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Description Predicts the occurrence times (in day-of-year) of spring phenological events. Three methods, including the accumulated degree days (ADD) method, the accumulated days transferred to a standardized temperature (ADTS) method, and the accumulated developmental progress (ADP) method, were used. See Shi et al. (2017a) <doi:10.1016/j.agrformet.2017.04.001> and Shi et al. (2017b) < tails.

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Contents

`ADD` *Function for Implementing the Accumulated Degree Days Method Using Mean Daily Temperatures*

Description

Estimates the starting date (S, in day-of-year) and base tempeature (T_0, in °C) in the accumulated degree days method using mean daily air temperatures (Aono, 1993; Shi et al., 2017a, b).

Usage

```
ADD(S.pd = NULL, T0.arr, Year1, Time, Year2, DOY, Temp, DOY.ul = 120,
    fig.opt = TRUE, S.def = 54, verbose = TRUE)
```

Arguments

`S.pd`	the pre-determined starting date for thermal accumulation (in day-of-year)
`T0.arr`	the candidate base temperatures (in °C)
`Year1`	the vector of the years in which a particular phenological event was recorded
`Time`	the vector of the occurrence times (in day-of-year) of a particular phenological event across many years
`Year2`	the vector of the years recording the climate data corresponding to the occurrence times
`DOY`	the vector of the dates (in day-of-year) for which climate data exist
`Temp`	the mean daily air temperature data (in °C) corresponding to `DOY`
`DOY.ul`	the upper limit of `DOY` used to predict the occurrence time
`fig.opt`	an optional argument to draw the figures associated with the determinations of the starting date and base temperature, and a comparison between the predicted and observed occurrence times
`S.def`	a mandatory defintion of the starting date when (i) `S.pd` is NULL and (ii) the minimum correlation coefficient method fails to find a suitable starting date
`verbose`	an optional argument allowing users to suppress the printing of computation progress

Details

The default of `S.pd` is NULL. In this case, the date associated with the minimum correlation coefficient [between the mean of the mean daily temperatures (from a candidate starting date to the observed occurrence time) and the observed occurrence time] will be determined to be the starting date on the condition that it is smaller than the mininum phenological occurrence time. If the determined date associated with the minimum correlation coefficient is greater than the mininum phenological occurrence time, `S.def` will be used as the starting date. If `S.pd` is not NULL, the starting date will be directly set as `S.pd` irrespective of the minimum correlation coefficient method and the value of `S.def`. This means that `S.pd` is superior to `S.def` in determining the starting date.

The function does not require that `Year1` is the same as `unique(Year2)`, and the intersection of the two vectors of years will be kept. The unused years that have phenological records but lack climate data will be showed in `unused.years` in the returned list.

The numerical value of `DOY.ul` should be greater than or equal to the maximum `Time`.

Value

`S.arr`	the candidate starting dates (in day-of-year), whose default ranges from the minimum `DOY` to min(`DOY.ul`, the maximum `DOY`)
`cor.coef.arr`	the candidate correlation coefficients between the mean of the mean daily tempertures (from a candidate starting date to the observed occurrence time) and the observed occurrence time
`cor.coef`	the minimum correlation coefficient, i.e., min(`cor.coef.arr`)
`search.failure`	a value of 0 or 1 of showing whether the starting date is successfully determined by the minimum correlation coefficient method when `S.pd = NULL`, where 0 represents success and 1 represents failure
`mAADD.arr`	an vector saving the interannual mean of the annual acccumulated degree days (AADD) values for each of the candidate base temperatures
`RMSE.arr`	a vector saving the candidate root-mean-square errors (in days) between the observed and predicted occurrence times for each of the candidate base temperatures
`AADD.arr`	the annual accumulated degree days (AADD) values in different years
`Year`	The overlapping years between `Year1` and `Year2`
`Time`	The observed occurrence times (day-of-year) in the overlapping years between `Year1` and `Year2`
`Time.pred`	the predicted occurrence times in different years
`S`	the determined starting date (day-of-year)
`T0`	the determined base temperature (in °C)
`AADD`	the expected annual accumulated degree days
`RMSE`	the smallest RMSE (in days) from the different candidate base temperatures
`unused.years`	the years that have phenological records but lack climate data

Note

The entire mean daily temperature data set for the spring of each year should be provided. `AADD` is represented by the mean of `AADD.arr` in the output. When the argument of `S.pd` is not `NULL`, the returned value of `search.failure` will be `NA`. When the argument of `S.pd` is `NULL`, and the minimum correlation coefficient method fails to find a suitable starting date, the argument of `S.def` is then defined as the determined starting date, i.e., the returned value of `S`. At the same time, the returned value of `cor.coef` is defined as `NA`.

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References

Aono, Y. (1993) Climatological studies on blooming of cherry tree (*Prunus yedoensis*) by means of DTS method. *Bulletin of the University of Osaka Prefecture. Ser. B, Agriculture and life sciences* 45, 155−192 (in Japanese with English abstract).

Shi, P., Chen, Z., Reddy, G.V.P., Hui, C., Huang, J., Xiao, M. (2017a) Timing of cherry tree blooming: Contrasting effects of rising winter low temperatures and early spring temperatures. *Agricultural and Forest Meteorology* 240−241, 78−89. doi:10.1016/j.agrformet.2017.04.001

Shi, P., Fan, M., Reddy, G.V.P. (2017b) Comparison of thermal performance equations in describing temperature-dependent developmental rates of insects: (III) Phenological applications. *Annals of the Entomological Society of America* 110, 558−564. doi:10.1093/aesa/sax063

See Also

predADD

Examples

```
data(apricotFFD)
data(BJDAT)
X1 <- apricotFFD
X2 <- BJDAT

Year1.val  <- X1$Year
Time.val   <- X1$Time
Year2.val  <- X2$Year
DOY.val    <- X2$DOY
Temp.val   <- X2$MDT
DOY.ul.val <- 120
T0.arr0    <- seq(-5, 5, by = 0.1)
S.pd0      <- NULL


  res1 <- ADD( S.pd = S.pd0, T0.arr = T0.arr0, Year1 = Year1.val, Time = Time.val,
               Year2 = Year2.val, DOY = DOY.val, Temp = Temp.val,
               DOY.ul = DOY.ul.val, fig.opt = TRUE, S.def=54, verbose = TRUE )
  res1
```

```
S0 <- res1$S.arr
r0 <- res1$cor.coef.arr

dev.new()
par1 <- par(family="serif")
par2 <- par(mar=c(5, 5, 2, 2))
par3 <- par(mgp=c(3, 1, 0))
plot( S0, r0, cex.lab = 1.5, cex.axis = 1.5, xlab = "Candidate starting date (day-of-year)",
      ylab="Correlation coefficient between the mean temperature and FFD", type="l" )
ind <- which.min(r0)
points(S0[ind], r0[ind], cex = 1.5, pch = 16)
text(S0[ind], r0[ind] + 0.1, bquote(paste(italic(S), " = ", .(S0[ind]), sep = "")), cex = 1.5)
par(par1)
par(par2)
par(par3)

resu1 <- ADD( S.pd = 47, T0.arr = seq(-10, 0, by = 0.1), Year1 = Year1.val, Time = Time.val,
              Year2 = Year2.val, DOY = DOY.val, Temp = Temp.val,
              DOY.ul = DOY.ul.val, fig.opt = TRUE, S.def = 54, verbose = TRUE )
resu1

# graphics.off()
```

`ADD2` *Function for Implementing the Accumulated Degree Days Method Using Minimum and Maximum Daily Temperatures*

Description

Estimates the starting date (S, in day-of-year) and base tempeature (T_0, in °C) in the accumulated degree days method using minimum and maximum daily air temperatures (Aono, 1993; Shi et al., 2017a, b).

Usage

```
ADD2(S.pd = NULL, T0.arr, Year1, Time, Year2, DOY, Tmin, Tmax,
     DOY.ul = 120, fig.opt = TRUE, S.def = 54, verbose = TRUE)
```

Arguments

`S.pd`	the pre-determined starting date for thermal accumulation (in day-of-year)
`T0.arr`	the candidate base temperatures (in °C)
`Year1`	the vector of the years in which a particular phenological event was recorded
`Time`	the vector of the occurrence times (in day-of-year) of a particular phenological event across many years

`Year2`	the vector of the years recording the climate data corresponding to the occurrence times
`DOY`	the vector of the dates (in day-of-year) for which climate data exist
`Tmin`	the minimum daily air temperature data (in °C) corresponding to `DOY`
`Tmax`	the maximum daily air temperature data (in °C) corresponding to `DOY`
`DOY.ul`	the upper limit of `DOY` used to predict the occurrence time
`fig.opt`	an optional argument to draw the figures associated with the determinations of the starting date and base temperature, and a comparison between the predicted and observed occurrence times
`S.def`	a mandatory defintion of the starting date when (i) `S.pd` is NULL and (ii) the minimum correlation coefficient method fails to find a suitable starting date
`verbose`	an optional argument allowing users to suppress the printing of computation progress

Details

The default of `S.pd` is NULL. In this case, the date associated with the minimum correlation coefficient [between the mean of the (`Tmin` + `Tmax`)/2 values (from a candidate starting date to the observed occurrence time) and the observed occurrence time] will be determined to be the starting date on the condition that it is smaller than the mininum phenological occurrence time. If the determined date associated with the minimum correlation coefficient is greater than the mininum phenological occurrence time, `S.def` will be used as the starting date. If `S.pd` is not NULL, the starting date will be directly set as `S.pd` irrespective of the minimum correlation coefficient method and the value of `S.def`. This means that `S.pd` is superior to `S.def` in determining the starting date.

The function does not require that `Year1` is the same as `unique(Year2)`, and the intersection of the two vectors of years will be kept. The unused years that have phenological records but lack climate data will be showed in `unused.years` in the returned list.

The numerical value of `DOY.ul` should be greater than or equal to the maximum `Time`.

Value

`S.arr`	the candidate starting dates (in day-of-year), whose default ranges from the minimum `DOY` to min(`DOY.ul`, the maximum `DOY`)
`cor.coef.arr`	the candidate correlation coefficients between the mean of the (`Tmin` + `Tmax`)/2 values (from a candidate starting date to the observed occurrence time) and the observed occurrence time
`cor.coef`	the minimum correlation coefficient, i.e., min(`cor.coef.arr`)
`search.failure`	a value of 0 or 1 of showing whether the starting date is successfully determined by the minimum correlation coefficient method when `S.pd = NULL`, where 0 represents success and 1 represents failure
`mAADD.arr`	an vector saving the interannual mean of the annual acccumulated degree days (AADD) values for each of the candidate base temperatures
`RMSE.arr`	a vector saving the candidate root-mean-square errors (in days) between the observed and predicted occurrence times for each of the candidate base temperatures

`AADD.arr`	the annual accumulated degree days (AADD) values in different years
`Year`	The overlapping years between `Year1` and `Year2`
`Time`	The observed occurrence times (day-of-year) in the overlapping years between `Year1` and `Year2`
`Time.pred`	the predicted occurrence times in different years
`S`	the determined starting date (day-of-year)
`T0`	the determined base temperature (in °C)
`AADD`	the expected annual accumulated degree days
`RMSE`	the smallest RMSE (in days) from the different candidate base temperatures
`unused.years`	the years that have phenological records but lack climate data

Note

The entire minimum and maximum daily temperature data set for the spring of each year should be provided. `AADD` is represented by the mean of `AADD.arr` in the output. When the argument of `S.pd` is not `NULL`, the returned value of `search.failure` will be `NA`. When the argument of `S.pd` is `NULL`, and the minimum correlation coefficient method fails to find a suitable starting date, the argument of `S.def` is then defined as the determined starting date, i.e., the returned value of `S`. At the same time, the returned value of `cor.coef` is defined as `NA`.

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Aono, Y. (1993) Climatological studies on blooming of cherry tree (*Prunus yedoensis*) by means of DTS method. *Bulletin of the University of Osaka Prefecture. Ser. B, Agriculture and life sciences* 45, 155−192 (in Japanese with English abstract).

Shi, P., Chen, Z., Reddy, G.V.P., Hui, C., Huang, J., Xiao, M. (2017a) Timing of cherry tree blooming: Contrasting effects of rising winter low temperatures and early spring temperatures. *Agricultural and Forest Meteorology* 240−241, 78−89. doi:10.1016/j.agrformet.2017.04.001

Shi, P., Fan, M., Reddy, G.V.P. (2017b) Comparison of thermal performance equations in describing temperature-dependent developmental rates of insects: (III) Phenological applications. *Annals of the Entomological Society of America* 110, 558−564. doi:10.1093/aesa/sax063

See Also

`predADD2`

Examples

```
data(apricotFFD)
data(BJDAT)
X1 <- apricotFFD
X2 <- BJDAT
```

```
Year1.val  <- X1$Year
Time.val   <- X1$Time
Year2.val  <- X2$Year
DOY.val    <- X2$DOY
Tmin.val   <- X2$MinDT
Tmax.val   <- X2$MaxDT
DOY.ul.val <- 120
T0.arr0    <- seq(3.5, 4, by = 0.1)
S.pd0      <- NULL


  cand.res1 <- ADD2( S.pd = S.pd0, T0.arr = T0.arr0, Year1 = Year1.val, Time = Time.val,
                     Year2 = Year2.val, DOY = DOY.val, Tmin = Tmin.val, Tmax = Tmax.val,
                     DOY.ul = DOY.ul.val, fig.opt = TRUE, S.def=54, verbose = TRUE )
  cand.res1

  S0 <- cand.res1$S.arr
  r0 <- cand.res1$cor.coef.arr

  dev.new()
  par1 <- par(family="serif")
  par2 <- par(mar=c(5, 5, 2, 2))
  par3 <- par(mgp=c(3, 1, 0))
 plot( S0, r0, cex.lab = 1.5, cex.axis = 1.5, xlab = "Candidate starting date (day-of-year)",
       ylab="Correlation coefficient between the mean temperature and FFD", type="l" )
  ind <- which.min(r0)
  points(S0[ind], r0[ind], cex = 1.5, pch = 16)
 text(S0[ind], r0[ind] + 0.1, bquote(paste(italic(S), " = ", .(S0[ind]), sep = "")), cex = 1.5)
  par(par1)
  par(par2)
  par(par3)

  # graphics.off()
```

ADP — *Function for Implementing the Accumulated Developmental Progress Method Using Mean Daily Temperatures*

Description

Estimates the starting date (S, in day-of-year) and the parameters of a developmental rate model in the accumulated developmental progress (ADP) method using mean daily air temperatures (Wagner et al., 1984; Shi et al., 2017a, b).

Usage

```
ADP( S.arr, expr, ini.val, Year1, Time, Year2, DOY, Temp, DOY.ul = 120,
     fig.opt = TRUE, control = list(), verbose = TRUE )
```

Arguments

`S.arr`	the candidate starting dates for thermal accumulation (in day-of-year)
`expr`	a user-defined model that is used in the accumulated developmental progress (ADP) method
`ini.val`	a vector or a list that saves the initial values of the parameters in `expr`
`Year1`	the vector of the years in which a particular phenological event was recorded
`Time`	the vector of the occurrence times (in day-of-year) of a particular phenological event across many years
`Year2`	the vector of the years recording the climate data corresponding to the occurrence times
`DOY`	the vector of the dates (in day-of-year) for which climate data exist
`Temp`	the mean daily air temperature data (in °C) corresponding to `DOY`
`DOY.ul`	the upper limit of `DOY` used to predict the occurrence time
`fig.opt`	an optional argument to draw the figures associated with the temperature-dependent developmental rate curve, the mean daily temperatures versus years, and a comparison between the predicted and observed occurrence times
`control`	the list of control parameters for using the `optim` function in the **stats** package
`verbose`	an optional argument allowing users to suppress the printing of computation progress

Details

It is better not to set too many candidate starting dates, as doing so will be time-consuming. If `expr` is selected as Arrhenius' equation, `S.arr` can be selected as the `S` obtained from the output of the `ADTS` function. Here, `expr` can be other nonlinear temperature-dependent developmental rate functions (see Shi et al. [2017b] for details). Further, `expr` can be any an arbitrary user-defined temperature-dependent developmental rate function, e.g., a function named `myfun`, but it needs to take the form of `myfun <- function(P, x){...}`, where `P` is the vector of the model parameter(s), and `x` is the vector of the predictor variable, i.e., the temperature variable.

The function does not require that `Year1` is the same as `unique(Year2)`, and the intersection of the two vectors of years will be kept. The unused years that have phenological records but lack climate data will be showed in `unused.years` in the returned list.

The numerical value of `DOY.ul` should be greater than or equal to the maximum `Time`.

Let r represent the temperature-dependent developmental rate, i.e., the reciprocal of the developmental duration required for completing a particular phenological event, at a constant temperature. In the accumulated developmental progress (ADP) method, when the annual accumulated developmental progress (AADP) reaches 100%, the phenological event is predicted to occurr for each year. Let AADP_i denote the AADP of the ith year, which equals

$$\mathrm{AADP}_i = \sum_{j=S}^{E_i} r_{ij}\left(\mathbf{P}; T_{ij}\right),$$

where S represents the starting date (in day-of-year), E_i represents the ending date (in day-of-year), i.e., the occurrence time of a pariticular phenological event in the ith year, $\mathbf{P}$ is the vector of the model parameters in `expr`, and T_{ij} represents the mean daily temperature of the jth day of the ith year (in °C or K). In theory, $\mathrm{AADP}_i = 100\%$, i.e., the AADP values of different years are a constant 100%. However, in practice, there is a certain deviation of AADP_i from 100%. The following approach is used to determine the predicted occurrence time. When $\sum_{j=S}^{F} r_{ij} = 100\%$ (where $F \geq S$), it follows that F is the predicted occurrence time; when $\sum_{j=S}^{F} r_{ij} < 100\%$ and $\sum_{j=S}^{F+1} r_{ij} > 100\%$, the trapezoid method (Ring and Harris, 1983) is used to determine the predicted occurrence time. Let $\hat{E}_i$ represent the predicted occurrence time of the ith year. Assume that there are n-year phenological records. When the starting date S and the temperature-dependent developmental rate model are known, the model parameters can be estimated using the Nelder-Mead optiminization method (Nelder and Mead, 1965) to minimize the root-mean-square error (RMSE) between the observed and predicted occurrence times, i.e.,

$$\hat{\mathbf{P}} = \arg\min_{\mathbf{P}} \{\mathrm{RMSE}\} = \arg\min_{\mathbf{P}} \sqrt{\frac{\sum_{i=1}^{n} \left(E_i - \hat{E}_i\right)^2}{n}}.$$

Because S is not determined, a group of candidate S values (in day-of-year) need to be provided. Assume that there are m candidate S values, i.e., $S_1, S_2, S_3, \cdots, S_m$. For each S_q (where q ranges between 1 and m), we can obtain a vector of the estimated model parameters, $\hat{\mathbf{P}}_q$, by minimizing RMSE_q using the Nelder-Mead optiminization method. Then we finally selected $\hat{\mathbf{P}}$ associated with $\min\{\mathrm{RMSE}_1, \mathrm{RMSE}_2, \mathrm{RMSE}_3, \cdots, \mathrm{RMSE}_m\}$ as the target parameter vector.

Value

`TDDR`	the temperature-dependent developmental rate matrix consisting of the year, day-of-year, mean daily temperature and developmental rate columns
`MAT`	a matrix consisting of the candidate starting dates and the estimates of candidate model parameters with the corresponding RMSEs
`Dev.accum`	the calculated annual accumulated developmental progresses in different years
`Year`	The overlapping years between `Year1` and `Year2`
`Time`	The observed occurrence times (day-of-year) in the overlapping years between `Year1` and `Year2`
`Time.pred`	the predicted occurrence times in different years
`S`	the determined starting date (day-of-year)
`par`	the estimates of model parameters
`RMSE`	the RMSE (in days) between the observed and predicted occurrence times
`unused.years`	the years that have phenological records but lack climate data

Note

The entire mean daily temperature data set for the spring of each year should be provided. In `TDDR`, the first column of `Year` saves the years, the second column of `DOY` saves the day-of-year values, the third column of `Temperature` saves the mean daily air temperatures calculated between the starting date to the occurrence times, and the fourth column of `Rate` saves the calculated developmental rates corresponding to the mean daily temperatures.

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Nelder, J.A., Mead, R. (1965) A simplex method for function minimization. *Computer Journal* 7, 308−313. doi:10.1093/comjnl/7.4.308

Ring, D.R., Harris, M.K. (1983) Predicting pecan nut casebearer (Lepidoptera: Pyralidae) activity at College Station, Texas. *Environmental Entomology* 12, 482−486. doi:10.1093/ee/12.2.482

Shi, P., Chen, Z., Reddy, G.V.P., Hui, C., Huang, J., Xiao, M. (2017a) Timing of cherry tree blooming: Contrasting effects of rising winter low temperatures and early spring temperatures. *Agricultural and Forest Meteorology* 240−241, 78−89. doi:10.1016/j.agrformet.2017.04.001

Shi, P., Fan, M., Reddy, G.V.P. (2017b) Comparison of thermal performance equations in describing temperature-dependent developmental rates of insects: (III) Phenological applications. *Annals of the Entomological Society of America* 110, 558−564. doi:10.1093/aesa/sax063

Wagner, T.L., Wu, H.-I., Sharpe, P.J.H., Shcoolfield, R.M., Coulson, R.N. (1984) Modelling insect development rates: a literature review and application of a biophysical model. *Annals of the Entomological Society of America* 77, 208−225. doi:10.1093/aesa/77.2.208

See Also

predADP

Examples

```
data(apricotFFD)
data(BJDAT)
X1 <- apricotFFD
X2 <- BJDAT

Year1.val  <- X1$Year
Time.val   <- X1$Time
Year2.val  <- X2$Year
DOY.val    <- X2$DOY
Temp.val   <- X2$MDT
DOY.ul.val <- 120
S.arr0     <- 47

#### Defines a re-parameterized Arrhenius' equation ###########################
Arrhenius.eqn <- function(P, x){
  B  <- P[1]
  Ea <- P[2]
  R  <- 1.987 * 10^(-3)
  x  <- x + 273.15
  10^12*exp(B-Ea/(R*x))
}
###############################################################################
```

```
#### Provides the initial values of the parameter of Arrhenius' equation #####
ini.val0 <- list( B = 20, Ea = 14 )
##############################################################################


 res5 <- ADP( S.arr = S.arr0, expr = Arrhenius.eqn, ini.val = ini.val0, Year1 = Year1.val,
              Time = Time.val, Year2 = Year2.val, DOY = DOY.val, Temp = Temp.val,
              DOY.ul = DOY.ul.val, fig.opt = TRUE, control = list(trace = FALSE,
              reltol = 1e-12, maxit = 5000), verbose = TRUE )
 res5

 TDDR <- res5$TDDR
 T    <- TDDR$Temperature
 r    <- TDDR$Rate
 Y    <- res5$Year
 DP   <- res5$Dev.accum

 dev.new()
 par1 <- par(family="serif")
 par2 <- par(mar=c(5, 5, 2, 2))
 par3 <- par(mgp=c(3, 1, 0))
 Ind <- sort(T, index.return=TRUE)$ix
 T1  <- T[Ind]
 r1  <- r[Ind]
 plot( T1, r1, cex.lab = 1.5, cex.axis = 1.5, pch = 1, cex = 1.5, col = 2, type = "l",
       xlab = expression(paste("Mean daily temperature (", degree, "C)", sep = "")),
    ylab = expression(paste("Calculated developmental rate (", {day}^{"-1"}, ")", sep = "")) )
 par(par1)
 par(par2)
 par(par3)

 dev.new()
 par1 <- par(family="serif")
 par2 <- par(mar=c(5, 5, 2, 2))
 par3 <- par(mgp=c(3, 1, 0))
 plot( Y, DP * 100, xlab = "Year",
       ylab = "Accumulated developmental progress (%)",
       ylim = c(50, 150), cex.lab=1.5, cex.axis = 1.5, cex = 1.5 )
 abline( h = 1 * 100, lwd = 1, col = 4, lty = 2 )
 par(par1)
 par(par2)
 par(par3)

 # graphics.off()
```

ADP2 *Function for Implementing the Accumulated Developmental Progress Method Using Minimum and Maximum Daily Temperatures*

Description

Estimates the starting date (S, in day-of-year) and the parameters of a developmental rate model in the accumulated developmental progress (ADP) method using minimum and maximum daily air temperatures (Wagner et al., 1984; Shi et al., 2017a, b).

Usage

```
ADP2( S.arr, expr, ini.val, Year1, Time, Year2, DOY, Tmin, Tmax,
      DOY.ul = 120, fig.opt = TRUE, control = list(), verbose = TRUE )
```

Arguments

`S.arr`	the candidate starting dates for thermal accumulation (in day-of-year)
`expr`	a user-defined model that is used in the accumulated developmental progress (ADP) method
`ini.val`	a vector or a list that saves the initial values of the parameters in `expr`
`Year1`	the vector of the years in which a particular phenological event was recorded
`Time`	the vector of the occurrence times (in day-of-year) of a particular phenological event across many years
`Year2`	the vector of the years recording the climate data corresponding to the occurrence times
`DOY`	the vector of the dates (in day-of-year) for which climate data exist
`Tmin`	the minimum daily air temperature data (in °C) corresponding to `DOY`
`Tmax`	the maximum daily air temperature data (in °C) corresponding to `DOY`
`DOY.ul`	the upper limit of `DOY` used to predict the occurrence time
`fig.opt`	an optional argument to draw the figures associated with the temperature-dependent developmental rate curve, the mean daily temperatures versus years, and a comparison between the predicted and observed occurrence times
`control`	the list of control parameters for using the `optim` function in the **stats** package
`verbose`	an optional argument allowing users to suppress the printing of computation progress

Details

It is better not to set too many candidate starting dates, as doing so will be time-consuming. If `expr` is selected as Arrhenius' equation, `S.arr` can be selected as the `S` obtained from the output of the `ADTS2` function. Here, `expr` can be other nonlinear temperature-dependent developmental rate functions (see Shi et al. [2017b] for details). Further, `expr` can be any an arbitrary user-defined temperature-dependent developmental rate function, e.g., a function named `myfun`, but it needs to take the form of `myfun <- function(P, x){...}`, where `P` is the vector of the model parameter(s), and `x` is the vector of the predictor variable, i.e., the temperature variable.

The function does not require that `Year1` is the same as `unique(Year2)`, and the intersection of the two vectors of years will be kept. The unused years that have phenological records but lack climate data will be showed in `unused.years` in the returned list.

The numerical value of `DOY.ul` should be greater than or equal to the maximum `Time`.

Let r represent the temperature-dependent developmental rate, i.e., the reciprocal of the developmental duration required for completing a particular phenological event, at a constant temperature. In the accumulated developmental progress (ADP) method, when the annual accumulated developmental progress (AADP) reaches 100%, the phenological event is predicted to occurr for each year. Let AADP_i denote the AADP of the ith year, which equals

$$\mathrm{AADP}_i = \sum_{j=S}^{E_i} \sum_{w=1}^{24} \frac{r_{ijw}\left(\mathbf{P}; T_{ijw}\right)}{24},$$

where S represents the starting date (in day-of-year), E_i represents the ending date (in day-of-year), i.e., the occurrence time of a pariticular phenological event in the ith year, $\mathbf{P}$ is the vector of the model parameters in `expr`, T_{ijw} represents the estimated mean hourly temperature of the wth hour of the jth day of the ith year (in °C or K), and r_{ijw} represents the developmental rate (per hour) at T_{ijw}, which is transferred to r_{ij} (per day) by dividing 24. This packages takes the method proposed by Zohner et al. (2020) to estimate the mean hourly temperature for each of 24 hours:

$$T_w = \frac{T_{\max} - T_{\min}}{2} \sin\left(\frac{w\pi}{12} - \frac{\pi}{2}\right) + \frac{T_{\max} + T_{\min}}{2},$$

where w represents the wth hour of a day, and $T_{\min}$ and $T_{\max}$ represent the minimum and maximum temperatures of the day, respectively.

In theory, $\mathrm{AADP}_i = 100\%$, i.e., the AADP values of different years are a constant 100%. However, in practice, there is a certain deviation of AADP_i from 100%. The following approach is used to determine the predicted occurrence time. When $\sum_{j=S}^{F} \sum_{w=1}^{24} r_{ijw}/24 = 100\%$ (where $F \geq S$), it follows that F is the predicted occurrence time; when $\sum_{j=S}^{F} \sum_{w=1}^{24} r_{ijw}/24 < 100\%$ and $\sum_{j=S}^{F+1} \sum_{w=1}^{24} r_{ijw}/24 > 100\%$, the trapezoid method (Ring and Harris, 1983) is used to determine the predicted occurrence time. Let $\hat{E}_i$ represent the predicted occurrence time of the ith year. Assume that there are n-year phenological records. When the starting date S and the temperature-dependent developmental rate model are known, the model parameters can be estimated using the Nelder-Mead optiminization method (Nelder and Mead, 1965) to minimize the root-mean-square error (RMSE) between the observed and predicted occurrence times, i.e.,

$$\hat{\mathbf{P}} = \arg \min_{\mathbf{P}} \{\mathrm{RMSE}\} = \arg \min_{\mathbf{P}} \sqrt{\frac{\sum_{i=1}^{n}\left(E_i - \hat{E}_i\right)^2}{n}}.$$

Because S is not determined, a group of candidate S values (in day-of-year) need to be provided. Assume that there are m candidate S values, i.e., $S_1, S_2, S_3, \cdots, S_m$. For each S_q (where q ranges between 1 and m), we can obtain a vector of the estimated model parameters, $\hat{\mathbf{P}}_q$, by minimizing RMSE_q using the Nelder-Mead optiminization method. Then we finally selected $\hat{\mathbf{P}}$ associated with $\min\{\mathrm{RMSE}_1, \mathrm{RMSE}_2, \mathrm{RMSE}_3, \cdots, \mathrm{RMSE}_m\}$ as the target parameter vector.

Value

`TDDR`	the temperature-dependent developmental rate matrix consisting of the year, day-of-year, estimated mean daily temperature (= (`Tmin` + `Tmax`)/2) and developmental rate columns

`MAT`	a matrix consisting of the candidate starting dates and the estimates of candidate model parameters with the corresponding RMSEs
`Dev.accum`	the calculated annual accumulated developmental progresses in different years
`Year`	The overlapping years between `Year1` and `Year2`
`Time`	The observed occurrence times (day-of-year) in the overlapping years between `Year1` and `Year2`
`Time.pred`	the predicted occurrence times in different years
`S`	the determined starting date (day-of-year)
`par`	the estimates of model parameters
`RMSE`	the RMSE (in days) between the observed and predicted occurrence times
`unused.years`	the years that have phenological records but lack climate data

Note

The entire minimum and maximum daily temperature data set for the spring of each year should be provided. In `TDDR`, the first column of `Year` saves the years, the second column of `DOY` saves the day-of-year values, the third column of `Temperature` saves the estimated mean daily air temperatures (= (`Tmin` + `Tmax`)/2) from the starting date to the occurrence times, and the fourth column of `Rate` saves the calculated developmental rates corresponding to the estimated mean daily temperatures.

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Shi, P., Fan, M., Reddy, G.V.P. (2017b) Comparison of thermal performance equations in describing temperature-dependent developmental rates of insects: (III) Phenological applications. *Annals of the Entomological Society of America* 110, 558−564. doi:10.1093/aesa/sax063

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See Also

predADP2

Examples

```
data(apricotFFD)
data(BJDAT)
X1 <- apricotFFD
X2 <- BJDAT

Year1.val  <- X1$Year
Time.val   <- X1$Time
Year2.val  <- X2$Year
DOY.val    <- X2$DOY
Tmin.val   <- X2$MinDT
Tmax.val   <- X2$MaxDT
DOY.ul.val <- 120
S.arr0     <- 46

#### Defines a re-parameterized Arrhenius' equation ###########################
Arrhenius.eqn <- function(P, x){
  B  <- P[1]
  Ea <- P[2]
  R  <- 1.987 * 10^(-3)
  x  <- x + 273.15
  10^12*exp(B-Ea/(R*x))
}
###############################################################################

#### Provides the initial values of the parameter of Arrhenius' equation #####
ini.val0 <- list( B = 20, Ea = 14 )
###############################################################################

# The usage is similar to that of the "ADP" function. There is only a need to
#   replace "Temp = Temp.val" with "Tmin = Tmin.val, Tmax = Tmax.val" when using
#   the "ADP2" function.
```

ADTS — *Function for Implementing the Accumulated Days Transferred to a Standardized Temperature Method Using Mean Daily Temperatures*

Description

Estimates the starting date (S, in day-of-year) and activation free energy (E_a, in kcal $\cdot$ mol^{-1}) in the accumulated days transferred to a standardized temperature (ADTS) method using mean daily air temperatures (Konno and Sugihara, 1986; Aono, 1993; Shi et al., 2017a, b).

Usage

```
ADTS( S.arr, Ea.arr, Year1, Time, Year2, DOY, Temp, DOY.ul = 120,
      fig.opt = TRUE, verbose = TRUE )
```

Arguments

`S.arr`	the candidate starting dates for thermal accumulation (in day-of-year)
`Ea.arr`	the candidate activation free energy values (in kcal $\cdot$ mol^{-1})
`Year1`	the vector of the years in which a particular phenological event was recorded
`Time`	the vector of the occurrence times (in day-of-year) of a particular phenological event across many years
`Year2`	the vector of the years recording the climate data corresponding to the occurrence times
`DOY`	the vector of the dates (in day-of-year) for which climate data exist
`Temp`	the mean daily air temperature data (in $^{\circ}$C) corresponding to `DOY`
`DOY.ul`	the upper limit of `DOY` used to predict the occurrence time
`fig.opt`	an optional argument to draw the figures associated with the determination of the combination the starting date and activation free energy, and a comparison between the predicted and observed occurrence times
`verbose`	an optional argument allowing users to suppress the printing of computation progress

Details

When `fig.opt` is equal to `TRUE`, it will show the contours of the root-mean-square errors (RMSEs) based on different combinations of S and E_a.

The function does not require that `Year1` is the same as `unique(Year2)`, and the intersection of the two vectors of years will be kept. The unused years that have phenological records but lack climate data will be showed in `unused.years` in the returned list.

The numerical value of `DOY.ul` should be greater than or equal to the maximum `Time`.

Value

`mAADTS.mat`	a matrix consisting of the means of the annual accumulated days transferred to a standardized temperature (AADTS) values from the combinations of S and E_a
`RMSE.mat`	the matrix consisting of the RMSEs (in days) from different combinations of S and E_a
`AADTS.arr`	the AADTS values in different years associated with the smallest value in `RMSE.mat`
`Year`	The overlapping years between `Year1` and `Year2`
`Time`	The observed occurrence times (day-of-year) in the overlapping years between `Year1` and `Year2`
`Time.pred`	the predicted occurrence times in different years
`S`	the determined starting date (day-of-year)

`Ea`	the determined activation free energy values (in kcal·mol^{-1})
`AADD`	the expected AADTS
`RMSE`	the smallest RMSE (in days) in `RMSE.mat` from different combinations of S and E_a
`unused.years`	the years that have phenological records but lack climate data

Note

The entire mean daily temperature data set for the spring of each year should be provided. `AADTS` is represented by the mean of `AADTS.arr` in the output.

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References

Aono, Y. (1993) Climatological studies on blooming of cherry tree (*Prunus yedoensis*) by means of DTS method. *Bulletin of the University of Osaka Prefecture. Ser. B, Agriculture and life sciences* 45, 155−192 (in Japanese with English abstract).

Konno, T., Sugihara, S. (1986) Temperature index for characterizing biological activity in soil and its application to decomposition of soil organic matter. *Bulletin of National Institute for Agro-Environmental Sciences* 1, 51−68 (in Japanese with English abstract).

Shi, P., Chen, Z., Reddy, G.V.P., Hui, C., Huang, J., Xiao, M. (2017a) Timing of cherry tree blooming: Contrasting effects of rising winter low temperatures and early spring temperatures. *Agricultural and Forest Meteorology* 240−241, 78−89. doi:10.1016/j.agrformet.2017.04.001

Shi, P., Fan, M., Reddy, G.V.P. (2017b) Comparison of thermal performance equations in describing temperature-dependent developmental rates of insects: (III) Phenological applications. *Annals of the Entomological Society of America* 110, 558−564. doi:10.1093/aesa/sax063

See Also

`predADTS`

Examples

```
data(apricotFFD)
data(BJDAT)
X1 <- apricotFFD
X2 <- BJDAT

Year1.val  <- X1$Year
Time.val   <- X1$Time
Year2.val  <- X2$Year
DOY.val    <- X2$DOY
Temp.val   <- X2$MDT
DOY.ul.val <- 120
S.arr0     <- seq(40, 60, by = 1)
```

```
Ea.arr0    <- seq(10, 20, by = 1)


  res3 <- ADTS( S.arr = S.arr0, Ea.arr = Ea.arr0, Year1 = Year1.val, Time = Time.val,
                Year2 = Year2.val, DOY = DOY.val, Temp = Temp.val, DOY.ul = DOY.ul.val,
                fig.opt = TRUE, verbose = TRUE)
  res3

  RMSE.mat0  <- res3$RMSE.mat
  RMSE.range <- range(RMSE.mat0)

  dev.new()
  par1 <- par(family="serif")
  par2 <- par(mar=c(5, 5, 2, 2))
  par3 <- par(mgp=c(3, 1, 0))
  image( S.arr0, Ea.arr0, RMSE.mat0, col = terrain.colors(200), axes = TRUE,
         cex.axis = 1.5, cex.lab = 1.5, xlab = "Starting date (day-of-year)",
       ylab = expression(paste(italic(E["a"]), " (kcal" %.% "mol"^{"-1"}, ")", sep = "")))
  points( res3$S, res3$Ea, cex = 1.5, pch = 16, col = 2 )
  contour( S.arr0, Ea.arr0, RMSE.mat0, levels = round(seq(RMSE.range[1],
        RMSE.range[2], len = 20), 4), add = TRUE, cex = 1.5, col = "#696969", labcex = 1.5)
  par(par1)
  par(par2)
  par(par3)

 resu3 <- ADTS( S.arr = 47, Ea.arr = seq(10, 20, by = 0.5), Year1 = Year1.val, Time = Time.val,
                 Year2 = Year2.val, DOY = DOY.val, Temp = Temp.val, DOY.ul = DOY.ul.val,
                 fig.opt = TRUE, verbose = TRUE)
  resu3

  # graphics.off()
```

ADTS2 *Function for Implementing the Accumulated Days Transferred to a Standardized Temperature Method Using Minimum and Maximum Daily Temperatures*

Description

Estimates the starting date (S, in day-of-year) and activation free energy (E_a, in kcal $\cdot$ mol^{-1}) in the accumulated days transferred to a standardized temperature (ADTS) method using minimum and maximum daily air temperatures (Konno and Sugihara, 1986; Aono, 1993; Shi et al., 2017a, b).

Usage

```
ADTS2( S.arr, Ea.arr, Year1, Time, Year2, DOY, Tmin, Tmax,
       DOY.ul = 120, fig.opt = TRUE, verbose = TRUE )
```

Arguments

S.arr	the candidate starting dates for thermal accumulation (in day-of-year)
Ea.arr	the candidate activation free energy values (in kcal $\cdot$ mol^{-1})
Year1	the vector of the years in which a particular phenological event was recorded
Time	the vector of the occurrence times (in day-of-year) of a particular phenological event across many years
Year2	the vector of the years recording the climate data corresponding to the occurrence times
DOY	the vector of the dates (in day-of-year) for which climate data exist
Tmin	the minimum daily air temperature data (in °C) corresponding to DOY
Tmax	the maximum daily air temperature data (in °C) corresponding to DOY
DOY.ul	the upper limit of DOY used to predict the occurrence time
fig.opt	an optional argument to draw the figures associated with the determination of the combination the starting date and activation free energy, and a comparison between the predicted and observed occurrence times
verbose	an optional argument allowing users to suppress the printing of computation progress

Details

When fig.opt is equal to TRUE, it will show the contours of the root-mean-square errors (RMSEs) based on different combinations of S and E_a.

The function does not require that Year1 is the same as unique(Year2), and the intersection of the two vectors of years will be kept. The unused years that have phenological records but lack climate data will be showed in unused.years in the returned list.

The numerical value of DOY.ul should be greater than or equal to the maximum Time.

Value

mAADTS.mat	a matrix consisting of the means of the annual accumulated days transferred to a standardized temperature (AADTS) values from the combinations of S and E_a
RMSE.mat	the matrix consisting of the RMSEs (in days) from different combinations of S and E_a
AADTS.arr	the AADTS values in different years associated with the smallest value in RMSE.mat
Year	The overlapping years between Year1 and Year2
Time	The observed occurrence times (day-of-year) in the overlapping years between Year1 and Year2
Time.pred	the predicted occurrence times in different years
S	the determined starting date (day-of-year)
Ea	the determined activation free energy values (in kcal$\cdot$mol^{-1})
AADD	the expected AADTS
RMSE	the smallest RMSE (in days) in RMSE.mat from different combinations of S and E_a
unused.years	the years that have phenological records but lack climate data

Note

The entire minimum and maximum daily temperature data set for the spring of each year should be provided. AADTS is represented by the mean of AADTS.arr in the output.

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References

Aono, Y. (1993) Climatological studies on blooming of cherry tree (*Prunus yedoensis*) by means of DTS method. *Bulletin of the University of Osaka Prefecture. Ser. B, Agriculture and life sciences* 45, 155−192 (in Japanese with English abstract).

Konno, T., Sugihara, S. (1986) Temperature index for characterizing biological activity in soil and its application to decomposition of soil organic matter. *Bulletin of National Institute for Agro-Environmental Sciences* 1, 51−68 (in Japanese with English abstract).

Shi, P., Chen, Z., Reddy, G.V.P., Hui, C., Huang, J., Xiao, M. (2017a) Timing of cherry tree blooming: Contrasting effects of rising winter low temperatures and early spring temperatures. *Agricultural and Forest Meteorology* 240−241, 78−89. doi:10.1016/j.agrformet.2017.04.001

Shi, P., Fan, M., Reddy, G.V.P. (2017b) Comparison of thermal performance equations in describing temperature-dependent developmental rates of insects: (III) Phenological applications. *Annals of the Entomological Society of America* 110, 558−564. doi:10.1093/aesa/sax063

See Also

predADTS2

Examples

```
data(apricotFFD)
data(BJDAT)
X1 <- apricotFFD
X2 <- BJDAT

Year1.val  <- X1$Year
Time.val   <- X1$Time
Year2.val  <- X2$Year
DOY.val    <- X2$DOY
Tmin.val   <- X2$MinDT
Tmax.val   <- X2$MaxDT
DOY.ul.val <- 120
S.arr0     <- seq(45, 47, by = 1)
Ea.arr0    <- seq(20, 24, by = 0.5)


  cand.res3 <- ADTS2( S.arr = S.arr0, Ea.arr = Ea.arr0, Year1 = Year1.val, Time = Time.val,
                      Year2 = Year2.val, DOY = DOY.val, Tmin = Tmin.val, Tmax = Tmax.val,
                       DOY.ul = DOY.ul.val, fig.opt = TRUE, verbose = TRUE)
```

```
cand.res3

RMSE.mat0  <- cand.res3$RMSE.mat
RMSE.range <- range(RMSE.mat0)

dev.new()
par1 <- par(family="serif")
par2 <- par(mar=c(5, 5, 2, 2))
par3 <- par(mgp=c(3, 1, 0))
image( S.arr0, Ea.arr0, RMSE.mat0, col = terrain.colors(200), axes = TRUE,
       cex.axis = 1.5, cex.lab = 1.5, xlab = "Starting date (day-of-year)",
     ylab = expression(paste(italic(E["a"]), " (kcal" %.% "mol"^{"-1"}, ")", sep = "")))
points( cand.res3$S, cand.res3$Ea, cex = 1.5, pch = 16, col = 2 )
contour( S.arr0, Ea.arr0, RMSE.mat0, levels = round(seq(RMSE.range[1],
      RMSE.range[2], len = 20), 4), add = TRUE, cex = 1.5, col = "#696969", labcex = 1.5)
par(par1)
par(par2)
par(par3)

# graphics.off()
```

---

apricotFFD *First flowering date records of* Prunus armeniaca

---

Description

The data consist of the first flowering date records of *Prunus armeniaca* at the Summer Palace (39°54′38″ N, 116°8′28″ E, 50 m a.s.l.) in Beijing, China between 1963 and 2010 with the exception of 1969−1971, and 1997−2002. **Data source**: Chinese Phenological Observation Network (Guo et al., 2015).

Usage

```
data(apricotFFD)
```

Details

In the data set, there are two columns of vectors: `Year` and `Time`. `Year` saves the recording years; and `Time` saves the 1963−2010 first flowering dates of *Prunus armeniaca* (in day-of-year).

References

Guo, L., Xu, J., Dai, J., Cheng, J., Wu, H., Luedeling, E. (2015) Statistical identification of chilling and heat requirements for apricotflower buds in Beijing, China. *Scientia Horticulturae* 195, 138−144. doi:10.1016/j.scienta.2015.09.006

Examples

```
data(apricotFFD)
attach(apricotFFD)

dev.new()
par1 <- par(family="serif")
par2 <- par(mar=c(5, 5, 2, 2))
par3 <- par(mgp=c(3, 1, 0))
plot( Year, Time, asp = 1, cex.lab = 1.5, cex.axis = 1.5,
      xlab = "Year", ylab = "First flowering date (day-of-year)" )
par(par1)
par(par2)
par(par3)

# graphics.off()
```

BJDAT — *Daily Air Temperature Data of Beijing from 1952 to 2012.*

Description

The data include the mean, minimum, and maximum daily temperatures (in °C) of Beijing between 1952 and 2012. **Data source**: China Meteorological Data Service Centre (https://data.cma.cn/en).

Usage

```
data(BJDAT)
```

Details

In the data set, there are seven columns of vectors: `Year`, `Month`, `Day`, `DOY`, `MDT`, `MinDT`, and `MaxDT`. `Year` saves the recording years; `Month` saves the recording months; `Day` saves the recording days; `DOY` saves the dates in day-of-year; `MDT` saves the mean daily temperatures (in °C) corresponding to `DOY`; `MinDT` saves the minimum daily temperatures (in °C) corresponding to `DOY`; `MaxDT` saves the maximum daily temperatures (in °C) corresponding to `DOY`.

References

Guo, L., Xu, J., Dai, J., Cheng, J., Wu, H., Luedeling, E. (2015) Statistical identification of chilling and heat requirements for apricotflower buds in Beijing, China. *Scientia Horticulturae* 195, 138−144. doi:10.1016/j.scienta.2015.09.006

Examples

```
data(BJDAT)
attach(BJDAT)

x    <- as.numeric( tapply(DOY, DOY, mean) )
y    <- as.numeric( tapply(MDT, DOY, mean) )
y.sd <- as.numeric( tapply(MDT, DOY, sd) )

dev.new()
par1 <- par(family="serif")
par2 <- par(mar=c(5, 5, 2, 2))
par3 <- par(mgp=c(3, 1, 0))
plot( x, y, cex = 1.5, xlim = c(0, 367), ylim = c(-10, 30),
      cex.lab = 1.5, cex.axis = 1.5, type = "n", xlab = "Day-of-year",
      ylab = expression(paste("Mean daily temperature (", degree, "C)", sep="")) )
for(i in 1:length(x)){
  lines(c(x[i], x[i]), c(y[i]-y.sd[i], y[i]+y.sd[i]), col=4)
}
points(x, y, cex = 1.5)
par(par1)
par(par2)
par(par3)

# graphics.off()
```

---

predADD *Prediction Function of the Accumulated Degree Days Method Using Mean Daily Temperatures*

Description

Predicts the occurrence times using the accumulated degree days method based on observed or predicted mean daily air temperatures (Aono, 1993; Shi et al., 2017a, b).

Usage

```
predADD(S, T0, AADD, Year2, DOY, Temp, DOY.ul = 120)
```

Arguments

`S`	the starting date for thermal accumulation (in day-of-year)
`T0`	the base temperature (in °C)
`AADD`	the expected annual accumulated degree days
`Year2`	the vector of the years recording the climate data for predicting the occurrence times
`DOY`	the vector of the dates (in day-of-year) for which climate data exist
`Temp`	the mean daily air temperature data (in °C) corresponding to `DOY`
`DOY.ul`	the upper limit of `DOY` used to predict the occurrence time

Details

In the accumulated degree days (ADD) method (Shi et al., 2017a, b), the starting date (S), the base temperature (T_0), and the annual accumulated degree days (AADD, which is denoted by k) are assumed to be constants across different years. Let k_i denote the AADD of the ith year, which equals

$$k_i = \sum_{j=S}^{E_i} \left(T_{ij} - T_0\right),$$

where E_i represents the ending date (in day-of-year), i.e., the occurrence time of a particular phenological event in the ith year, and T_{ij} represents the mean daily temperature of the jth day of the ith year (in °C). If $T_{ij} \leq T_0$, $T_{ij} - T_0$ is defined to be zero. In theory, $k_i = k$, i.e., the AADD values of different years are a constant. However, in practice, there is a certain deviation of k_i from k that is estimated by $\overline{k}$ (i.e., the mean of the k_i values). The following approach is used to determine the predicted occurrence time. When $\sum_{j=S}^{F} \left(T_{ij} - T_0\right) = \overline{k}$ (where $F \geq S$), it follows that F is the predicted occurrence time; when $\sum_{j=S}^{F} \left(T_{ij} - T_0\right) < \overline{k}$ and $\sum_{j=S}^{F+1} \left(T_{ij} - T_0\right) > \overline{k}$, the trapezoid method (Ring and Harris, 1983) is used to determine the predicted occurrence time.

Value

`Year`	the years with climate data
`Time.pred`	the predicted occurrence times (day-of-year) in different years

Note

The entire mean daily temperature data set for the spring of each year should be provided.

Author(s)

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References

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Shi, P., Fan, M., Reddy, G.V.P. (2017b) Comparison of thermal performance equations in describing temperature-dependent developmental rates of insects: (III) Phenological applications. *Annals of the Entomological Society of America* 110, 558−564. doi:10.1093/aesa/sax063

See Also

ADD

Examples

```
data(apricotFFD)
data(BJDAT)
X1 <- apricotFFD
X2 <- BJDAT
Year1.val  <- X1$Year
Time.val   <- X1$Time
Year2.val  <- X2$Year
DOY.val    <- X2$DOY
Temp.val   <- X2$MDT
DOY.ul.val <- 120
S.val      <- 65
T0.val     <- -0.5
AADD.val   <- 235.5282

res2 <- predADD( S = S.val, T0 = T0.val, AADD = AADD.val,
                 Year2 = Year2.val, DOY = DOY.val, Temp = Temp.val,
                 DOY.ul = DOY.ul.val )
res2


ind1  <- res2$Year %in% intersect(res2$Year, Year1.val)
ind2  <- Year1.val %in% intersect(res2$Year, Year1.val)
RMSE1 <- sqrt( sum((Time.val[ind2]-res2$Time.pred[ind1])^2) / length(Time.val[ind2]) )
RMSE1
```

---

predADD2 *Prediction Function of the Accumulated Degree Days Method Using Minimum and Maximum Daily Temperatures*

Description

Predicts the occurrence times using the accumulated degree days method based on observed or predicted minimum and maximum daily air temperatures (Aono, 1993; Shi et al., 2017a, b).

Usage

```
predADD2(S, T0, AADD, Year2, DOY, Tmin, Tmax, DOY.ul = 120)
```

Arguments

`S`	the starting date for thermal accumulation (in day-of-year)
`T0`	the base temperature (in °C)
`AADD`	the expected annual accumulated degree days
`Year2`	the vector of the years recording the climate data for predicting the occurrence times
`DOY`	the vector of the dates (in day-of-year) for which climate data exist
`Tmin`	the minimum daily air temperature data (in °C) corresponding to `DOY`
`Tmax`	the maximum daily air temperature data (in °C) corresponding to `DOY`
`DOY.ul`	the upper limit of `DOY` used to predict the occurrence time

Details

In the accumulated degree days (ADD) method (Shi et al., 2017a, b), the starting date (S), the base temperature (T_0), and the annual accumulated degree days (AADD, which is denoted by k) are assumed to be constants across different years. Let k_i denote the AADD of the ith year, which equals

$$k_i = \sum_{j=S}^{E_i} \sum_{w=1}^{24} \frac{(T_{ijw} - T_0)}{24},$$

where E_i represents the ending date (in day-of-year), i.e., the occurrence time of a particular phenological event in the ith year, and T_{ijw} represents the estimated mean hourly temperature of the wth hour of the jth day of the ith year (in °C). If $T_{ijw} \leq T_0$, $T_{ijw} - T_0$ is defined to be zero. This packages takes the method proposed by Zohner et al. (2020) to estimate the mean hourly temperature (T_w) for each of 24 hours:

$$T_w = \frac{T_{\max} - T_{\min}}{2} \sin\left(\frac{w\pi}{12} - \frac{\pi}{2}\right) + \frac{T_{\max} + T_{\min}}{2},$$

where w represents the wth hour of a day, and $T_{\min}$ and $T_{\max}$ represent the minimum and maximum temperatures of the day, respectively.

In theory, $k_i = k$, i.e., the AADD values of different years are a constant. However, in practice, there is a certain deviation of k_i from k that is estimated by $\overline{k}$ (i.e., the mean of the k_i values). The following approach is used to determine the predicted occurrence time. When $\sum_{j=S}^{F} \sum_{w=1}^{24} \left(T_{ijw} - T_0\right)/24 = \overline{k}$ (where $F \geq S$), it follows that F is the predicted occurrence time; when $\sum_{j=S}^{F} \sum_{w=1}^{24} \left(T_{ijw} - T_0\right)/24 < \overline{k}$ and $\sum_{j=S}^{F+1} \sum_{w=1}^{24} \left(T_{ijw} - T_0\right)/24 > \overline{k}$, the trapezoid method (Ring and Harris, 1983) is used to determine the predicted occurrence time.

Value

`Year`	the years with climate data
`Time.pred`	the predicted occurrence times (day-of-year) in different years

Note

The entire minimum and maximum daily temperature data set for the spring of each year should be provided.

Author(s)

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References

Aono, Y. (1993) Climatological studies on blooming of cherry tree (*Prunus yedoensis*) by means of DTS method. *Bulletin of the University of Osaka Prefecture. Ser. B, Agriculture and life sciences* 45, 155−192 (in Japanese with English abstract).

Ring, D.R., Harris, M.K. (1983) Predicting pecan nut casebearer (Lepidoptera: Pyralidae) activity at College Station, Texas. *Environmental Entomology* 12, 482−486. doi:10.1093/ee/12.2.482

Shi, P., Chen, Z., Reddy, G.V.P., Hui, C., Huang, J., Xiao, M. (2017a) Timing of cherry tree blooming: Contrasting effects of rising winter low temperatures and early spring temperatures. *Agricultural and Forest Meteorology* 240−241, 78−89. doi:10.1016/j.agrformet.2017.04.001

Shi, P., Fan, M., Reddy, G.V.P. (2017b) Comparison of thermal performance equations in describing temperature-dependent developmental rates of insects: (III) Phenological applications. *Annals of the Entomological Society of America* 110, 558−564. doi:10.1093/aesa/sax063

Zohner, C.M., Mo, L., Sebald, V., Renner, S.S. (2020) Leaf-out in northern ecotypes of wide-ranging trees requires less spring warming, enhancing the risk of spring frost damage at cold limits. *Global Ecology and Biogeography* 29, 1056−1072. doi:10.1111/geb.13088

See Also

ADD2

Examples

```
data(apricotFFD)
data(BJDAT)
X1 <- apricotFFD
X2 <- BJDAT
Year1.val  <- X1$Year
Time.val   <- X1$Time
Year2.val  <- X2$Year
DOY.val    <- X2$DOY
Tmin.val   <- X2$MinDT
Tmax.val   <- X2$MaxDT
DOY.ul.val <- 120
S.val      <- 65
T0.val     <- 3.8
AADD.val   <- 136.5805


  cand.res2 <- predADD2( S = S.val, T0 = T0.val, AADD = AADD.val, Year2 = Year2.val,
```

```
                              DOY = DOY.val, Tmin = Tmin.val, Tmax = Tmax.val,
                              DOY.ul = DOY.ul.val )
cand.res2


ind1  <- cand.res2$Year %in% intersect(cand.res2$Year, Year1.val)
ind2  <- Year1.val %in% intersect(cand.res2$Year, Year1.val)
RMSE1 <- sqrt( sum((Time.val[ind2]-cand.res2$Time.pred[ind1])^2) / length(Time.val[ind2]) )
RMSE1
```

`predADP` *Prediction Function of the Accumulated Developmental Progress Method Using Mean Daily Temperatures*

Description

Predicts the occurrence times using the accumulated developmental progress (ADP) method based on observed or predicted mean daily air temperatures (Wagner et al., 1984; Shi et al., 2017a, b).

Usage

```
predADP(S, expr, theta, Year2, DOY, Temp, DOY.ul = 120)
```

Arguments

`S`	the starting date for thermal accumulation (in day-of-year)
`expr`	a user-defined model that is used in the accumulated developmental progress (ADP) method
`theta`	a vector saves the numerical values of the parameters in `expr`
`Year2`	the vector of the years recording the climate data for predicting the occurrence times
`DOY`	the vector of the dates (in day-of-year) for which climate data exist
`Temp`	the mean daily air temperature data (in °C) corresponding to `DOY`
`DOY.ul`	the upper limit of `DOY` used to predict the occurrence time

Details

Organisms exhibiting phenological events in early spring often experience several cold days during their development. In this case, Arrhenius' equation (Shi et al., 2017a, b, and references therein) has been recommended to describe the effect of the absolute temperature (T in Kelvin [K]) on the developmental rate (r):

$$r = \exp\left(B - \frac{E_a}{RT}\right),$$

where E_a represents the activation free energy (in kcal $\cdot$ mol^{-1}); R is the universal gas constant (= 1.987 cal $\cdot$ mol^{-1} $\cdot$ K^{-1}); B is a constant. To maintain consistency between the units used for E_a and R, we need to re-assign R to be 1.987×10^{-3}, making its unit 1.987×10^{-3} kcal $\cdot$ mol^{-1} $\cdot$ K^{-1} in the above formula.

In the accumulated developmental progress (ADP) method, when the annual accumulated developmental progress (AADP) reaches 100%, the phenological event is predicted to occur for each year. Let AADP_i denote the AADP of the ith year, which equals

$$\mathrm{AADP}_i = \sum_{j=S}^{E_i} r_{ij},$$

where E_i represents the ending date (in day-of-year), i.e., the occurrence time of a pariticular phenological event in the ith year. If the temperature-dependent developmental rate follows Arrhenius' equation, the AADP of the ith year is equal to

$$\mathrm{AADP}_i = \sum_{j=S}^{E_i} \exp\left(B - \frac{E_a}{R\,T_{ij}}\right),$$

where T_{ij} represents the mean daily temperature of the jth day of the ith year (in K). In theory, $\mathrm{AADP}_i = 100\%$, i.e., the AADP values of different years are a constant 100%. However, in practice, there is a certain deviation of AADP_i from 100%. The following approach is used to determine the predicted occurrence time. When $\sum_{j=S}^{F} r_{ij} = 100\%$ (where $F \geq S$), it follows that F is the predicted occurrence time; when $\sum_{j=S}^{F} r_{ij} < 100\%$ and $\sum_{j=S}^{F+1} r_{ij} > 100\%$, the trapezoid method (Ring and Harris, 1983) is used to determine the predicted occurrence time.

The argument of `expr` can be any an arbitrary user-defined temperature-dependent developmental rate function, e.g., a function named `myfun`, but it needs to take the form of `myfun <- function(P, x){...}`, where `P` is the vector of the model parameter(s), and `x` is the vector of the predictor variable, i.e., the temperature variable.

Value

`Year`	the years with climate data
`Time.pred`	the predicted occurrence times (day-of-year) in different years

Note

The entire mean daily temperature data set for the spring of each year should be provided. It should be noted that the unit of `Temp` in **Arguments** is °C, not K. In addition, when using Arrhenius' equation to describe r, to reduce the size of B in this equation, Arrhenius' equation is multiplied by 10^{12} in calculating the AADP value for each year, i.e.,

$$\mathrm{AADP}_i = \sum_{j=S}^{E_i} \left[10^{12} \cdot \exp\left(B - \frac{E_a}{R\,T_{ij}}\right)\right].$$

Author(s)

Peijian Shi <pjshi@njfu.edu.cn>, Zhenghong Chen <chenzh64@126.com>, Jing Tan <jmjwyb@163.com>, Brady K. Quinn <Brady.Quinn@dfo-mpo.gc.ca>.

References

Ring, D.R., Harris, M.K. (1983) Predicting pecan nut casebearer (Lepidoptera: Pyralidae) activity at College Station, Texas. *Environmental Entomology* 12, 482−486. doi:10.1093/ee/12.2.482

Shi, P., Chen, Z., Reddy, G.V.P., Hui, C., Huang, J., Xiao, M. (2017a) Timing of cherry tree blooming: Contrasting effects of rising winter low temperatures and early spring temperatures. *Agricultural and Forest Meteorology* 240−241, 78−89. doi:10.1016/j.agrformet.2017.04.001

Shi, P., Fan, M., Reddy, G.V.P. (2017b) Comparison of thermal performance equations in describing temperature-dependent developmental rates of insects: (III) Phenological applications. *Annals of the Entomological Society of America* 110, 558−564. doi:10.1093/aesa/sax063

Wagner, T.L., Wu, H.-I., Sharpe, P.J.H., Shcoolfield, R.M., Coulson, R.N. (1984) Modelling insect development rates: a literature review and application of a biophysical model. *Annals of the Entomological Society of America* 77, 208−225. doi:10.1093/aesa/77.2.208

See Also

ADP

Examples

```
data(apricotFFD)
data(BJDAT)
X1 <- apricotFFD
X2 <- BJDAT
Year1.val  <- X1$Year
Time.val   <- X1$Time
Year2.val  <- X2$Year
DOY.val    <- X2$DOY
Temp.val   <- X2$MDT
DOY.ul.val <- 120
S.val      <- 47

# Defines a re-parameterized Arrhenius' equation
Arrhenius.eqn <- function(P, x){
  B  <- P[1]
  Ea <- P[2]
  R  <- 1.987 * 10^(-3)
  x  <- x + 273.15
  10^12*exp(B-Ea/(R*x))
}

P0 <- c(-4.3787, 15.0431)
T2 <- seq(-10, 20, len = 2000)
r2 <- Arrhenius.eqn(P = P0, x = T2)

dev.new()
```

```
par1 <- par(family="serif")
par2 <- par(mar=c(5, 5, 2, 2))
par3 <- par(mgp=c(3, 1, 0))
plot( T2, r2, cex.lab = 1.5, cex.axis = 1.5, pch = 1, cex = 1.5, col = 2, type = "l",
      xlab = expression(paste("Temperature (", degree, "C)", sep = "")),
      ylab = expression(paste("Developmental rate (", {day}^{"-1"}, ")", sep="")) )
par(par1)
par(par2)
par(par3)

res6 <- predADP( S = S.val, expr = Arrhenius.eqn, theta = P0, Year2 = Year2.val,
                 DOY = DOY.val, Temp = Temp.val, DOY.ul = DOY.ul.val )
res6

ind5 <- res6$Year %in% intersect(res6$Year, Year1.val)
ind6  <- Year1.val %in% intersect(res6$Year, Year1.val)
RMSE3 <- sqrt( sum((Time.val[ind6]-res6$Time.pred[ind5])^2) / length(Time.val[ind6]) )
RMSE3
```

---

predADP2 *Prediction Function of the Accumulated Developmental Progress Method Using Minimum and Maximum Daily Temperatures*

Description

Predicts the occurrence times using the accumulated developmental progress (ADP) method based on observed or predicted minimum and maximum daily air temperatures (Wagner et al., 1984; Shi et al., 2017a, b).

Usage

```
predADP2(S, expr, theta, Year2, DOY, Tmin, Tmax, DOY.ul = 120)
```

Arguments

S	the starting date for thermal accumulation (in day-of-year)
expr	a user-defined model that is used in the accumulated developmental progress (ADP) method
theta	a vector saves the numerical values of the parameters in expr
Year2	the vector of the years recording the climate data for predicting the occurrence times
DOY	the vector of the dates (in day-of-year) for which climate data exist
Tmin	the minimum daily air temperature data (in °C) corresponding to DOY
Tmax	the maximum daily air temperature data (in °C) corresponding to DOY
DOY.ul	the upper limit of DOY used to predict the occurrence time

Details

Organisms exhibiting phenological events in early spring often experience several cold days during their development. In this case, Arrhenius' equation (Shi et al., 2017a, b, and references therein) has been recommended to describe the effect of the absolute temperature (T in Kelvin [K]) on the developmental rate (r):

$$r = \exp\left(B - \frac{E_a}{RT}\right),$$

where E_a represents the activation free energy (in kcal $\cdot$ mol^{-1}); R is the universal gas constant (= 1.987 cal $\cdot$ mol^{-1} $\cdot$ K^{-1}); B is a constant. To maintain consistency between the units used for E_a and R, we need to re-assign R to be 1.987$\times 10^{-3}$, making its unit 1.987$\times 10^{-3}$ kcal $\cdot$ mol^{-1} $\cdot$ K^{-1} in the above formula.

In the accumulated developmental progress (ADP) method, when the annual accumulated developmental progress (AADP) reaches 100%, the phenological event is predicted to occur for each year. Let AADP_i denote the AADP of the ith year, which equals

$$\mathrm{AADP}_i = \sum_{j=S}^{E_i}\sum_{w=1}^{24}\frac{r_{ijw}}{24},$$

where E_i represents the ending date (in day-of-year), i.e., the occurrence time of a pariticular phenological event in the ith year. r_{ijw} is the developmental rate (per hour), which is transferred to r_{ij} (per day) by dividing 24. If the temperature-dependent developmental rate follows Arrhenius' equation, the AADP of the ith year is equal to

$$\mathrm{AADP}_i = \sum_{j=S}^{E_i}\sum_{w=1}^{24}\left\{\frac{1}{24}\exp\left(B - \frac{E_a}{RT_{ijw}}\right)\right\},$$

where T_{ijw} represents the estimated mean hourly temperature of the wth hour of the jth day of the ith year (in K). This packages takes the method proposed by Zohner et al. (2020) to estimate the mean hourly temperature (T_w) for each of 24 hours:

$$T_w = \frac{T_{\mathrm{max}} - T_{\mathrm{min}}}{2}\sin\left(\frac{w\pi}{12} - \frac{\pi}{2}\right) + \frac{T_{\mathrm{max}} + T_{\mathrm{min}}}{2},$$

where w represents the wth hour of a day, and T_{min} and T_{max} represent the minimum and maximum temperatures of the day, respectively.

In theory, $\mathrm{AADP}_i = 100\%$, i.e., the AADP values of different years are a constant 100%. However, in practice, there is a certain deviation of AADP_i from 100%. The following approach is used to determine the predicted occurrence time. When $\sum_{j=S}^{F}\sum_{w=1}^{24}\left(r_{ijw}/24\right) = 100\%$ (where $F \geq S$), it follows that F is the predicted occurrence time; when $\sum_{j=S}^{F}\sum_{w=1}^{24}\left(r_{ijw}/24\right) < 100\%$ and $\sum_{j=S}^{F+1}\sum_{w=1}^{24}\left(r_{ijw}/24\right) > 100\%$, the trapezoid method (Ring and Harris, 1983) is used to determine the predicted occurrence time.

The argument of `expr` can be any an arbitrary user-defined temperature-dependent developmental rate function, e.g., a function named `myfun`, but it needs to take the form of `myfun <- function(P, x){...}`, where `P` is the vector of the model parameter(s), and `x` is the vector of the predictor variable, i.e., the temperature variable.

Value

`Year`	the years with climate data
`Time.pred`	the predicted occurrence times (day-of-year) in different years

Note

The entire minimum and maximum daily temperature data set for the spring of each year should be provided. It should be noted that the unit of `Tmin` and `Tmax` in **Arguments** is °C, not K. In addition, when using Arrhenius' equation to describe r, to reduce the size of B in this equation, Arrhenius' equation is multiplied by 10^{12} in calculating the AADP value for each year, i.e.,

$$\mathrm{AADP}_i = \sum_{j=S}^{E_i} \sum_{w=1}^{24} \left[10^{12} \cdot \frac{1}{24} \cdot \exp\left(B - \frac{E_a}{R\,T_{ijw}} \right) \right].$$

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References

Ring, D.R., Harris, M.K. (1983) Predicting pecan nut casebearer (Lepidoptera: Pyralidae) activity at College Station, Texas. *Environmental Entomology* 12, 482−486. doi:10.1093/ee/12.2.482

Shi, P., Chen, Z., Reddy, G.V.P., Hui, C., Huang, J., Xiao, M. (2017a) Timing of cherry tree blooming: Contrasting effects of rising winter low temperatures and early spring temperatures. *Agricultural and Forest Meteorology* 240−241, 78−89. doi:10.1016/j.agrformet.2017.04.001

Shi, P., Fan, M., Reddy, G.V.P. (2017b) Comparison of thermal performance equations in describing temperature-dependent developmental rates of insects: (III) Phenological applications. *Annals of the Entomological Society of America* 110, 558−564. doi:10.1093/aesa/sax063

Wagner, T.L., Wu, H.-I., Sharpe, P.J.H., Shcoolfield, R.M., Coulson, R.N. (1984) Modelling insect development rates: a literature review and application of a biophysical model. *Annals of the Entomological Society of America* 77, 208−225. doi:10.1093/aesa/77.2.208

Zohner, C.M., Mo, L., Sebald, V., Renner, S.S. (2020) Leaf-out in northern ecotypes of wide-ranging trees requires less spring warming, enhancing the risk of spring frost damage at cold limits. *Global Ecology and Biogeography* 29, 1056−1072. doi:10.1111/geb.13088

See Also

`ADP2`

Examples

```
data(apricotFFD)
data(BJDAT)
X1 <- apricotFFD
X2 <- BJDAT
Year1.val  <- X1$Year
```

```
Time.val   <- X1$Time
Year2.val  <- X2$Year
DOY.val    <- X2$DOY
Tmin.val   <- X2$MinDT
Tmax.val   <- X2$MaxDT
DOY.ul.val <- 120
S.val      <- 46

# Defines a re-parameterized Arrhenius' equation
Arrhenius.eqn <- function(P, x){
  B  <- P[1]
  Ea <- P[2]
  R  <- 1.987 * 10^(-3)
  x  <- x + 273.15
  10^12*exp(B-Ea/(R*x))
}

P0 <- c(8.220327, 22.185942)
T2 <- seq(-10, 20, len = 2000)
r2 <- Arrhenius.eqn(P = P0, x = T2)

dev.new()
par1 <- par(family="serif")
par2 <- par(mar=c(5, 5, 2, 2))
par3 <- par(mgp=c(3, 1, 0))
plot( T2, r2, cex.lab = 1.5, cex.axis = 1.5, pch = 1, cex = 1.5, col = 2, type = "l",
      xlab = expression(paste("Temperature (", degree, "C)", sep = "")),
      ylab = expression(paste("Developmental rate (", {day}^{"-1"}, ")", sep="")) )
par(par1)
par(par2)
par(par3)


  cand.res6 <- predADP2( S = S.val, expr = Arrhenius.eqn, theta = P0, Year2 = Year2.val,
                    DOY = DOY.val, Tmin = Tmin.val, Tmax = Tmax.val, DOY.ul = DOY.ul.val )
  cand.res6

  ind5  <- cand.res6$Year %in% intersect(cand.res6$Year, Year1.val)
  ind6  <- Year1.val %in% intersect(cand.res6$Year, Year1.val)
 RMSE3 <- sqrt( sum((Time.val[ind6]-cand.res6$Time.pred[ind5])^2) / length(Time.val[ind6]) )
  RMSE3
```

`predADTS` *Prediction Function of the Accumulated Days Transferred to a Standardized Temperature Method Using Mean Daily Temperatures*

Description

Predicts the occurrence times using the accumulated days transferred to a standardized temperature (ADTS) method based on observed or predicted mean daily air temperatures (Konno and Sugihara, 1986; Aono, 1993; Shi et al., 2017a, b).

Usage

```
predADTS(S, Ea, AADTS, Year2, DOY, Temp, DOY.ul = 120)
```

Arguments

`S`	the starting date for thermal accumulation (in day-of-year)
`Ea`	the activation free energy (in kcal $\cdot$ mol^{-1})
`AADTS`	the expected annual accumulated days transferred to a standardized temperature
`Year2`	the vector of the years recording the climate data for predicting the occurrence times
`DOY`	the vector of the dates (in day-of-year) for which climate data exist
`Temp`	the mean daily air temperature data (in °C) corresponding to `DOY`
`DOY.ul`	the upper limit of `DOY` used to predict the occurrence time

Details

Organisms exhibiting phenological events in early spring often experience several cold days during their development. In this case, Arrhenius' equation (Shi et al., 2017a, b, and references therein) has been recommended to describe the effect of the absolute temperature (T in Kelvin [K]) on the developmental rate (r):

$$r = \exp\left(B - \frac{E_a}{RT}\right),$$

where E_a represents the activation free energy (in kcal $\cdot$ mol^{-1}); R is the universal gas constant (= 1.987 cal $\cdot$ mol^{-1} $\cdot$ K^{-1}); B is a constant. To maintain consistence between the units used for E_a and R, we need to re-assign R to be 1.987×10^{-3}, making its unit 1.987×10^{-3} kcal $\cdot$ mol^{-1} $\cdot$ K^{-1} in the above formula.

According to the definition of the developmental rate (r), it is the developmental progress per unit time (e.g., per day, per hour), which equals the reciprocal of the developmental duration D, i.e., $r = 1/D$. Let T_s represent the standard temperature (in K), and r_s represent the developmental rate at T_s. Let r_j represent the developmental rate at T_j, an arbitrary temperature (in K). It is apparent that $D_s r_s = D_j r_j = 1$. It follows that

$$\frac{D_s}{D_j} = \frac{r_j}{r_s} = \exp\left[\frac{E_a\left(T_j - T_s\right)}{R\,T_j\,T_s}\right],$$

where D_s/D_j is referred to as the number of days transferred to a standardized temperature (DTS) (Konno and Sugihara, 1986; Aono, 1993).

In the accumulated days transferred to a standardized temperature (ADTS) method, the annual accumulated days transferred to a standardized temperature (AADTS) is assumed to be a constant. Let AADTS_i denote the AADTS of the ith year, which equals

$$\mathrm{AADTS}_i = \sum_{j=S}^{E_i}\left\{\exp\left[\frac{E_a\left(T_{ij} - T_s\right)}{R\,T_{ij}\,T_s}\right]\right\},$$

where E_i represents the ending date (in day-of-year), i.e., the occurrence time of a pariticular phenological event in the ith year, and T_{ij} represents the mean daily temperature of the jth day of the ith year (in K). In theory, $\mathrm{AADTS}_i = \mathrm{AADTS}$, i.e., the AADTS values of different years are a constant. However, in practice, there is a certain deviation of AADTS_i from AADTS that is estimated by $\overline{\mathrm{AADTS}}$ (i.e., the mean of the AADTS_i values). The following approach is used to determine the predicted occurrence time. When $\sum_{j=S}^{F}\left\{\exp\left[\frac{E_a(T_{ij}-T_s)}{R\,T_{ij}\,T_s}\right]\right\} = \overline{\mathrm{AADTS}}$ (where $F \geq S$), it follows that F is the predicted occurrence time; when $\sum_{j=S}^{F}\left\{\exp\left[\frac{E_a(T_{ij}-T_s)}{R\,T_{ij}\,T_s}\right]\right\} < \overline{\mathrm{AADTS}}$ and $\sum_{j=S}^{F+1}\left\{\exp\left[\frac{E_a(T_{ij}-T_s)}{R\,T_{ij}\,T_s}\right]\right\} > \overline{\mathrm{AADTS}}$, the trapezoid method (Ring and Harris, 1983) is used to determine the predicted occurrence time.

Value

`Year`	the years with climate data
`Time.pred`	the predicted occurrence times (day-of-year) in different years

Note

The entire mean daily temperature data set for the spring of each year should be provided. It should be noted that the unit of `Temp` in **Arguments** is °C, not K.

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References

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See Also

`ADTS`

Examples

```
data(apricotFFD)
data(BJDAT)
X1 <- apricotFFD
X2 <- BJDAT
Year1.val  <- X1$Year
Time.val   <- X1$Time
Year2.val  <- X2$Year
DOY.val    <- X2$DOY
Temp.val   <- X2$MDT
DOY.ul.val <- 120
S.val      <- 47
Ea.val     <- 15
AADTS.val  <- 8.5879

res4 <- predADTS( S = S.val, Ea = Ea.val, AADTS = AADTS.val,
                  Year2 = Year2.val, DOY = DOY.val, Temp = Temp.val,
                  DOY.ul = DOY.ul.val )
res4

ind3  <- res4$Year %in% intersect(res4$Year, Year1.val)
ind4  <- Year1.val %in% intersect(res4$Year, Year1.val)
RMSE2 <- sqrt( sum((Time.val[ind4]-res4$Time.pred[ind3])^2) / length(Time.val[ind4]) )
RMSE2
```

`predADTS2` *Prediction Function of the Accumulated Days Transferred to a Standardized Temperature Method Using Minimum and Maximum Daily Temperatures*

Description

Predicts the occurrence times using the accumulated days transferred to a standardized temperature (ADTS) method based on observed or predicted minimum and maximum daily air temperatures (Konno and Sugihara, 1986; Aono, 1993; Shi et al., 2017a, b).

Usage

```
predADTS2(S, Ea, AADTS, Year2, DOY, Tmin, Tmax, DOY.ul = 120)
```

Arguments

`S`	the starting date for thermal accumulation (in day-of-year)
`Ea`	the activation free energy (in kcal $\cdot$ mol^{-1})
`AADTS`	the expected annual accumulated days transferred to a standardized temperature
`Year2`	the vector of the years recording the climate data for predicting the occurrence times

`DOY`	the vector of the dates (in day-of-year) for which climate data exist
`Tmin`	the minimum daily air temperature data (in °C) corresponding to `DOY`
`Tmax`	the maximum daily air temperature data (in °C) corresponding to `DOY`
`DOY.ul`	the upper limit of `DOY` used to predict the occurrence time

Details

Organisms exhibiting phenological events in early spring often experience several cold days during their development. In this case, Arrhenius' equation (Shi et al., 2017a, b, and references therein) has been recommended to describe the effect of the absolute temperature (T in Kelvin [K]) on the developmental rate (r):

$$r = \exp\left(B - \frac{E_a}{R\,T}\right),$$

where E_a represents the activation free energy (in kcal $\cdot$ mol^{-1}); R is the universal gas constant (= 1.987 cal $\cdot$ mol^{-1} $\cdot$ K^{-1}); B is a constant. To maintain consistence between the units used for E_a and R, we need to re-assign R to be 1.987×10^{-3}, making its unit 1.987×10^{-3} kcal $\cdot$ mol^{-1} $\cdot$ K^{-1} in the above formula.

According to the definition of the developmental rate (r), it is the developmental progress per unit time (e.g., per day, per hour), which equals the reciprocal of the developmental duration D, i.e., $r = 1/D$. Let T_s represent the standard temperature (in K), and r_s represent the developmental rate at T_s. Let r_j represent the developmental rate at T_j, an arbitrary temperature (in K). It is apparent that $D_s r_s = D_j r_j = 1$. It follows that

$$\frac{D_s}{D_j} = \frac{r_j}{r_s} = \exp\left[\frac{E_a\,(T_j - T_s)}{R\,T_j\,T_s}\right],$$

where D_s/D_j is referred to as the number of days transferred to a standardized temperature (DTS) (Konno and Sugihara, 1986; Aono, 1993).

In the accumulated days transferred to a standardized temperature (ADTS) method, the annual accumulated days transferred to a standardized temperature (AADTS) is assumed to be a constant. Let AADTS_i denote the AADTS of the ith year, which equals

$$\mathrm{AADTS}_i = \sum_{j=S}^{E_i}\sum_{w=1}^{24}\left\{\frac{1}{24}\exp\left[\frac{E_a\,(T_{ijw} - T_s)}{R\,T_{ijw}\,T_s}\right]\right\},$$

where E_i represents the ending date (in day-of-year), i.e., the occurrence time of a pariticular phenological event in the ith year, and T_{ijw} represents the estimated mean hourly temperature of the wth hour of the jth day of the ith year (in K). This packages takes the method proposed by Zohner et al. (2020) to estimate the mean hourly temperature (T_w) for each of 24 hours:

$$T_w = \frac{T_{\max} - T_{\min}}{2}\sin\left(\frac{w\pi}{12} - \frac{\pi}{2}\right) + \frac{T_{\max} + T_{\min}}{2},$$

where w represents the wth hour of a day, and $T_{\min}$ and $T_{\max}$ represent the minimum and maximum temperatures of the day, respectively.

In theory, $\mathrm{AADTS}_i = \mathrm{AADTS}$, i.e., the AADTS values of different years are a constant. However, in practice, there is a certain deviation of AADTS_i from AADTS that is estimated by

$\overline{\mathrm{AADTS}}$ (i.e., the mean of the AADTS_i values). The following approach is used to determine the predicted occurrence time. When $\sum_{j=S}^{F}\sum_{w=1}^{24}\left\{\frac{1}{24}\exp\left[\frac{E_a(T_{ijw}-T_s)}{R\,T_{ijw}\,T_s}\right]\right\} = \overline{\mathrm{AADTS}}$ (where $F \geq S$), it follows that F is the predicted occurrence time; when $\sum_{j=S}^{F}\sum_{w=1}^{24}\left\{\frac{1}{24}\exp\left[\frac{E_a(T_{ijw}-T_s)}{R\,T_{ijw}\,T_s}\right]\right\} < \overline{\mathrm{AADTS}}$ and $\sum_{j=S}^{F+1}\sum_{w=1}^{24}\left\{\frac{1}{24}\exp\left[\frac{E_a(T_{ijw}-T_s)}{R\,T_{ijw}\,T_s}\right]\right\} > \overline{\mathrm{AADTS}}$, the trapezoid method (Ring and Harris, 1983) is used to determine the predicted occurrence time.

Value

`Year`	the years with climate data
`Time.pred`	the predicted occurrence times (day-of-year) in different years

Note

The entire minimum and maximum daily temperature data set for the spring of each year should be provided. It should be noted that the unit of `Tmin` and `Tmax` in **Arguments** is °C, not K.

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See Also

`ADTS2`

Examples

```
data(apricotFFD)
data(BJDAT)
X1 <- apricotFFD
X2 <- BJDAT
Year1.val  <- X1$Year
Time.val   <- X1$Time
Year2.val  <- X2$Year
DOY.val    <- X2$DOY
Tmin.val   <- X2$MinDT
Tmax.val   <- X2$MaxD
DOY.ul.val <- 120
S.val      <- 46
Ea.val     <- 22.3
AADTS.val  <- 4.911035


  cand.res4 <- predADTS2( S = S.val, Ea = Ea.val, AADTS = AADTS.val,
                          Year2 = Year2.val, DOY = DOY.val, Tmin = Tmin.val,
                          Tmax = Tmax.val, DOY.ul = DOY.ul.val )
  cand.res4

  ind3  <- cand.res4$Year %in% intersect(cand.res4$Year, Year1.val)
  ind4  <- Year1.val %in% intersect(cand.res4$Year, Year1.val)
 RMSE2 <- sqrt( sum((Time.val[ind4]-cand.res4$Time.pred[ind3])^2) / length(Time.val[ind4]) )
  RMSE2
```

---

spphpr — *Spring Phenological Prediction*

Description

Predicts the occurrence times (in day-of-year) of spring phenological events. Three methods, including the accumulated degree days (ADD) method, the accumulated days transferred to a standardized temperature (ADTS) method, and the accumulated developmental progress (ADP) method, were used. See Shi et al. (2017a, 2017b) for details.

Details

The DESCRIPTION file:

Package:	spphpr
Type:	Package
Title:	Spring Phenological Prediction
Version:	1.1.4
Date:	2025-04-06
Authors@R:	c(person(given="Peijian", family="Shi", email="pjshi@njfu.edu.cn", role=c("aut", "cre")), person(given=c("Z

Author:	Peijian Shi [aut, cre], Zhenghong Chen [aut], Jing Tan [aut], Brady K. Quinn [aut]
Maintainer:	Peijian Shi <pjshi@njfu.edu.cn>
Description:	Predicts the occurrence times (in day-of-year) of spring phenological events. Three methods, including the acc
Depends:	R (>= 4.2.0)
License:	GPL (>= 2)

Index of help topics:

```
ADD                     Function for Implementing the Accumulated
                        Degree Days Method Using Mean Daily
                        Temperatures
ADD2                    Function for Implementing the Accumulated
                        Degree Days Method Using Minimum and Maximum
                        Daily Temperatures
ADP                     Function for Implementing the Accumulated
                        Developmental Progress Method Using Mean Daily
                        Temperatures
ADP2                    Function for Implementing the Accumulated
                        Developmental Progress Method Using Minimum and
                        Maximum Daily Temperatures
ADTS                    Function for Implementing the Accumulated Days
                        Transferred to a Standardized Temperature
                        Method Using Mean Daily Temperatures
ADTS2                   Function for Implementing the Accumulated Days
                        Transferred to a Standardized Temperature
                        Method Using Minimum and Maximum Daily
                        Temperatures
BJDAT                   Daily Air Temperature Data of Beijing from 1952
                        to 2012.
apricotFFD              First flowering date records of _Prunus
                        armeniaca_
predADD                 Prediction Function of the Accumulated Degree
                        Days Method Using Mean Daily Temperatures
predADD2                Prediction Function of the Accumulated Degree
                        Days Method Using Minimum and Maximum Daily
                        Temperatures
predADP                 Prediction Function of the Accumulated
                        Developmental Progress Method Using Mean Daily
                        Temperatures
predADP2                Prediction Function of the Accumulated
                        Developmental Progress Method Using Minimum and
                        Maximum Daily Temperatures
predADTS                Prediction Function of the Accumulated Days
                        Transferred to a Standardized Temperature
                        Method Using Mean Daily Temperatures
predADTS2               Prediction Function of the Accumulated Days
                        Transferred to a Standardized Temperature
```

	Method Using Minimum and Maximum Daily Temperatures
spphpr	Spring Phenological Prediction
toDOY	Function for Transferring a Date to the Value of Day-of-Year

Note

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References

Shi, P., Chen, Z., Reddy, G.V.P., Hui, C., Huang, J., Xiao, M. (2017a) Timing of cherry tree blooming: Contrasting effects of rising winter low temperatures and early spring temperatures. *Agricultural and Forest Meteorology* 240–241, 78–89. doi:10.1016/j.agrformet.2017.04.001

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toDOY — *Function for Transferring a Date to the Value of Day-of-Year*

Description

Transfers the date (from year, month and day) to the value of day-of-year.

Usage

```
toDOY(Year, Month, Day)
```

Arguments

Year	the vector of years
Month	the vector of months
Day	the vector of days

Details

The user needs to provide the three separate vectors of `Year`, `Month` and `Day`, rather than providing a single date vector. The arguments can be numerical vectors or character vectors.

Value

The returned value is a vector of transferred dates in day-of-year.

Note

The returned vector, DOY, usually matches with the year vector and the mean daily temperature vector as arguments in other functions, e.g., the ADD function.

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References

Shi, P., Chen, Z., Reddy, G.V.P., Hui, C., Huang, J., Xiao, M. (2017a) Timing of cherry tree blooming: Contrasting effects of rising winter low temperatures and early spring temperatures. *Agricultural and Forest Meteorology* 240−241, 78−89. doi:10.1016/j.agrformet.2017.04.001

Shi, P., Fan, M., Reddy, G.V.P. (2017b) Comparison of thermal performance equations in describing temperature-dependent developmental rates of insects: (III) Phenological applications. *Annals of the Entomological Society of America* 110, 558−564. doi:10.1093/aesa/sax063

See Also

BJDAT

Examples

```
data(BJDAT)
X2   <- BJDAT
DOY2 <- toDOY(X2$Year, X2$Month, X2$Day)
# cbind(X2$DOY, DOY2)
```

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