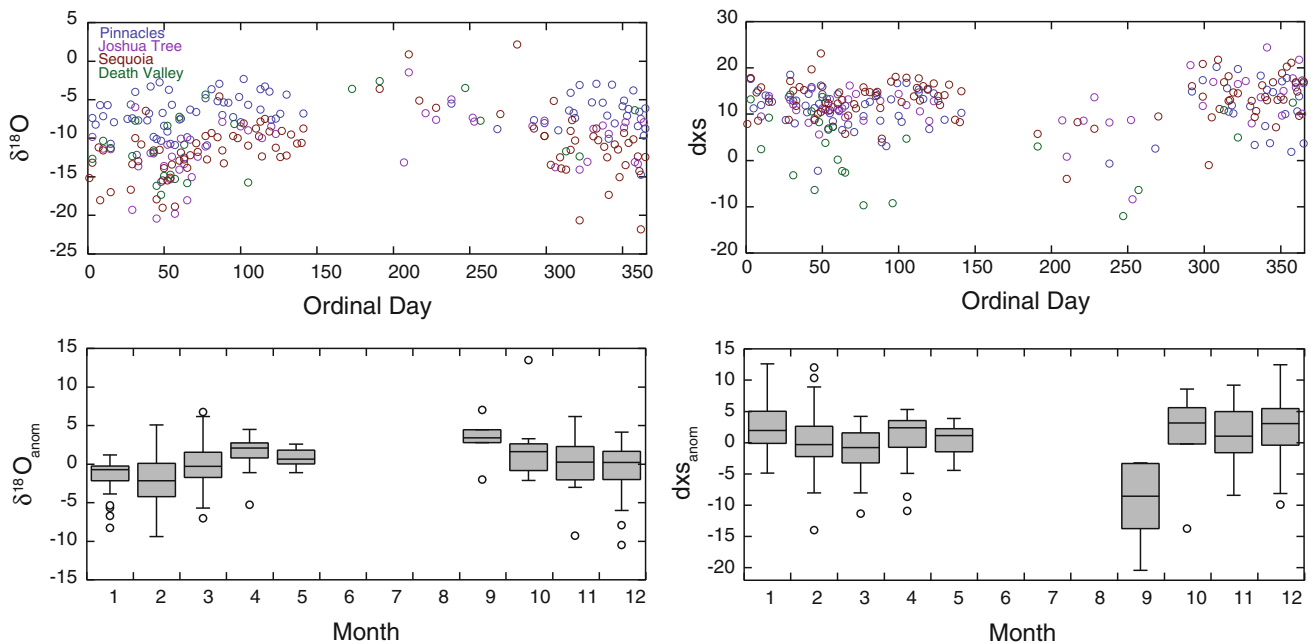
**Fig. 2** Meteoric water line for all data used in this study. Colors delineate the four collections sites

but offset altitudinally by 1,600 m. In order to compare our estimates directly with Friedman et al. (1992), we calculate the  $\delta\text{D}$  lapse rate, which is linearly related to  $\delta^{18}\text{O}$ . For the spring and summer months we estimate a lapse rate of  $-14.3\text{‰}/\text{km}$ , a lapse rate during fall and winter months of  $-37.1\text{‰}/\text{km}$  and a mean lapse rate of  $-25.7\text{‰}/\text{km}$ . These estimates compare favorably with those of Friedman et al. (1992) who reported a winter lapse rate of  $-40\text{‰}/\text{km}$  and a mean lapse rate of  $-22\text{‰}/\text{km}$ , the former being based on a snow transect in the Sierra Nevada Mountains and the latter from their wider network of sites across southeastern California. The seasonal change in isotopic lapse rate primarily reflect the seasonal changes in temperature lapse rate.

### 3.2 Local controls

The individual precipitation samples are correlated against surface temperature, precipitation amount, percentage of convective precipitation and relative humidity prior to precipitation (assumed near saturation during the actual event). We observe a weak correlation with surface temperature and no significant correlation with precipitation amount, consistent with Friedman et al. (1992). A significant positive correlation is observed between the isotopic composition of precipitation and percent convective precipitation and a negative correlation with relative humidity ( $r^2 = 0.36$ ,  $p \leq 0.0001$  and  $r^2 = 0.20$ ,  $p \leq 0.001$ ; respectively). The positive relationship between percentage of convective precipitation and the isotopic composition of precipitation indicate an important role of local meteorological conditions (condensation height, droplet size and velocity) (Coplen et al. 2008; Friedman et al. 2002). The negative relationship between relative humidity prior to precipitation and isotopic composition of precipitation, reflects the influence that precipitation re-evaporation has on the residual precipitate (Risi et al. 2008b). The relative influence of these two variables can account for 39% of the observed intra-storm variance using multiple linear regression analysis (Johnson and Ingram 2004). The response of  $\delta^{18}\text{O}$  to both of these variables is primarily sigmoidal (s-shaped) showing a linear response for isotopic values near the mean of the population but an asymptotic response to these variables during the most enriched and depleted events. Therefore, while the influence of relative humidity and percent convective precipitation is important in explaining a percentage of the variance for the inner range of the dataset, it fails to explain the processes that bring about the isotopic end members.

A similar series of analysis were conducted for deuterium-excess. The results suggest a weakly negative relationship between deuterium-excess and surface temperature and a weakly positive relationship with relative humidity.



**Fig. 3** Left panels  $\delta^{18}\text{O}$  for all data used in this study plotted as a function of ordinal day (top) and binned by month (bottom) with box plots showing the 95th, 75th, median, 25th and 5th percentiles and

dots showing outlier values. Right panels same as left panels except for deuterium-excess

The strength and sign of the correlation coefficients vary considerable between sites, with positive relationships between relative humidity and deuterium-excess at Joshua Tree and Death Valley and a negative relationship at the Pinnacles and Sequoia sites. Interpreting why the sources of deuterium-excess variability differs across such a small region, goes beyond the scope of the study.

### 3.3 Remote controls

Additional processes that influence the isotopic composition, which cannot be accounted for by local meteorological conditions are assumed, following Friedman et al. (1992), to arise from changes in the moisture source between storms (Dansgaard 1964). We conduct a series of field correlation analyses between the isotopic composition of precipitation and latent heat flux and integrated meridional moisture flux (Fig. 4) to assess how synoptic scale circulation influence isotopic variability. The strongest correlation between the isotopic composition of precipitation and these climate fields, appear as a region of positive correlations between the isotopic composition of the precipitate and both latent heat flux and meridional moisture flux stretching on a southwesterly trajectory from the southwestern US to near the Hawaiian Islands.

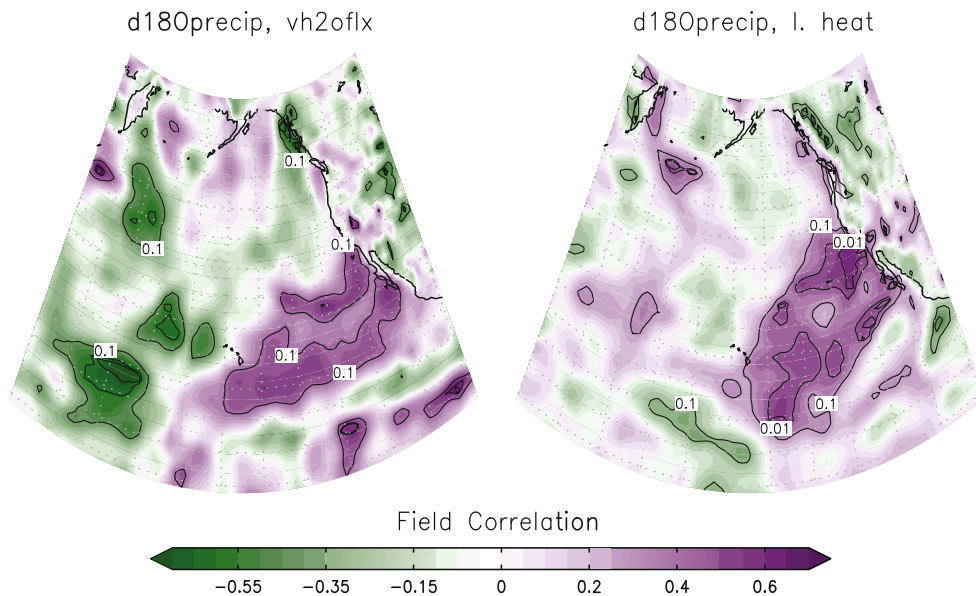
An additional set of experiments are conducted where the most enriched and depleted 10% of events are selected from the entire population and the probable moisture source is calculated using a Lagrangian approach as

outlined in Sect. 2.2. The threshold to delineate the enriched and depleted composites is drawn at the approximate location where the relationship between precipitation  $\delta^{18}\text{O}$  and percent convective precipitation and relative humidity begins to asymptote. This occurs for events that are  $\sim 7\text{‰}$  above or below the mean  $\delta^{18}\text{O}$  value. The enriched and depleted composites therefore represent the section of the population whose variance cannot be explained by local controls. The storms that were used to generate the composite for the Lagrangian trajectory analysis and in the subsequent analyses discussed in Sect. 5.1 are noted as “enriched” and “depleted” in Supplementary Table 1.

In Fig. 5 (top), we show a difference map between air mass origins for the depleted and enriched composites. Each composite was generated by calculating the number of times a trajectory crossed each grid box and then dividing by the total number of trajectories. In this way, we produce air mass origin PDFs that can be compared between composites despite the fact that the number of trajectories used for each was not the same (351 trajectories for the depleted composite and 324 for the enriched composite). The difference map highlights the presence of a source region near  $50^{\circ}\text{N}$  and  $150^{\circ}\text{W}$  for the depleted events and a source region for the enriched composite that follows a southwesterly trajectory stretching from the southwestern US to  $20^{\circ}\text{N}$ . The trajectories associated with the depleted events show considerably more geographic spread, with certain trajectories stretching due west across the entire Pacific Basin and north into the Arctic.

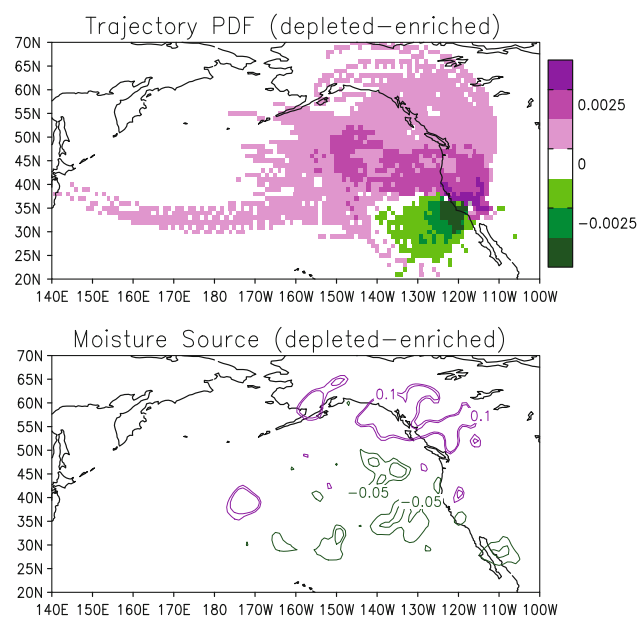


**Fig. 4** Correlation coefficient ( $r$ ) between  $\delta^{18}\text{O}$  of measured events and moisture flux in the v-direction (*left*) and surface latent heat release (*right*). Contour lines indicate the region where  $p$  values for the correlation are  $\leq 0.1$ . Gridded data is from NCEP-II Reanalysis and the isotopic data is from Supplementary Table 1



In the bottom panel of Fig. 5, we show probable moisture sources for the enriched and depleted composites based on changes in specific humidity along each of the trajectories. The result from this analysis is similar to that presented in the top panel of Fig. 5 but creates a distinction in showing not simply the trajectory for each air parcel but distinguishing where the parcel experienced a change in moisture concentration. The difference map highlights moisture sources along the southern coastline of Alaska

and the Yukon and the central Pacific for the depleted events while the moisture sources for the enriched events are spotted along a southwesterly trajectory and in the Gulf of California. Trajectories arriving from the Gulf of California are uncommon and therefore do not appear in the top panel of Fig. 5 due to scaling. However, the few trajectories arriving from this region do experience significant moistening as they pass over this body of water, thus explaining the prominence of this signal in the bottom panel of Fig. 5.



**Fig. 5** Top difference between the air parcel trajectory PDFs associated with the most depleted and enriched events (see text for details). Bottom moisture source differences between the depleted and enriched events based on changes in specific humidity at each time step in the trajectory model

#### 4 Model validation

As shown previously by Yoshimura et al. (2008), *IsoGSM* is able to replicate global precipitation patterns as depicted by the satellite-derived Global Precipitation Climatology Project (GPCP) (Adler et al. 2009). In Fig. 6, we show a comparison between grids from *IsoGSM* and GPCP with the “eastern” region encompassing the Death Valley and Joshua Tree sites and the “western” region encompassing the Sequoia and Pinnacles sites. The geographic distinction is made in order to address the fact that certain storms reaching the western sites fail to reach the inland sites while periodic storms from the Gulf of California or storms arriving along easterly trajectories may only influence the eastern sites. The 5-year daily precipitation timeseries for the two regions from GPCP are well replicated by the model in both regions and indicate a first-order accuracy in the model’s representation of the regional hydrology. Importantly for this study, we did not have a single precipitation event in which we measured its isotopic composition that was not accompanied by a paired rainfall event from the model.

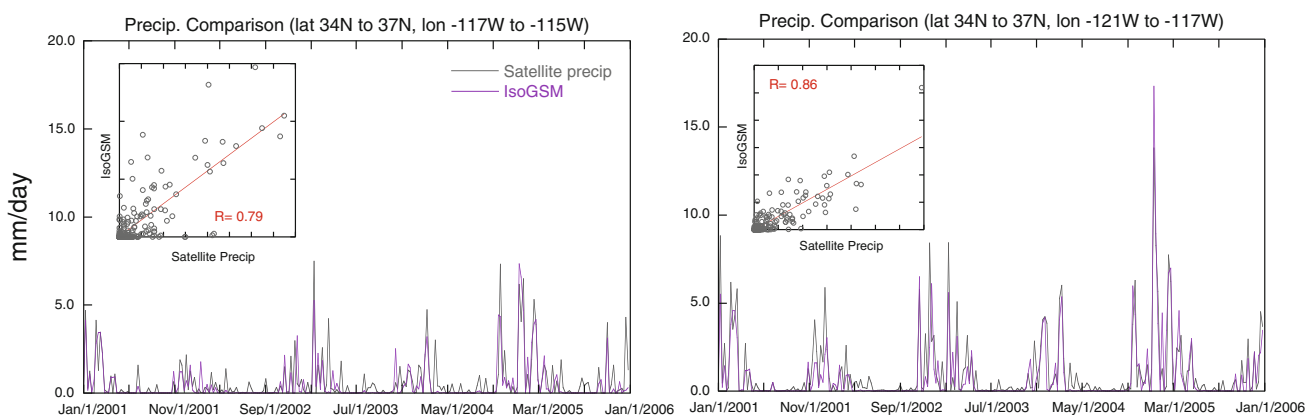
As a test of the influence that spectral nudging has on the model isotope climatology we generate maps of the difference between the isotopic composition of precipitation and vapor from the nudged and free run (i.e. only prescribed SSTs) simulations (Fig. 7). During ONDJFM there are no systematic differences between the isotope hydrology of the free run and nudged simulations in our study region. This implies that while the nudging adjusts the timing of events (i.e. to produce model-observation coupling) it does not produce any real changes in the climatology. With respect to the warmer season months, we do observe notable differences over land where the free run produces more enriched vapor and precipitation. Summer precipitation in the region differs from winter precipitation in that it arises from localized convection (as opposed to large frontal systems), which may be more significantly influenced by the nudging procedure. A larger dataset of summer precipitation and additional vapor isotopic measurements would be useful in addressing the significance of this difference.

As a first benchmark of the *IsoGSM* simulation for the western US we utilize satellite estimates of the  $\delta D$  of atmospheric water vapor from the Scanning Imaging Absorption Spectrometer for Atmospheric Chartography (hereafter SCIAMACHY) aboard ENVIASAT (Frankenberg et al. 2009) and the Tropospheric Emissions Spectrometer aboard the Aura spacecraft (Worden et al. 2006). Retrievals from SCIAMACHY are done in the shortwave infrared, making the measurements most sensitive to moisture in the lower troposphere (Frankenberg et al. 2009). Frankenberg et al. (2009) previously used global averages from these retrievals to diagnose the global isotope hydrology of *IsoGSM*. We use the isotopic data as published with all corrections applied by the original authors and generate a monthly-resolved timeseries for 34°

to 37°N and -115° to 119°W from 2003 to 2005. TES retrievals are done in the thermal infrared and therefore are most sensitive to moisture at  $\sim 600$  hPa (Brown et al. 2008; Worden et al. 2007; Worden et al. 2006). Data spanning 2005–2008 are utilized with corrections applied as specified by the original authors. A timeseries spanning 2005–2008 is generated for the same region as the SCIAMACHY data. Although the current study is concerned primarily with higher frequency (event-scale) signals, the model-satellite comparison is done at monthly timescales to accommodate the spatio-temporal patchiness of the satellite data. The comparison at this time scale thus only serves as a general validation of the model's capacity to replicate regional isotopic vapor characteristics.

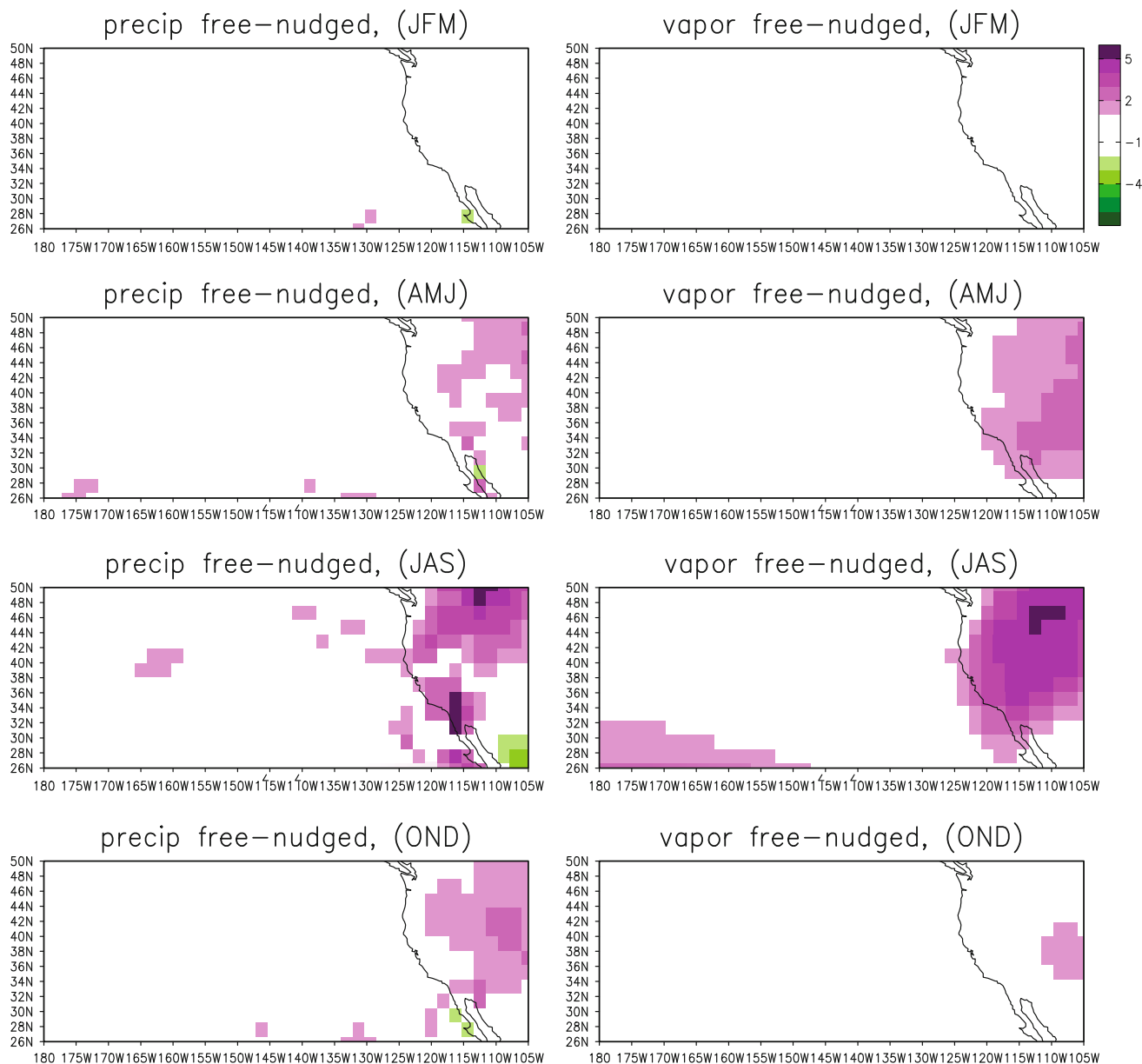
We find the fit between *IsoGSM* and TES is best at the expected 600 hPa level. The model replicates with good skill ( $r = 0.68$ ) the satellite retrievals over the study period (Fig. 8). The fit with SCIAMACHY is best when the model derived monthly vapor fields are integrated between 700 and 800 hPa. This is consistent with the fact that the SCIAMACHY retrievals are more sensitive to moisture at a lower atmospheric height than TES. The model fit with SCIAMACHY is similar in strength to that with TES ( $r = 0.65$ ).

Vertical isotopic lapse rates are determined by using the gradient between the different satellite observations for the same grid cells and from a series of flight measurements from Ehhalt (1971) over the eastern Pacific and Death Valley (Fig. 9). Because none of these measurements were made synchronously, we calculate a seasonal cycle for isotopic lapse rate focussing on the difference between  $\delta D$  of atmospheric vapor at the 800 and 600 hPa levels. The observations show a steep lapse rate during the winter months ( $\sim 30 - 50\text{‰}$ ) and an absence of any gradient during the summer months. The vertical lapse rate of  $\delta D$  in the atmosphere represents the preferential condensation of



**Fig. 6** Timeseries of precipitation from Global Precipitation Climatology Project (Adler et al. 2009) and from the nudged *IsoGSM* simulation (Yoshimura et al. 2008). The inset box shows the correlation between the modeled and observed precipitation. The *left*

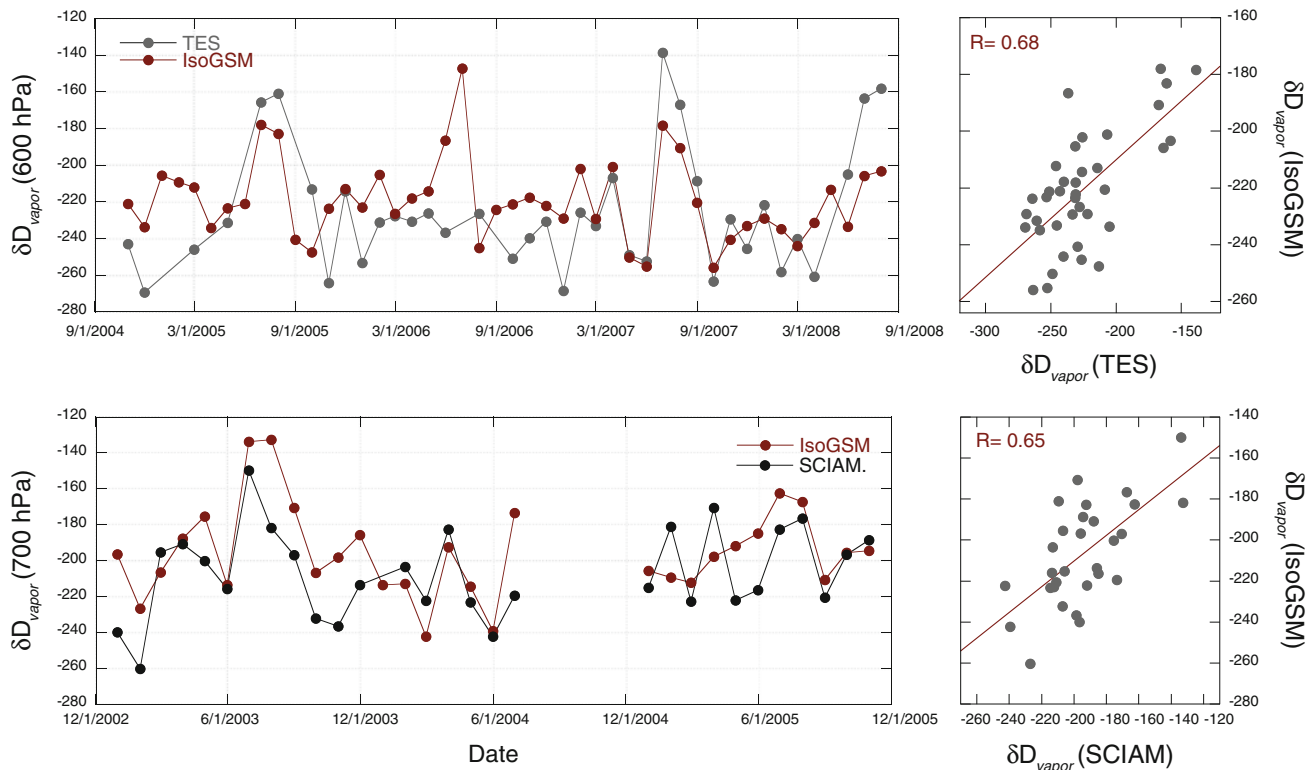
and *right* panels show the area bounded by Death Valley and Joshua Tree and the area bounded by the Pinnacles and Sequoia sites, respectively



**Fig. 7** Difference maps between the seasonal isotope climatology in the nudged and free run *IsoGSM* simulations. *Left panels* are for  $\delta^{18}\text{O}$  of precipitation and *right panels* are for  $\delta^{18}\text{O}$  of integrated water vapor

heavy water molecules as moisture cools and condenses with height (Rozanski and Sonntag 1982; Gedzelman 1988), the steepness of which is modified by exchange between moisture and gaseous water (Rozanski and Sonntag 1982). The steep winter profile is comparable to other global estimates (Rozanski and Sonntag 1982) and the shallowing of the gradient during the summer can be attributed to the drier summer atmosphere (i.e. minimal exchange), and increased vertical transport. An analogous seasonal lapse rate cycle for *IsoGSM* is calculated by subtracting the monthly climatological mean  $\delta\text{D}$  of vapor for the 800 and 600 hpa levels for these same grid cells

(Fig. 9). The observed seasonal lapse rate cycle is well replicated by *IsoGSM*. A curious aspect of Fig. 9 is that the lapse rate derived from the satellite estimates resemble the pattern in Death Valley as measured by Ehhalt (1971) while the model outputs resemble the pattern over the Eastern Pacific. The satellite resemblance of the Death Valley profile may reflect a lack of measurements on cloudy days leading to a lapse rate that looks more like a dry air profile while the model produces a lapse rate that is equally sensitive to moist conditions. Further analysis using *in situ* isotopic measurements would be necessary to further explore this issue.



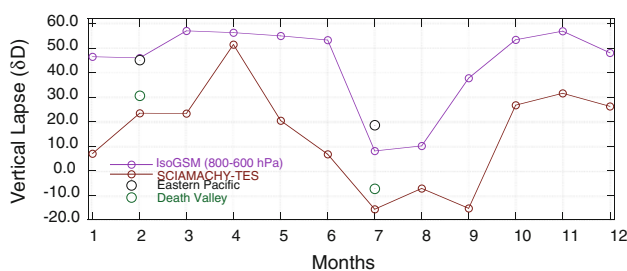
**Fig. 8** Comparison between satellite derived  $\delta D$  fields and IsoGSM modeled values. *Top panel* monthly averaged IsoGSM  $\delta D_{vapor}$  at the 600 hPa level (red) and monthly  $\delta D_{vapor}$  from the Tropospheric Emissions Spectrometer (Worden et al. 2007) (gray) over the region

bounded by the sample sites. *Bottom panel* shows monthly averaged IsoGSM  $\delta D_{vapor}$  integrated between the 700 and 800 hPa (red) level and monthly  $\delta D_{vapor}$  from SCIAMCHY (Frankenberg et al. 2009) over the region bounded by the sample sites

### 4.1 Observed versus modeled values

To validate IsoGSM's ability to accurately depict isotopic variability at an event scale, we compared the measured  $\delta^{18}O$  for each storm event with their model-predicted  $\delta^{18}O$  value. If a measured isotopic value represented precipitation from three consecutive days of precipitation, we identified these three model days and calculated the amount-weighted isotopic value of the total precipitation.

Event-scale sampling produces an episodic dataset and thus this approach is only effective if the model is able to produce isotopic estimates at the correct time that a storm made landfall, which we have shown to be the case in Fig. 6. The only necessary adjustment that is required to compare the model-simulated values with the measured values involve the effects of elevation, which the model's coarse topographic resolution does not resolve well due to the complex orographic nature of the western US. As a consequence, the modeled values are positively offset from the measured values at the two higher altitude sites (Sequoia at 1,902 m and Joshua Tree at 1,239 m, respectively). The magnitude of the mean isotopic offset between modeled and observed values is within uncertainty of that which would be predicted from the isotopic lapse rate of precipitation as discussed in Sect. 2.1 The difference between mean modeled and observed values at the Death Valley and Pinnacles sites are negligible. Cumulative comparisons between paired modeled and measured events are shown for each site in Fig. 10. The fit is highly significant for each site, demonstrating the skill of the model in simulating the observed storm-to-storm isotopic



**Fig. 9** The vertical lapse rate for  $\delta D_{vapor}$  between 800 and 600 hPa level calculated based on satellite retrievals (red), IsoGSM (purple) and by measurements made by Ehhalt (1971) over the eastern Pacific (black) and Death Valley (green)

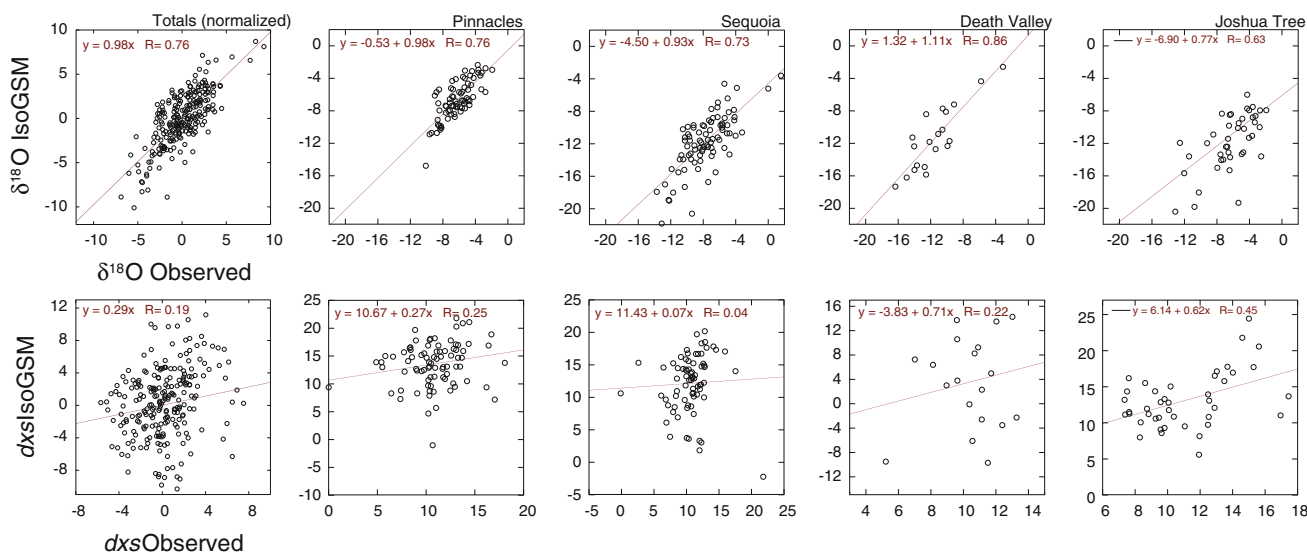
variability. The strongest fit occurs at the Death Valley site, which suggests that the precipitation samples from Death Valley were not significantly influenced by post landfall evaporation from the collector. The cumulative correlation between the isotopic composition of all measured and modeled storm events is high ( $r^2 = 0.58$ ,  $n = 240$ ,  $p \leq 0.001$ ). In the bottom panel of Fig. 10, we show the paired model-observation estimates for deuterium-excess. The fit is considerably worse for this variable, which was previously discussed in Yoshimura et al. (2008). Because deuterium-excess is a second-order parameter, it accumulates small errors in both  $\delta^{18}\text{O}$  and  $\delta\text{D}$ , which may partially account for the degraded fit. However, there may be systematic reasons the model fails to appropriately capture deuterium-excess trends but this is beyond the scope of the current study.

We correlate the residual between each model and measured values against a suite of climatic variables to identify systematic errors in the simulation. For example, does the model produce consistent errors for highly convective events (indicative of non-ideal convective parameterization scheme i.e. (Lee et al. 2009)) or during periods of low antecedent relative humidity (indicate of improperly parameterized rainfall re-evaporation). We find the model-observed residuals are not consistently sensitive to season, precipitation amount, antecedent relative humidity or percentage of convective precipitation (all non-significant correlations coefficients), suggesting the model errors do not arise from a single systematic bias in the numerical formulation. Instead, the model errors arise from the culmination of a suite of stochastic error sources.

## 5 Modeled controls

### 5.1 Synoptic controls

With confidence that the model is accurately reproducing the processes that generate the storm to storm isotopic variability, we employ it to test the hypothesis that moisture sources of distinct isotopic compositions are necessary to generate the end-member isotopic values. We utilize the same events that were used in creating the enriched and depleted composites discussed in Sect. 3.3. For each of the events, a timeseries of areally-averaged precipitation rate was generated from the *IsoGSM* simulation and centered at the time of the precipitation rate maxima (Fig. 11). The precipitation rate for all storms is shown in the middle column of Fig. 11, with the enriched events located in the top row and the depleted events in the bottom row. The storm events included in the two composites, produced the predominance of their precipitation during a period of approximately 24 h ( $4 \times 6$  h time steps). The events were associated with a large range of maximum precipitation rates ( $0.001 \text{ kg}^2\text{m}^{-2}\text{s}^{-1}$ ) but we observe no significant difference between the average rate of precipitation for the enriched ( $0.0032 \text{ kg}^2\text{m}^{-2}\text{s}^{-1}$ ) and depleted ( $0.0036 \text{ kg}^2\text{m}^{-2}\text{s}^{-1}$ ) events. The major difference between the two subset of storms is observable when a time series of the vertically integrated isotopic composition of moisture is calculated. As each storm system approached the western US, there was a sharp change in the isotopic composition of the moisture in the atmospheric column, coincident with the peak of precipitable water (Fig. 11, right and left panels). In the model simulation, the isotopic composition



**Fig. 10** Comparison between all paired measured and modeled precipitation events for  $\delta^{18}\text{O}$  (top) and deuterium-excess (bottom). Each panels includes data from the different sites with the leftmost

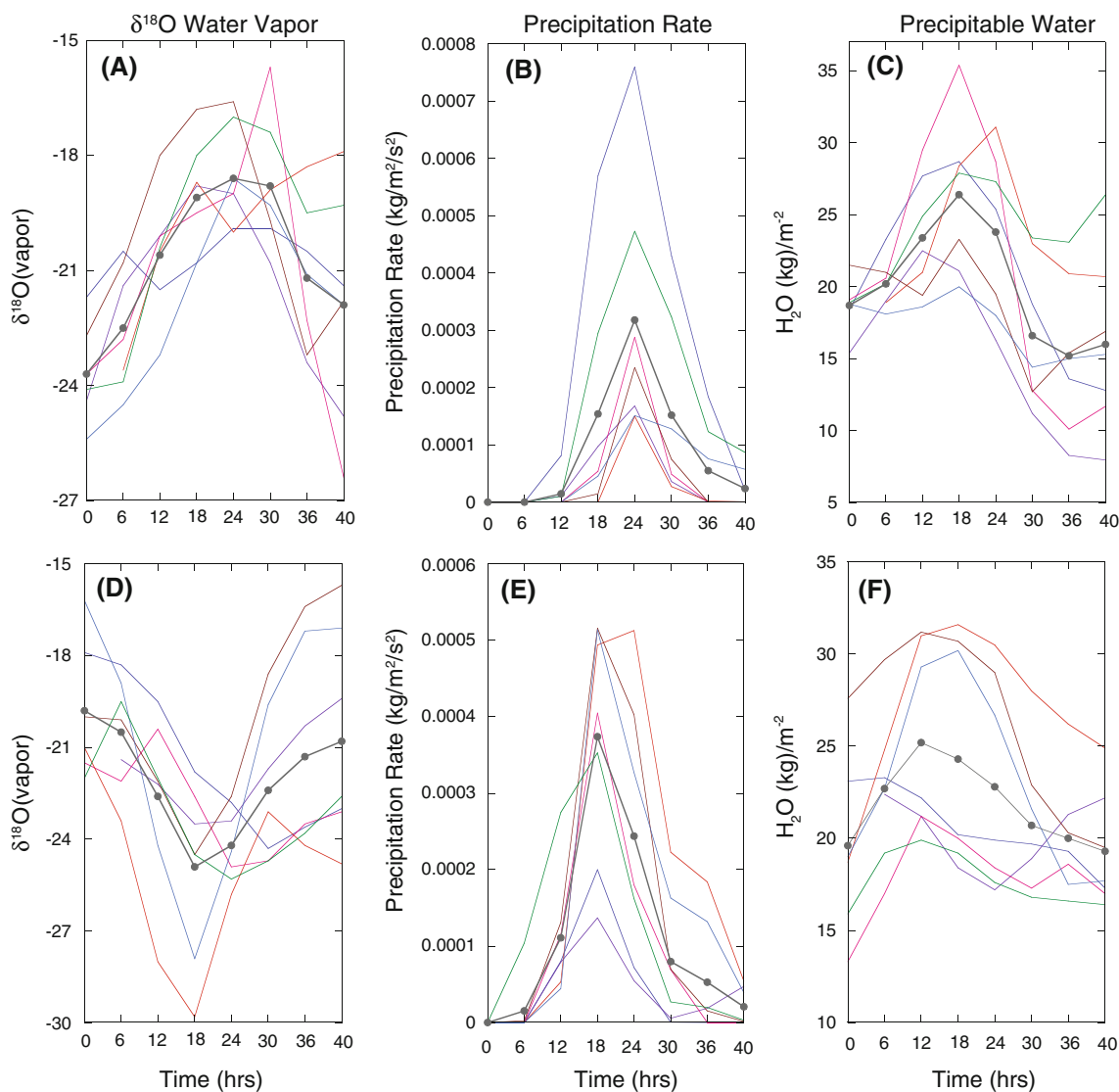
panel showing all event after being set to a mean of 0 for comparison. The red line is the best fit linear model described with the equation on the panel



of the water column rises or falls by as much as 8‰ relative to the background moisture (i.e. prior to and after the storm system passes through). As the precipitation rate fell to zero, the amount of water in the atmospheric column and its isotopic composition returned to their background values (Fig. 11). Coplen et al. (2008) argue that the isotopic variability within precipitation events reflects changes in the temperature at which condensation occurs and thus isotopic values could be driven positive or negative with negligible antecedent changes in the isotopic composition of the integrated water column. The model results shown in Fig. 11 indicate the range of storm to storm isotopic variability reflects a comprehensive isotopic flushing of the

entire water column, not variations in the magnitude of fractionation during condensation.

The convergence of moisture that leads to saturation in the atmospheric column includes vapor derived from a wide radius surrounding the frontal storm center. The isotopic changes in the atmospheric column (Fig. 11, left column) thus track an evolving mixture of moisture composed both of vapor that is entrained into the system directly prior to making landfall (local) and from remote sources that include vapor, which has been transported by the storm system (Trenberth et al. 2003). We consider the significance of this issue by assessing whether there is a difference in local moisture fluxes associated with the



**Fig. 11** Time evolution of  $\delta^{18}\text{O}$  of precipitable water (a, d), precipitation rate (b, e), and Integrated Precipitable Water Content (c, f) during a sequence of enriched (a–c) and depleted (d–f) storms. Details of how events were selected for the composites are found in Sect. 3.3 of the text and events are marked in Supplementary Table 1.

The gray line with dotted markers is the composite times series derived from the mean of the individual time series. Each storm was centered at the precipitation rate maxima and time 0 represents an arbitrary beginning point before precipitation began to fall. All data is taken from *IsoGSM*

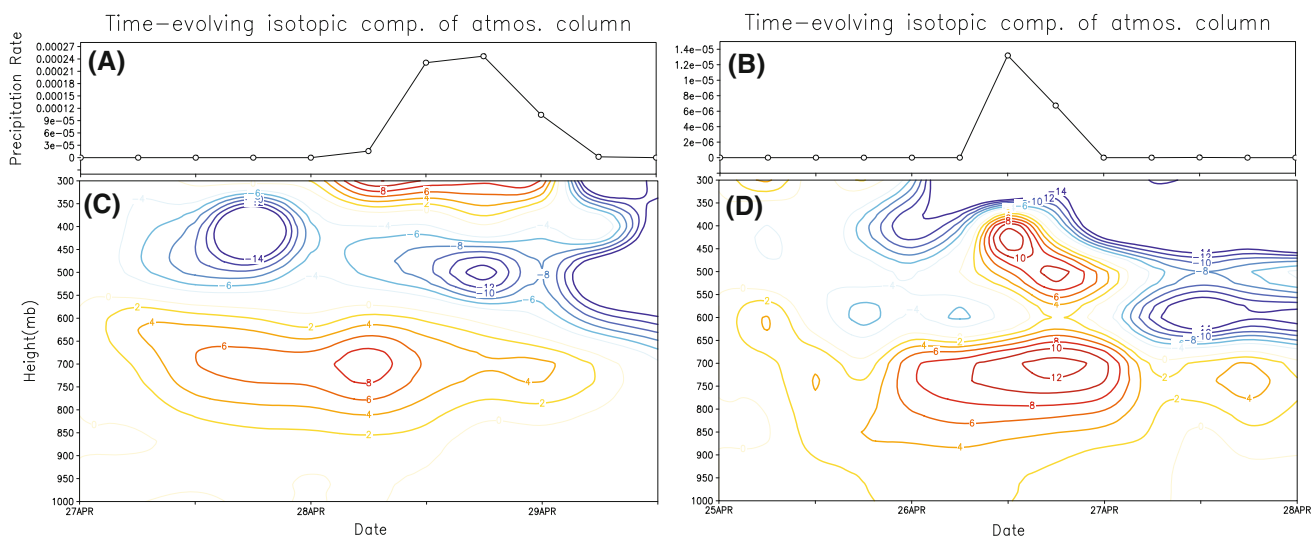


isotopically enriched and the isotopically depleted storms and how wind fields and moisture transport influences the source and relative contribution of remote moisture. In Fig. 4, it is shown that the enriched storm events are associated with higher surface latent heat flux (taken as a proxy for evaporation) just offshore. Thus, a portion of the isotopic difference between the enriched and depleted columns can be attributed to increased evaporation from the underlying local coastal waters prior to landfall. This is consistent with what would be predicted using a Rayleigh distillation model where local (i.e. younger) waters are more isotopically enriched (Dansgaard 1964; Craig and Gordon 1965) and the increased flux of this source would thus shift the column towards more isotopically enriched values.

To distinguish how the locally entrained and the remotely advected moisture influence the storm to storm isotopic differences, the isotopic values of the moisture in the atmospheric column are considered in discrete pressure horizons and we identify the height in the atmospheric column at which isotopic changes were most pronounced for the same composite of enriched and depleted storm events (Fig. 12). The most pronounced isotopic changes occur not along the surface, but rather between the 800 and 700 mb pressure surfaces. The large isotopic changes at these heights reflect moisture that has been advected into the region via winds aloft. This observation is consistent with theoretical discussions in Trenberth et al. (2007) who suggest that up to 70% of the moisture associated with major landfalling storms in the subtropics and mid-latitudes is composed of vapor from distant sources. Similarly, experiments with tagged water molecules in an ensemble of GCM simulations, show that midlatitude cyclones, characteristic of the major rainfall

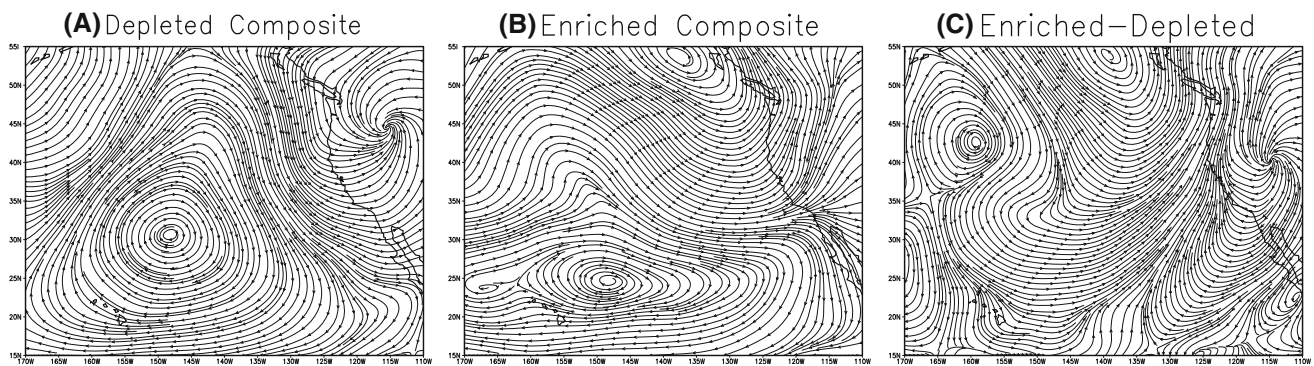
events in the western US, may draw upon moisture from a radius of over  $25^\circ$  latitude (Kelley 2003). Bao et al. (2006) test this idea by looking at moisture convergence and moisture trajectories in a subset of land-falling storms along the west coast of the US and provide evidence for the dominant presence of remote moisture sources in certain landfalling low pressure systems. Thus, based on the magnitude and height at which maximum isotopic changes occur within the atmospheric column and the water-tagging experiments of Kelley (2003) as well as the empirical moisture convergence studies (Bao et al. 2006), we infer that the principal mechanism affecting the storm to storm water column isotope budget is convergence of moisture from distant sources rather than variable moisture flux from local terrestrial or marine surfaces.

In Figs. 13 and 14 we show both the mean prevailing 850 mb wind fields and  $\delta^{18}\text{O}$  of integrated water vapor over the Pacific during the enriched and depleted composite. Isotopically depleted storms are associated with a high pressure anomaly that is centered near  $30^\circ\text{N}$  over the central Pacific (Fig. 13). This generates strong low level northerly flow along the west coast of the US, which advects isotopically depleted moisture from the Aleutian Low region over the southwestern US. This is in clear contrast with the isotopically enriched storms that are characterized by more zonal flow and a high pressure center that is located further south near  $25^\circ\text{N}$  (Fig. 13). By subtracting the composite wind vectors from one another it is evident that anomalous southwesterly flow is characteristic of the most enriched isotopic storm events (Fig. 13). The prevailing southwesterly winds lead to a wide swath of isotopically enriched moisture that stretches from the central Pacific, near Hawaii,

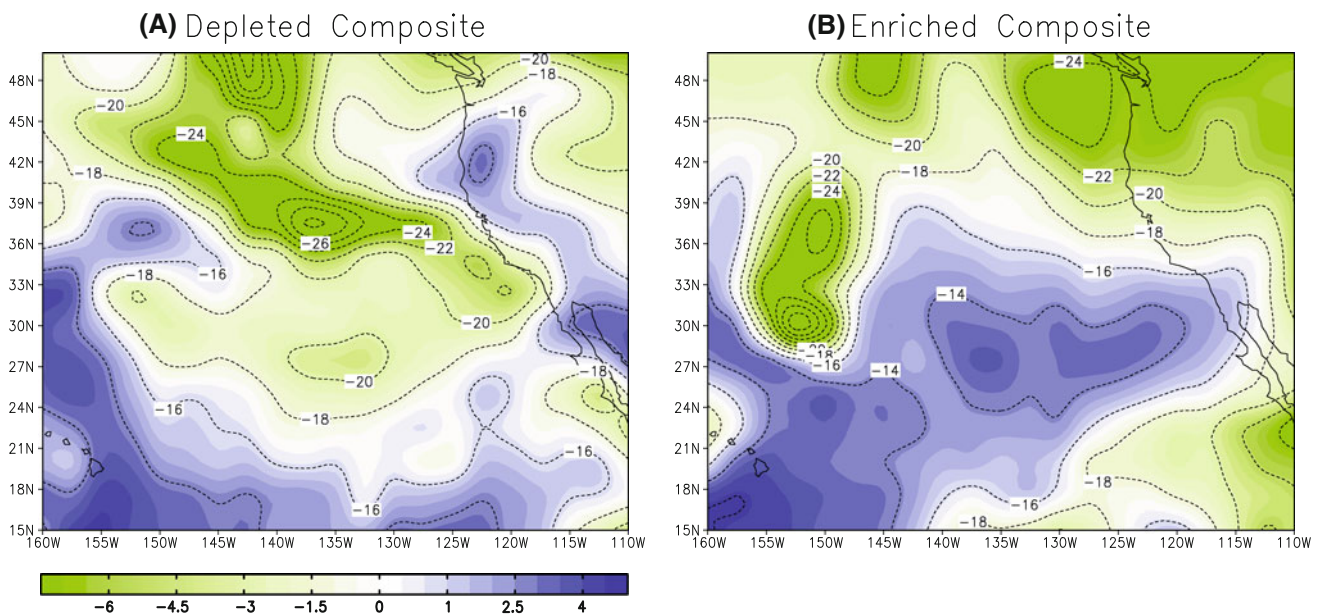


**Fig. 12** Isotopic composition of vapor between the surface and 300 mb level as two enriched storms make landfall. The top (a, b) shows the precipitation rate ( $\text{kg m}^{-2} \text{s}^{-1}$ ) in 6-h time steps while the bottom (c, d) shows the isotopic composition of the vapor ( $\delta^{18}\text{O}$ ) plotted as

an anomaly for each height relative to the vapor prior to the storm making landfall (i.e. “background values”). All data is taken from *IsoGSM*



**Fig. 13** 850 mb wind fields from *IsoGSM* during the most depleted (a) and enriched events (b) and the difference between the two (c)



**Fig. 14** Isotopic concentrations of  $\delta^{18}\text{O}_{\text{vapor}}$  during depleted (a) and enriched (b) events. Water vapor is taken for the 850 mb level. Colors show isotopic anomalies relative to the field in view while contours show absolute isotopic concentration relative to VSMOW

to the southwestern US (Fig. 14). The isotopes provide a tracer of the poleward flux of low latitude moisture and are consistent with the suggestion of Dettinger et al. (2004) that southwesterly storms efficiently import low latitude water vapor to the western US.

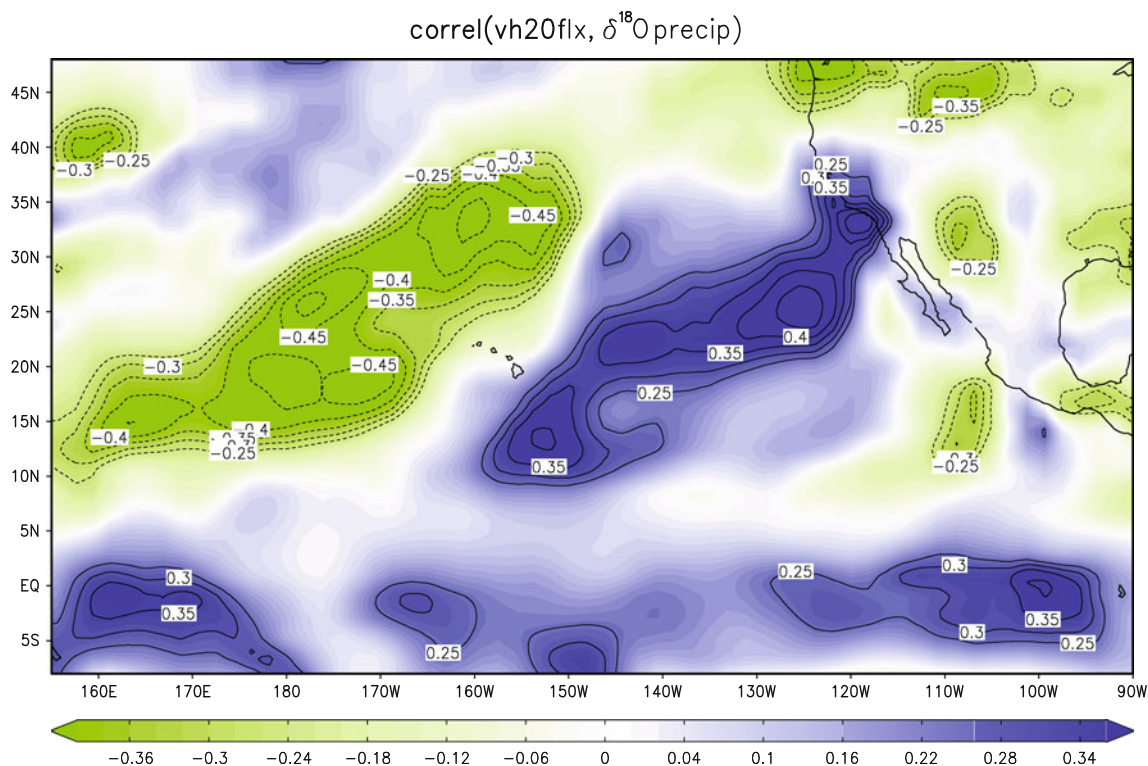
We seek further validation of the isotopic influence of distant moisture sources by calculating the correlation between annually-averaged  $\delta^{18}\text{O}$  of precipitation over southern California from *IsoGSM* and gridded meridional moisture flux. This is an identical analysis to that shown in Fig. 4, except it takes advantage of the longer timeseries available from the *IsoGSM* simulation, which allows for an assessment of whether the relationships inferred on an event-scale are stable on longer timescales (e.g. annually-resolved). Figure 15 shows that meridional moisture flux from across the tropical Pacific is significantly correlated with the isotopic composition of precipitation in southern

California, which suggests this region would be particularly sensitive to ocean-atmosphere changes in this region. In addition, enriched isotopic values also result from increased moisture flux focused along the southwesterly storm track. Figure 15 also shows the presence of negative correlations between  $\delta^{18}\text{O}$  of precipitation and meridional moisture flux on the west side of the Pacific Basin, consistent with the enhanced southerly flow west of  $150^\circ\text{W}$  during depleted storm events as presented in the left panel of Figs. 4 and 13.

## 6 Discussion

### 6.1 Isotopic controls

As has been widely noted (Gedzelman and Arnold 1994; Field et al. 2010; Risi et al. 2008b; Coplen et al. 2008;



**Fig. 15** Correlation coefficient between vertically integrated annual average meridional moisture flux and amount-weighted  $\delta^{18}\text{O}$  of precipitation over the southwestern US ( $-122^{\circ}\text{W}$  to  $-115^{\circ}\text{W}$  and

$32^{\circ}\text{N}$  to  $36^{\circ}\text{N}$ ). Contours indicate correlations that are significant and positive at  $\geq 95\%$  confidence

Lawrence et al. 1982), the isotopic composition of precipitation on event time-scales can be profoundly affected by processes such as condensation height, melting level and relative humidity that influence the magnitude of fractionation during condensation and post-condensational exchange processes. We find evidence of these processes influencing the isotopic composition of precipitation in the western US in the form of significant correlations with the relative humidity near the surface prior to precipitation and the percentage of precipitation that is convective. The former is understood through modeling exercises as arising from rainfall re-evaporation (Dansgaard 1964; Lee and Fung 2008). The positive relationship between  $\delta^{18}\text{O}$  and percent of convective precipitation is surprising as it has been shown in numerous studies that strong vertical ascent and large raindrops (characteristic of strong convection) lead to depleted isotopic values (Lawrence et al. 1982; Bony et al. 2008). However, as noted by Gedzelman and Arnold (1994) and Field et al. (2010), a lowered melting height produces an additionally strong influence by arresting post-condensational exchange processes. The higher melting point associated with convective systems, seems therefore to result in precipitate that is, on average, more enriched.

These local-scale processes, however, are not sufficient to explain the wide range of isotopic values observed

between storms. We call upon the mechanism initially proposed by Friedman et al. (1992), which is the advection of moisture from source regions of distinct isotopic composition, to explain how the isotopic values can reach such a wide range of values. It is shown through Lagrangian trajectory analysis, that precipitation over California, which is most isotopically enriched, arises from storms associated with a large poleward flux of moisture from subtropical and tropical regions and a moisture source that is closer to landfall. These systems differ from the more commonly observed northerly systems, which take a circuitous path around the Gulf of Alaska. The shorter path length between the moisture source and landfall, therefore reduces the amount of distillation and thus the amount of isotopic depletion that is reflected in the precipitation. When the  $\delta^{18}\text{O}_{\text{vapor}}$  fields over the Pacific for the most enriched and depleted events are modeled with atmospheric circulation patterns prescribed, we find evidence of what appear to be plumes of enriched and depleted moisture being advected within the large cyclonic system.

An important byproduct of our diagnosis of the isotopic controls for the western US analysis, is a test of the skill of *IsoGSM* to reproduce the processes that drive storm to storm isotopic variability. While isotopic tracers have shown to be important in testing the representation of the



hydrological cycle in GCM simulations at seasonal or intra-annual timescales, the results presented here illustrate the utility of using isotope tracers for simulations at the event-scale. We find the correlation between observed and modeled isotopic variability to be robust despite the fact that convective processes that entrain water into the storm system and cloud physics are simplified in this type of model (Risi et al. 2008a; Lee et al. 2009). Continued efforts to refine the analytical representation of these processes will undoubtedly improve isotope simulations of this kind, though for regions where moisture convergence is predominately the result of large-scale frontal systems, the major processes appear well-represented. Similar validation exercises using other GCMs would be integral to assessing their relative strengths in representing the hydrological cycle for this region and consequently in their skill at forecasting precipitation changes that are predicted to occur in the region in the coming decades (Seager et al. 2007).

The large cyclonic storms that bring most of the annual winter precipitation to the western US draw on moisture from a wide radius, and thus delineation of a single source region neglects processes operating on larger spatio-temporal scales that influence the distribution of water isotopologues across the Pacific Basin. On a basin-wide scale, low-level meridional moisture flux will enrich the vapor sources across the subtropics and into the mid latitudes. Changes in poleward moisture transport, consequently shifts the average isotopic value of storms more positive. In contrast, an increased vigor of overturning circulation, would deplete the vapor fields across the prevailing trajectory of the storm track and shift the average isotopic value of precipitation towards progressively depleted values.

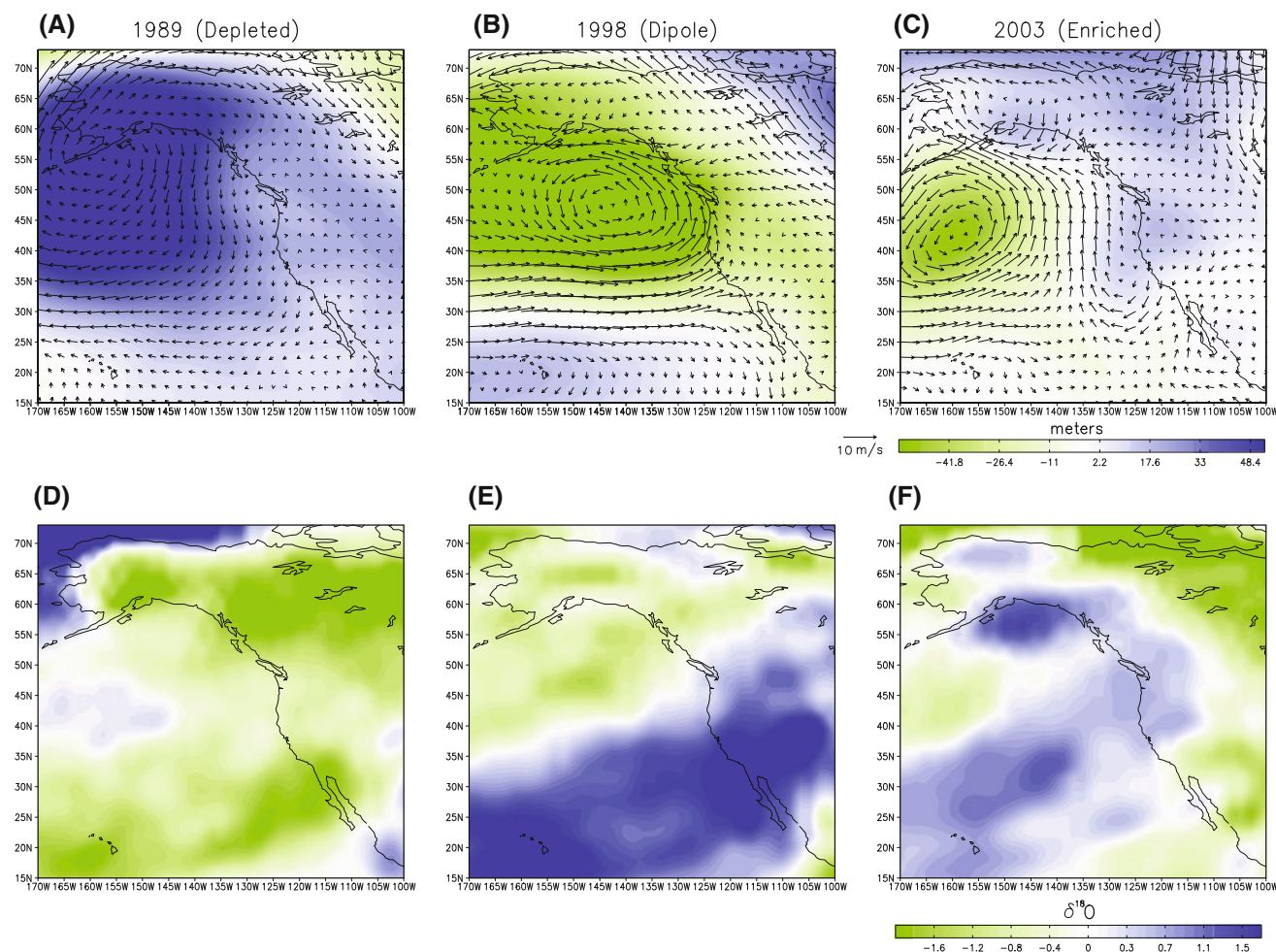
Climate projections for the twenty-first century predict a northward shift in the mid-latitude storm track driven by increased overturning circulation with a slight reduction in the latitudinal temperature gradient (Rind et al. 2001; Yin 2005; Vecchi et al., 2006). If these changes in circulation were acting alone, a poleward shift in the storm track would lead to a reduction in the isotopic composition of precipitation during the twenty-first century for the mid-latitudes by increasing (decreasing) the relative contributions of water from northerly (southerly) storms. However, an increase in the water holding capacity of warmer air over the tropics (Schneider et al. 2010) would tend to enhance poleward moisture transport from the tropics to the extratropics, and could theoretically offset the isotopic impact that would arise from the poleward shift in the storm tracks. To the extent that these changes have already begun, a compilation of isotopic records from subtropical to midlatitude sites would aid in assessing if the hydrological changes in the subtropical high pressure zones as

predicted by GCMs driven with rising greenhouse gas concentration have indeed begun to take place (Seager et al. 2007). For example, rising isotopic values of precipitation in the subtropics and mid latitudes, would indicate that the poleward shift in the storm track is being offset by changes in the poleward moisture flux from the tropical atmosphere. On the contrary, if the isotopic values document a long term decline, this would be consistent with reduced flux of low latitude moisture to the region. Delineating which of these two scenarios is underway is important to decadal-scale regional hydrologic forecasts.

## 6.2 Proxy record

One of the central motivations to study isotopes in precipitation is to link isotopic variability to specific climate states or modes of variability for the purposes of calibrating paleoclimate records. When we consider the multiple competing influences on the isotopic composition of precipitation along the west coast of the US, it is clear that caution must be exercised in how best to interpret isotopic variability from this region. We find that the processes, which influence the isotopic values between storms are operating on a multitude of scales and display non-linear behavior. It is therefore simply not feasible to look at isotopic changes at a single site and make a definitive assessment of the climatic origin of the signal. A preliminary approach to overcome this challenge, would be to utilize spatiotemporal isotopic patterns across the west coast by integrating multiple records. This could theoretically be used to deconvolve processes that are local (i.e. percent convective precipitation) from synoptic to basin-scale changes.

An example of how this could be applied is illustrated in Fig. 16, where enriched (depleted) isotopic values occur across the entire west coast of the US in years with a strong (weak) and westward shifted Aleutian Low and anomalous southerly (northerly) flow (Fig. 16, left and right panels) while an isotopic dipole pattern emerges, with enriched values south of 45°N during years when there is a deep and eastward Aleutian Low and anomalously strong Westerly winds (Fig. 16, center panel). Therefore, a latitudinal transect of proxy reconstructions from along the western US could be used to delineate between paleo-circulation patterns that generate basinwide or dipole-like patterns. The interpretation of isotopic variability in western North America in terms of specific atmospheric “modes” was suggested by Birks and Edwards (2009) who find that the Pacific North American pattern (a leading mode of low frequency pressure anomalies over the North Pacific) is a good predictor of isotopic values in central Canada. Their approach shows the strong isotopic response across Canada to this established climate mode. Because the Pacific North



**Fig. 16** Average annual 850 mb geopotential height (m) and wind vector anomalies from NCEP II Reanalysis (Kanamitsu et al. 2002) during 1989, 1998 and 2003 (a–c) and the isotopic anomalies in precipitation from *IsoGSM* associated with these same years (d–f)

American pattern has such well-documented teleconnection patterns, it is an attractive target for paleoclimate reconstruction as its variability in time yields considerable information on the global climate system. Longer isotopic simulations that would sufficiently capture multiple cycles of decadal climate modes, would allow for more rigorous approaches to defining spatial isotopic patterns and test whether isotopic modes are truly analogous to climate modes defined through SLP or SST patterns. For example, Field (2010) shows that the isotopic composition of precipitation over Europe appears related to a “NAO-like” mode but with centers of action that are in fact distinct than those defined strictly through SLP patterns. Because there are few long observational isotopic datasets available, these calibration exercises will ultimately require well-validated isotope models that can be used to generate longer isotope climatologies.

Reconstructions of such isotopic modes that stretch beyond the instrumental period would provide information about atmospheric circulation that is potentially distinct and

complementary to climate reconstructions based on surface climate conditions (i.e. precipitation amount or temperature). For example, there is an outstanding debate regarding whether cool conditions in the tropical Pacific were responsible for each of the megadroughts that affected the western US during the Medieval Climate Anomaly (Cook et al. 2007; Graham et al. 2007; Herweijer et al. 2006; Conroy et al. 2009). Because of the observed sensitivity between isotopes and moisture flux from the central tropical Pacific, a critical test of the driver of these droughts would be though a characterization of the isotopic patterns that prevailed during these prolonged arid episodes.

There are a handful of existing and emerging isotopic records from the western US that can be evaluated in light of these findings. High resolution isotopic records from ice cores in the north Pacific (Fisher et al. 2004), lake sediments from the Yukon (Anderson et al. 2005) and from tree-ring cellulose in southeastern California and western Canada (Edwards et al. 2008) all document negative  $\delta^{18}\text{O}$  shifts at the end of the Little Ice Age (LIA) (nominally AD

1850), coincident with rising northern hemispheric temperatures, slackening trade winds and the jet stream migrating poleward (Zhao and Moore 2006; Mann et al. 2009). If we consider the isotopic patterns depicted in Fig. 16, it would suggest the LIA was associated with enhanced meridional moisture flux relative to the twentieth century and a persistently strong Aleutian Low system. The isotopic variability in the proxy records are large relative to the isotopic anomalies depicted in Fig. 16, which potentially implies a close coupling between local *in situ* storm processes and larger scale climatic behavior that influences not only the mean atmospheric circulation (large scale overturning) but also the regional-scale behavior associated with storm track trajectories.

## 7 Conclusions

This study presents a new catalog of 240 isotopic measurements from individual storm events striking four sites in the western US between 2001 and 2005. The new catalog supplements existing monthly and seasonal records from the region by highlighting the large isotopic changes in precipitation that occur on daily to weekly timescales. We used the storm to storm isotopic variability to (1) understand the isotopic controls on regional precipitation and (2) provide a test of the skill of the Experimental Climate Prediction Center's isotope-enabled Global Spectral Model *IsoGSM* for the western US. With respect to the latter, through a comparison between paired model and observed isotopic values from both precipitation and satellite observations of atmospheric vapor, we show the model largely reproduces the isotopic patterns for the region. This suggests that, to a first order, the model is reproducing the moisture transport processes associated with large frontal storms that constitute most of the annual water budget across the southwestern United States. Through the analyses conducted in this study, we were not able to identify any systematic sources of bias in the model, but rather, it appears that instances when the model fails to reproduce observations arise from a number of possible error sources. Additional experiments using different atmospheric fields for the nudging procedure, convective parameterizations schemes (Lee et al. 2009) or in the representation of rainfall evaporation (Field et al. 2010) would all be useful to diagnose ways to improve the model skill.

Using regression analysis between observed isotopic and climate fields and modeled isotopic and climate fields, we find that some of the observed isotopic variability arises from processes that influences condensational (percent convective precipitation) and post-condensational isotopic exchange (relative humidity) while the additional source of variability is attributable to changes in the isotopic

composition of moisture that is advected within the storm system. Southwesterly storms are associated with the most enriched isotope values, as they draw isotopically enriched low latitude moisture poleward. Storms drawing on moisture from the northern Gulf of Alaska are associated with the most depleted events. We conjecture through an analysis of the model simulation, that additional isotopic variability arises because of changes in the distribution of water isotopologues across the Pacific basin in response to increased meridional and vertical moisture flux. Nonetheless, it is the distinctive difference in isotopic composition between low and high latitude atmospheric moisture that provides the dominant control on the isotopic values of wintertime rain and snow that falls over the western US.

Isotopic changes in the moisture over the western US could therefore be used to distinguish different atmospheric processes that influence the regional moisture budget. For example, despite model to model discrepancies in how the tropical ocean-atmosphere system responds to increased radiative forcing, the consensus result is a drying of the subtropical high zones during the twenty-first century (Seager et al. 2007). If rising specific humidity is synchronous and paced with dynamical changes in poleward eddy-driven moisture transport from the tropics, then the rate and severity of twenty-first century drying across the subtropical high pressure zones could be more (or less) than predicted from GCM simulations. Modern and proxy reconstructed records of  $\delta^{18}\text{O}$  can be used to investigate how these two competing processes have varied in the past in response to different modes of ocean and atmospheric variability. However, because the isotopic response of precipitation to climate forcing is non-linear and operating on multiple scales, interpreting isotopic records from the region requires a conservative approach. Analyses that integrate multiple records to provide both spatial and temporal isotopic information would therefore be the most useful in providing quantitative information on paleo-circulation patterns.

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